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ScienceDirect

Energy Procedia 140 (2017) 67–79

Energy Procedia

www.elsevier.com/locate/procedia

AiCARR 50th International Congress; Beyond NZEB Buildings, 10-11 May 2017, Matera, Italy

A high performance home in the Mediterranean climate: from the design principle to actual measurements

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Abstract

Experience developed in the northern European countries led, in the last decades, to standard and shared procedures for the design and construction of passive houses and similar high performance buildings. These approaches are specifically developed for cold climates, therefore cannot be directly applied to the Mediterranean climate, where substantially different climatic conditions must be challenged.

The design and early monitoring of a customized zero energy house, located in Sicily, is proposed as an exemplary case study for the future generation of high performance and nearly-zero energy buildings in the Mediterranean area. The key role played by the control of heat gains, and the correct use of thermal mass is highlighted, showing similarities and differences with passive houses built in the North Europe. The measurements of energy and environmental performance of the building show the effectiveness of the response of the adopted design approach to the specific climatic conditions.

Peer-review under responsibility of the scientific committee of the AiCARR 50th International Congress; Beyond NZEB Buildings.

Keywords: zero energy buildings; Mediterranean climate; energy performance; thermal comfort; passive house

1. Introduction

A passive solar approach to the design and construction of buildings has been extensively adopted since the ancient times, as pointed out by the study of vernacular architecture [1]. However, it was only in the 1988 that the first formally defined passive protocol was established under the name of "Passivhaus", by Bo Adamson of Lund

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Peer-review under responsibility of the scientific committee of the AiCARR 50th International Congress; Beyond NZEB Buildings
10.1016/j.egypro.2017.11.124

University, Sweden, and Wolfgang Feist of the Institut für Wohnen und Umwelt. In September 1996 the Passivhaus-Institut was founded, in Darmstadt, to promote and control the Passivhaus standard. The very first Passihaus building was eventually built in 1991, in Darmstad, Germany, i.e., the Darmstadt-Kranichstein Passive House [2].

The focus of the Passivhaus standard is on the reduction of energy needs for heating, and this may be achieved by applying a proper building orientation and shape, an adequate thermal insulation of the building envelope, and by airtightness and mechanical ventilation with heat recovery [3]. The Passivhaus certification method was, indeed, originally developed for countries with a continental climate (e.g. Germany), 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 this climate, especially for residential buildings.

Other similar certification methods exist in parallel to the Passivhaus, especially in central Europe, such as Minergies (Switzerland and Liechtenstein) and Casaclima (Bolzano province – Italy). These certification methods share with the Passivhaus standard, the emphasis on the reduction of the energy need for heating, as have mainly been applied in cold climates. The technologies and the overall energy concept developed to comply with the Passivhaus, Minergie and Casaclima certification methods in the continental climate, might, nevertheless, not necessarily be effective in other climates.

In the last years, however, the Passivhaus certification method tried to extend its applicability to warmer climates, under the Passive-on Project [4]. The current major technical requirements to comply with the standard are:

- Energy need for space heating lower than 15 kWh/m^2 per year
- Energy need for cooling and dehumidification lower than 15 kWh/m^2 per year
- Primary energy for all domestic applications (heating, hot water and domestic electricity) lower than 120 kWh/m^2 per year
- Air tightness at 50 Pa (n_{50}) lower than 0.6 air change per hour (ACH).

The Botticelli project, a single family detached house located in Sicily (Italy), was conceived to assess the possibility to extend the passive house concept to the Mediterranean climate. It is a living lab, inhabited all year long and designed on the basis of a new approach. Sensors and logging equipment have been installed and optimized to monitor its energy and comfort performance under different operational conditions [5,6]. The early monitoring results show the effectiveness of the adopted design approach in addressing the specific climatic conditions.

2. Building principles in the mediterranean climate

The Mediterranean climate - Csa/Csb under the Köppen climate classification [7] - is a particular variety of subtropical climate. The lands around the Mediterranean Sea form the largest area where this climate type is found. The majority of the regions with Mediterranean climates have relatively mild winters and very warm summers. Because most regions with a Mediterranean climate are near large bodies of water, temperatures are generally moderate with a comparatively small range of temperatures between the winter low and summer high (although the daily range of temperature during the summer is large due to dry and clear conditions, except along the immediate coasts) [8]. Under the Köppen-Geiger system, “C” zones have an average temperature above 10 °C in their warmest months, and an average in the coldest between 18 to −3 °C. Areas with this climate receive almost all of their precipitation during their winter season, and may go anywhere from 4 to 6 months during the summer without having any significant precipitation [8].

Building cooling is the most challenging issue in the Mediterranean climate, due to the strong solar radiation and to the high ambient temperature. The large daily range of temperature during the summer provides, nevertheless, a considerable potential for nigh-time ventilative cooling [9,10]. Figure 1 reports a brief summary of key weather data in Catania, as an example of Mediterranean climate.

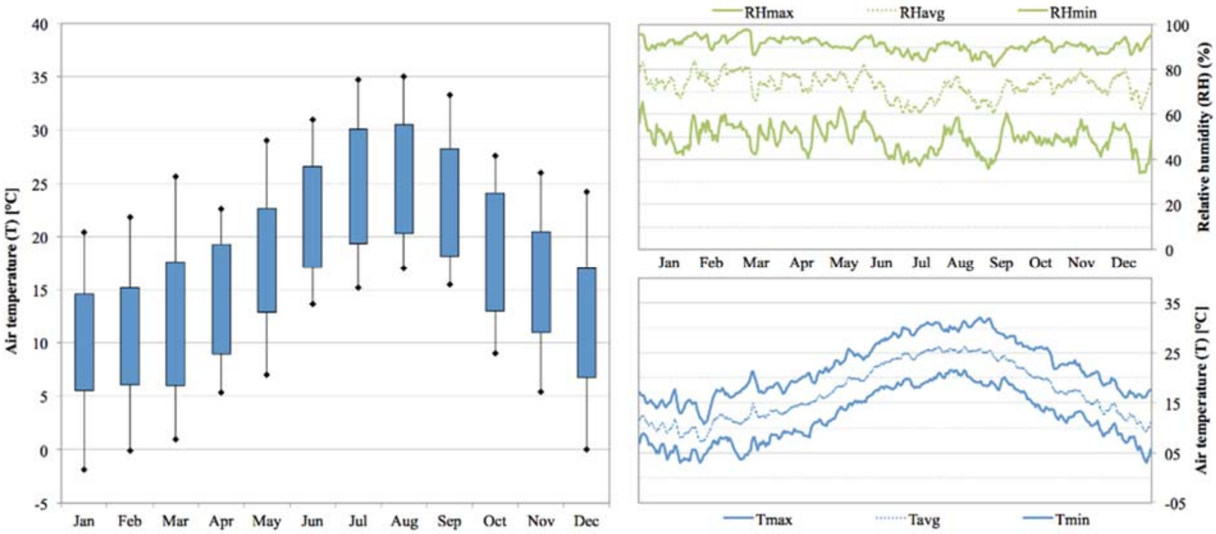


Fig. 1. Catania (Italy) weather data: (left) maximum and minimum values of the outdoor air temperature and interquartile range per each month (blue bar); (right) daily maximum, average and minimum outdoor air temperatures and relative humidity.

The Mediterranean climate provides a relevant potential to exploit passive strategies for building design [9]. The Passivhaus principle of reducing heating energy need is useful in this climate too, because even when outdoor conditions are not extreme, (e.g. outdoor temperature around 5 °C – Fig. 1), some heating may be required in order to keep the indoor operative temperature within the comfort ranges suggested by the standards [11,12]. Designing a performing envelope is therefore a key element both to reduce the energy need for heating and to improve occupants' comfort. However, in the Mediterranean climate the reduction of the energy need for cooling, maintaining good thermal comfort conditions, becomes the major design task. The building as a whole must be designed to perform well both under extreme summer conditions and under mild winter weather. The four corner stones of the Passivhaus standard (proper building orientation and shape, adequate thermal insulation of the building envelope, airtightness and mechanical ventilation with heat recovery) are still valid, but must be integrated with new basic principles, as follows:

- Proper building orientation and shape
- Adequate thermal insulation of the building envelope
- Adequate exploitation of thermal mass (thermal mass activation)
- Adjustable solar shading
- Adequate exploitation of natural ventilation (especially at night-time)
- Airtightness and mechanical ventilation with heat recovery (including by-pass option)
- Control of solar shading and ventilation (natural and mechanical).

The optimal exploitation of solar gains through the transparent elements of the envelope during the heating season, and their minimization during the cooling season, is the major task performed by adjustable solar shading devices.

The adequate thermal insulation of the building envelope is useful both to reduce heat loss through the whole envelope during the heating season, and to reduce heat gains (especially due to impinging solar radiation) through the opaque envelope during the cooling season. It may be obtained both selecting a stratigraphy including insulating layers able to attenuate and delay heat waves propagation from the outdoor environment to the indoor one, and using an outdoor coating of the opaque envelope with a high reflectance to solar radiation and high IR emissivity.

The thermal mass of building components may be used as well to delay heat waves propagation from the outdoor environment to the indoor one, and to manage the effect of the internal and solar gains inside of the building.

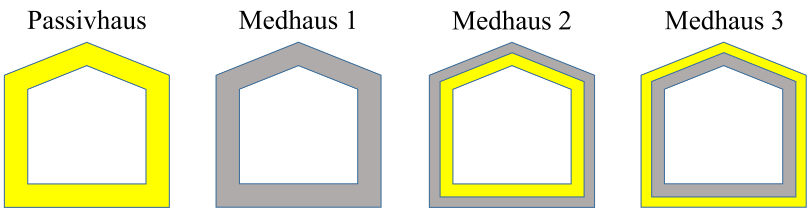
The first option relies on the exposition of the thermal mass of the envelope to the outdoor environment. A technical solution could be a wall composed of a layer with high thermal mass facing the outdoor environment and an insulation layer facing the indoor one (Fig. 2 – Medhaus 2). This solution may have drawbacks in terms of interstitial condensation and it does not provide a smoothing effect on internal heat gains and solar heat gains entering through the windows. Alternatively, it is possible to use just a single, and often thick, layer with high thermal mass (Fig. 2 – Medhaus 1), which may perform well under cooling conditions but could decrease the comfort conditions (mean radiant temperature) during the heating season, or increase the energy need for heating.

The second way of exploiting thermal mass requires an envelope stratigraphy including an insulating layer facing outdoor and a layer provided of some thermal mass (bricks, concrete, etc.) facing indoor (Fig. 2 – Medhaus 3). Horizontal massive slabs may also work for this purpose. This approach requires nevertheless a logic for activation of the thermal mass, allowing for adequate charge and discharge loops during the day. The activation may rely on ventilation (natural and/or mechanical) or on the mechanical circulation of a fluid inside of the building's slabs, i.e. a thermally activated building system (TABS). If the thermal mass is properly designed, this solution has no drawback during the heating season. However, a very large thermal capacity may affect the heating system performance, if this is used intermittently, and require a high installed active power to recover comfort conditions in a reasonable time after, e.g., a night or week-end setback. A proper balance must be therefore established.

Moreover, the use of thermal mass inside the building (mostly the floor slab) has been shown effective to reduce heating demand, when coupled with thermally insulated walls, because it helps providing a useful storage of internal and solar heat gains along the day [13]. This strategy showed to be mostly effective when thermal insulation is on the outer face of the wall [13]. Even from the thermal comfort point of view, the use of thermal mass inside of the building may provide a more homogeneous and acceptable surface temperature distribution along the day [14].

Whatever option is chosen for thermal mass, a kind of control is required. This may be provided in a manual way by the building user, if properly informed, highly motivated, and substantially present in the building – this is possible sometimes in private houses. A more reliable "automatic" form of control may be provided by a Building Automation Control System (BACS).

The Botticelli project was build adopting the principle sketched by Medhaus 3 in Fig. 2, where the thermal mass of walls, slab and roof is exposed to the indoor environment, and an insulation layer is placed on the external face of the envelope.



Design principles	• Thermal insulation • Airthight • Mech. ventilation	• Airthight • Mixed-mode Ventilation • Solar shading • Thermal mass • Smart control	• Thermal insulation • Airthight • Mixed-mode Ventilation • Solar shading • Thermal mass • Smart control	• Thermal insulation • Airthight • Mixed-mode Ventilation • Solar shading • Thermal mass • Smart control • Night-time ventilation
Possible drawbacks	• Overheating	• Cold discomfort • Heating energy need	• Lack of heat gain passive control • Interstitial condensation	• Heating system performance

Fig. 2. Passivhaus and three options for Mediterranean Passive House (Medhaus), including design principles and possible drawbacks

This design choice relies on a few considerations about the dynamic thermal characteristics of the building envelope, as defined by standard EN ISO 13786 [15]:

- The decrement factor (f): ratio of the modulus of the periodic thermal transmittance to the steady-state thermal transmittance (U-value)
- The time shift: period of time between the maximum amplitude of a cause (e.g. outdoor temperature) and the maximum amplitude of its effect (e.g. internal heat flux)
- The periodic thermal transmittance (U_p): complex quantity defined as the complex amplitude of the density of heat flow rate through the surface of the component adjacent to zone m, divided by the complex amplitude of the temperature in zone n when the temperature in zone m is held constant
- The thermal admittance (Y): complex quantity defined as the complex amplitude of the density of heat flow rate through the surface of the component adjacent to zone m, divided by the complex amplitude of the temperature in the same zone when the temperature on the other side is held constant.

When the thermal insulation layer is moved from the internal to the external face of the wall, the periodic thermal transmittance (U_p) decreases, and so it does the decrement factor (f), while the thermal admittance at the internal surface (Y_i) increases (Table 1). This is coherent with the fact that there is hence active thermal mass directly exposed to internal air, which is necessary for the effectiveness of summer night ventilative cooling and has a stabilising effect on the indoor operative temperature all-year round.

Detailed and extensive dynamic energy simulations [16], confirmed the potentially quite good performance of the building both in terms of energy and of thermal comfort when adopting the Medhaus 3 configuration reported in Fig. 2.

Table 1. Dynamic thermal characteristics of two wall stratigraphy options.

Outdoor thermal insulation	ρ	λ	L	R	c	U	U_p	f	Y_i	Y_e	f_R	Time Shift
homogeneous layer description	kg/m³	W/mK	m	m²K/W	J/kg K	W/(m²K)	W/(m²K)	-	W/(m²K)	W/(m²K)	-	[h]
Surface heat transfer coefficient (indoor)				0.130								
Indoor Clay plaster	1300	0.560	0.030	0.054	910							
Brick	920	0.142	0.300	2.113	1000	0.127	0.001	0.012	3.308	1.545	0.898	-0.287
Rookwool	90	0.036	0.200	5.556	1030							
Outdoor plaster	1800	0.900	0.010	0.011	910							
Surface heat transfer coefficient (outdoor)				0.040								

Indoor thermal insulation	ρ	λ	L	R	c	U	U_p	f	Y_i	Y_e	f_R	Time Shift
homogeneous layer description	kg/m³	W/mK	m	m²K/W	J/kg K	W/(m²K)	W/(m²K)	-	W/(m²K)	W/(m²K)	-	[h]
Surface heat transfer coefficient (indoor)				0.130								
Indoor Clay plaster	1300	0.560	0.030	0.054	910							
Rookwool	90	0.036	0.200	5.556	1030	0.127	0.002	0.015	2.575	3.577	0.954	-0.123
Brick	920	0.142	0.300	2.113	1000							
Outdoor plaster	1800	0.900	0.010	0.011	910							
Surface heat transfer coefficient (outdoor)				0.040								

note: ρ is the volumetric mass density; λ is the thermal conductivity; L is the layer's thickness; R is the unit thermal resitance; c is the specific capacity; U is the steady-state thermal transmittance; U_p is the periodic thermal transmittance; f is the decremental factor; Y_i is the internal surface admittance; Y_e is the external surface admittance; f_R is the internal surface factor

3. The Botticelli project

3.1. Building and systems

The Botticelli project is among the first examples of Net Zero Energy Buildings located in the Mediterranean climate [5]. The building, certified according to Passivhaus standard, is a single-family house monitored for research purposes and operated by a BACS, which is controlling the external solar blinds, the mixed-mode ventilation system, the PV and thermal solar panels and the Earth-to-Air Heat Exchanger (EAHE).

The building is a single story home, composed by a living room (including the kitchen), three bedrooms, a study room and three bathrooms (Fig. 3). The layout has a U shape, with an internal patio communicating with the garden and allowing for cross-flow ventilation and night-time ventilation strategies. The patio contributes also to daylighting, which is not analysed in this paper.

During the design phase, an optimization procedure, based on thermal discomfort minimization, has been adopted in order to select the optimal combinations of design variants. The parameters allowed to vary include: (i) steady-state thermal transmittance and (ii) time shift of the opaque envelope components, (iii) thermal transmittance and (iv) solar factor for windows, (v) options for controlling solar shading devices and (vi) windows opening during summer nights. A previous publication [16] provides more details on this optimization procedure, which has been conducted using the dynamic simulation engine of EnergyPlus [17] driven by the optimization engine of GenOpt [18].

The optimization process suggested to opt for a high level of thermal insulation and airtightness of the building envelope, with values in line with the Passivhaus standard requirements, as shown in Table 2. An adequate level of thermal mass and its activation via ventilation was also suggested. The technological application of these design indications was a multilayer wall including a continuous mineral wool layer facing the outdoor environment, and a core layer of massive elements such as masonry (for walls) and concrete (for slabs), facing the building interiors.

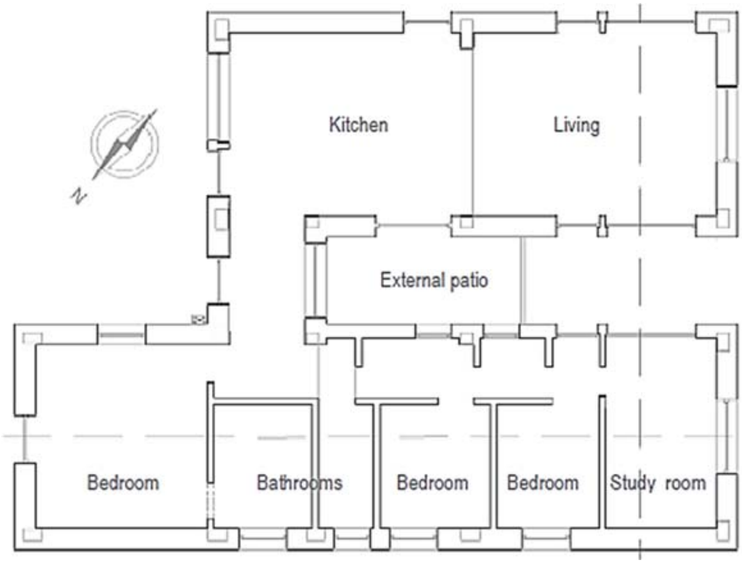


Fig. 3. Plan view of the building.

Table 2. Building main features.

Project name	Progetto Botticelli
Location	Mascalucia (Catania) - Sicily, Italy
Building type	Detached single family house
Conditioned floor area:	144 m^2
External walls thermal transmittance	0.13 $W/(m^2K)$
Roof thermal transmittance	0.13 $W/(m^2K)$
Basement thermal transmittance	0.23 $W/(m^2K)$
Windows thermal transmittance	0.90 – 1.10 $W/(m^2K)$
Envelope air tightness (n_{50})	Lower than 0.60 volume/h
Construction type	Structural concrete and masonry, with mineral wool thermal insulation

Building shape, windows locations and dimensions were defined to enhance free cooling strategies for passive control of heat gains. The building has been designed to exploit cross-ventilation in the living room, in the study room and in the bedrooms. In addition, the large openings in the living room promote high airflow rates, daylight and a nice view of the garden. Windows are equipped with external automatic shading, consisting of movable venetian blinds or roller shades. They guarantee the control of solar radiation during the whole year.

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 processed by the heating/cooling coils and distributed to the bedrooms and the living room. 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 [19] and it can be excluded from the ventilation system by means of a by-pass duct, when required, according to the chosen control strategy.

An electrical air to water heat pump 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).

Finally, a PV system is installed on the roof, with a peak power of 8.14 kW. The electricity production by the PV panels is continuously monitored and compared with the instantaneous energy use of the building and delivered energy (from the grid).

3.2. Control and monitoring systems

A comprehensive system has been designed and installed to provide an adequate control of the building and of its 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 handles indoor environmental parameters monitoring and the basic control of shading devices and of the heat pumps. It is based on the Konnex (KNX) standard and communication protocol [20]. The second part integrates and supervises the first, it is based on the BACnet communication protocol [21] and it has the purpose to complete the control potential of the first part. It includes the monitoring of a high number of sensors positioned in different sections of the building systems, and it allows for the implementation of further control algorithms for the heat pump and the ventilation systems. Finally, the thermal energy meters, installed in all the hydraulic loops, are communicating by means of the Meter-Bus (M-Bus) protocol [22,23], also integrated and supervised by the BACnet system. The structure of the entire system is reported in Fig. 4.

The KNX system and protocol are characterized by distributed intelligence; the installed components can, in fact, communicate with each other via the bus network. All the devices of the KNX system can act independently and include a part of the software code allowing them to perform some basic functions. Due to these features, the KNX system was initially installed as an independent system showing a high potential of replicability in other homes. It was eventually integrated by the BACnet system, which provides a general supervision and the advanced control and monitoring options, required in a living lab, such as the Botticelli project.

The system can control the following functions:

- External movable solar shadings
- Artificial lighting
- Mechanical ventilation for indoor air quality
- Space heating
- Space cooling
- Domestic how water production
- Scheduling of electrical appliances
- Watering of the garden and management of rain water storage
- Communication with occupants.

The monitoring set-up, consisting of about 130 sensors, was designed to adequately observe and log key parameters of indoor and outdoor environments, the status of components and devices, and of active and passive systems. It allows analysing in fine detail the building's energy and comfort performance.

The vertical position of the external roller shading and the venetian blinds angles can be automatically controlled according to threshold values for the external solar radiation (global horizontal or incident on the considered facade). Alternatively, they may be controlled on the basis of the external illuminance on the horizontal plane, or of the indoor environment temperature. The manual control by building's users is however always possible.

The control system can send messages to the building occupants (via SMS, e-mail, or a PC interface) to suggest windows operation, according to the indoor and outdoor temperature. Moreover, mechanical ventilation is prevented if any window or the entrance door is open. The speed of ventilation fans may be adjusted according to the measured level of carbon dioxide (CO_2), Volatile Organic Compounds (VOC), Relative Humidity, and indoor temperatures, via a proportional-integral-derivative (PID) control loops.

On the basis of indoor and outdoor air temperatures and of the air temperature at the exit section of the EAHE, the control system automatically selects the use of the EAHE as a supply to the ventilation system or bypasses it. With the same inputs the control also sets the activation or not of the heating and cooling coils.

Fig. 4. Scheme of communication protocols, control functions and monitored variable of the different part of the installed control and monitoring system.

4. Early results

The living lab's control and monitoring system required a series of interventions to define the final operational set-up. Eventually, a monitoring campaign started with the purpose to characterise the building energy and comfort performance under different operational conditions, giving priority to the free-floating mode, in order to test the passive behaviour of the home. Future experimental campaigns will test different control strategies and will allow the research team to evaluate their influence on the final performance of the building. Early monitoring results are summarised in the following part of the paper.

Figure 5 (a) reports the evolution of the external and average internal air temperature during the period from 4th to 21st September 2015, when the building was operated in free-floating mode. Although the external air temperature reaches values up to 36 °C, the average temperature into the building's rooms remains stable around 27 °C. The fluctuation of the indoor temperature is very low during the entire period, and included into a narrow range between 24 and 29 °C, whereas the outdoor temperature fluctuates between 12 and 36 °C. Since the mechanical ventilation was turned off during the whole period, the comfort levels were guaranteed exclusively by means of passive strategies, i.e., the operation of the solar shading systems and the activation of the thermal mass of the building via natural ventilation. The building showed therefore an excellent passive behaviour under typical mid-season conditions, where hot days alternate to fresh rainy days. From the 7th to the 9th, in fact, the production of the PV system is quite low (Fig. 5 (b)) and the outdoor relative humidity is quite high (Fig. 5 (c)), these are typical conditions of overcast rainy days. Figure 5(c) shows that, in the whole considered period, the electrical energy generated by the PV system is much higher than the total electricity demand of the home. The building is, therefore, a "prosumer", suppling a lot of energy to the national grid.

Figure 6 reports the temperature, humidity and grid interaction data for the period from 17th to 25th January 2016, assumed as a typical heating period. The outdoor temperature fluctuates between -1 °C and 12 °C, whereas the average internal temperature keeps stable around a comfort temperature of 20 °C. The indoor relative humidity keeps also quite stable, in a range between 50 and 60 %. In the same period, the energy demand due to heating, lighting and other appliances is quite low (Fig. 6 (c)). During the sunny days, such as the 21st and the 23rd, the electrical energy generated by the PV system is indeed able to compensate, and sometimes overcome, the building's energy demand. However, the energy balance during the entire period is slightly negative, i.e. the building imported more energy from the grid than supplied to it.

Figure 7 reports the monthly energy balance of the home from September 2015 to July 2016. The building energy demand including all energy uses related to the conditioned spaces and also the service spaces (i.e. garage, outdoor lighting, etc.) is in total 5 921 kWh, corresponding to 41.1 kWh/m^2 of treated floor area. This is largely overcome by the electrical energy generation from the PV system installed on the roof, that is 9 726 kWh, corresponding to 67.5 kWh/m^2.

Considering only the heating period, from the 15th November 2015 to the 31st March 2016 (according the national regulation - D.P.R. n. 412/93), the energy demand of the building is 3 118 kWh, corresponding to 21.7 kWh/m^2 of treated floor area. In the same period, the electrical energy generation from the PV system is 2 944 kWh corresponding to 20.4 kWh/m^2. During the heating season the energy balance of the building is therefore slightly negative, however, the production of electrical energy during the summer months substantially compensates and overcomes the energy demand, demonstrating that the building, on a yearly basis, is producing more energy than its actual energy use.

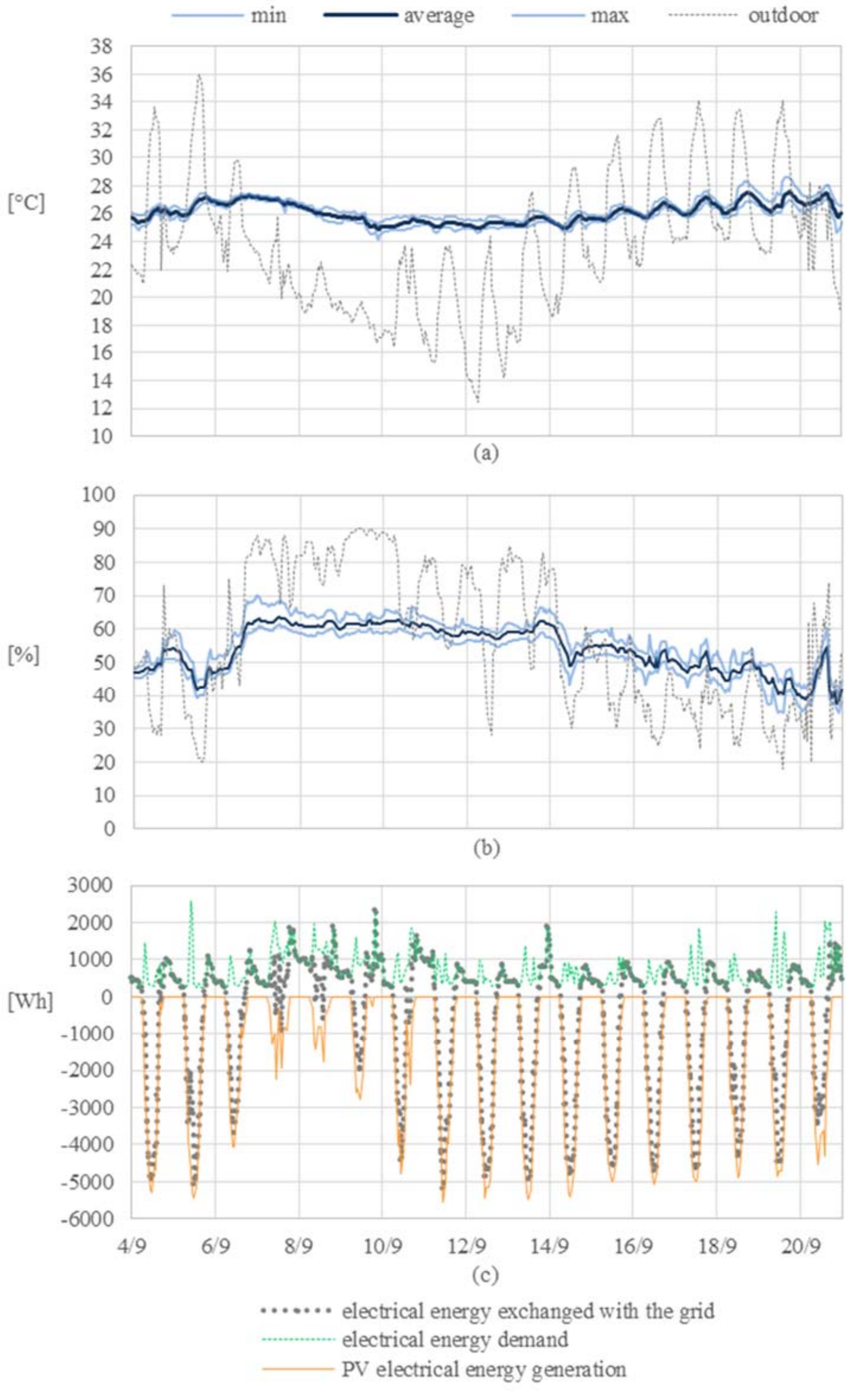


Fig. 5. Measured data in a warm period (4th-21st September 2015), building in free-floating mode: min, max and average values of air temperature in indoor rooms and outdoor environment (a) relative humidity (b); and electrical energy demand, generation from PV and exchanged with the grid (c).

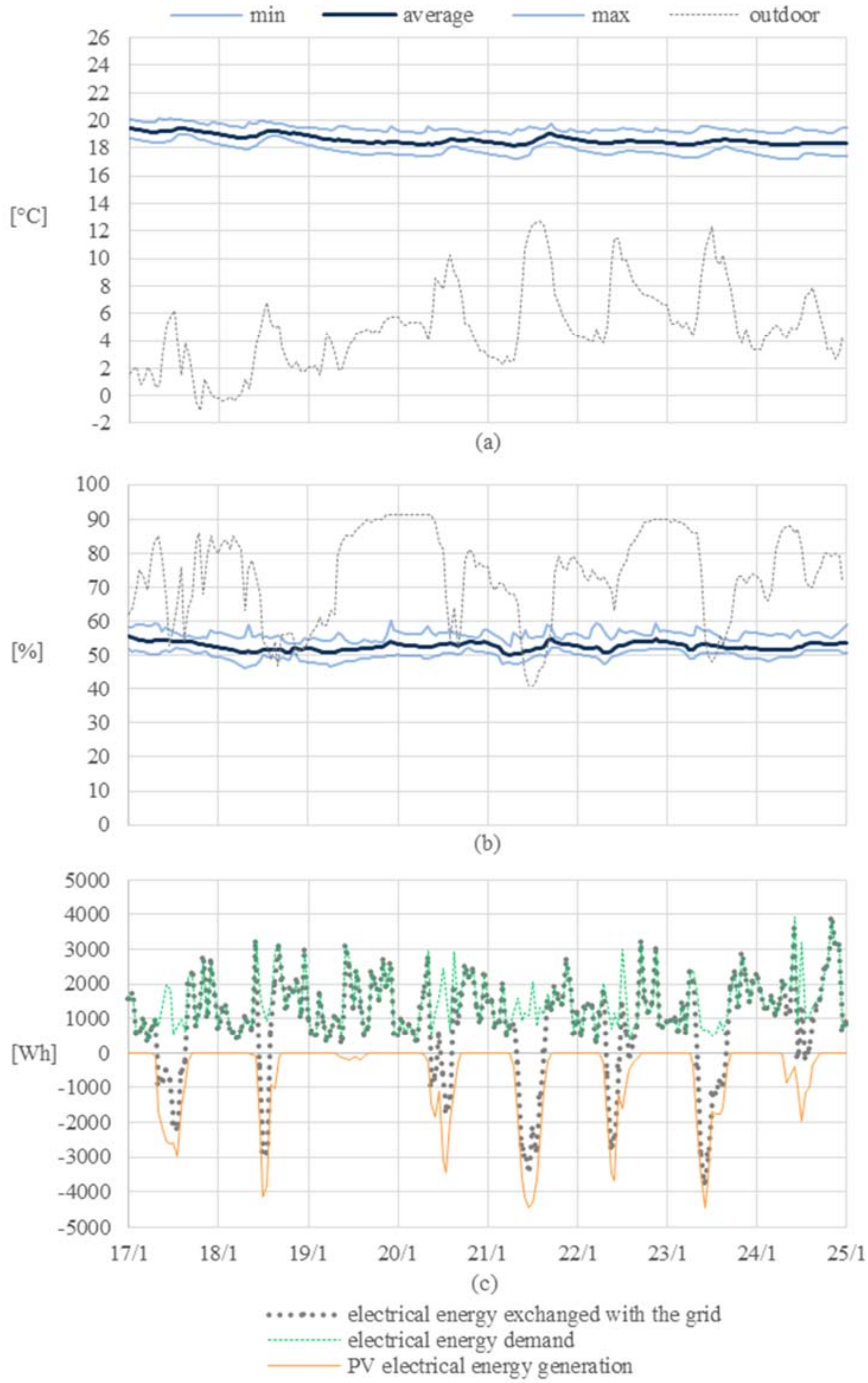


Fig. 6. Measured data in a heating period (17th-25st January 2016): min, max and average values of air temperature in indoor rooms and outdoor environment (a) relative humidity (b); and electrical energy demand, generation from PV and exchanged with the grid (c).

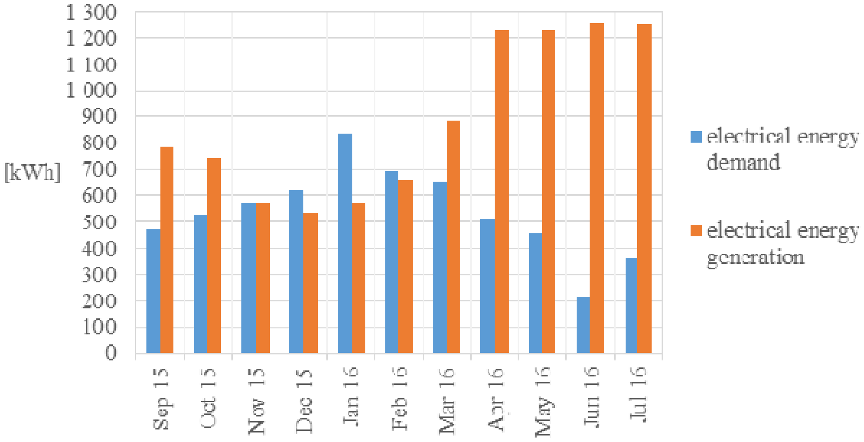


Fig. 7. Monthly electrical energy demand and generation (September 2015 - July 2016).

5. Conclusions

The Botticelli project was designed and built, with the objective to study the possibilities and limitations to extend passive design principles to the Mediterranean climate. The building is a living lab, equipped with an advanced control and monitoring system, that allows to test different control strategies, operational settings and to carefully assess the energy and comfort performance of the home. The early monitoring outcomes show that the building is able to maintain stable comfort conditions in free-floating mode, i.e., without active systems, during mid-season warm weather. It shows very good indoor comfort values also during typical heating season conditions, with a very low energy demand. On yearly basis, the energy balance of the building is positive, providing evidence of the possibility to go beyond the zero energy balance objective.

Acknowledgements

The authors would like to thank SIEMENS Building Technologies, ROCKWOOL Italia and Ing. Carmelo Sapienza of Sapienza&Partners engineering firm for technical support. This research was partly conducted within the frame of the QUANTUM project (Quality management for building performance - improving energy performance by life cycle quality management), supported by the Horizon 2020 programme, and of the PAR2015 research program, supported by ENEA. Fruitful discussions with colleagues of Annex 62 Ventilative cooling are also acknowledged.

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