



Article

# NZEB Analyses by Means of Dynamic Simulation and Experimental Monitoring in Mediterranean Climate

Anna Magrini \*  and Giorgia Lentini 

Department of Civil Engineering and Architecture, University of Pavia, 27100 Pavia, Italy;  
giorgia.lentini01@universitadipavia.it

\* Correspondence: magrini@unipv.it

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**Abstract:** The reduction of energy consumption in the building sector has promoted the spread of the NZEB (Nearly Zero Energy Building) model. A future target is represented by positive-energy buildings (PEB), which produce more energy than they consume. The study is centred on the examination of some peculiarities of NZEB through a case study and on the analysis of opportunities for further increase in energy performance, to trace the road that each designer should take, through an extensive evaluation of the potentials variations on the project that could lead to better results. The project assessments are developed through a dynamic simulation model and the data from the monitoring of the building's performance are used to evaluate the actual energy saving conditions. The analyses demonstrate the importance of an accurate design of the envelope and technical building systems associated with a smart management of the control systems and the setting of the set points, for the optimal operation of the systems. Ambitious but feasible design choices and an accurate analysis of the possibility of increasing the energy performance of a NZEB can lead to reaching the PEB target and energy independence, enhancing the production of energy from renewable sources.

**Keywords:** energy efficiency policy; nearly zero energy building; Positive Energy Building; energy performance of buildings; thermal behaviour; thermal dynamic simulation

## 1. Introduction

This research aims at enriching the knowledge of some of the most useful actions in building design to reach the best energy performance towards the NZEB (Nearly Zero Energy Building) target, outlining some steps of the building design, providing examples of the assessments that should be developed, to support the best choices, depending on the specific context in which the building is located (Section 2). The focus is on new buildings, even if most of the aspects here considered can be applied also to existing buildings retrofit.

Through the analysis of an exemplary case study, a good combination of envelope-system design and smart management is analysed, simulation results and monitored data are considered, and some variations are proposed and evaluated, to show advantages and problems, depending on a cost analysis. The main characteristics of the building envelope and the technical systems of the case study are typical of a single family house in an urban context not densely populated (Section 3).

The energy analysis is carried out by means of dynamic simulation to highlight the aspects relating to real-time control combined with smart management of the temperature set point, and the systems operating times (Section 4). Firstly, a comparison between this approach and the results of a semi-stationary model in winter conditions is presented, and the energy performance data are compared with the real consumption to critically analyse the different methods.

The results of the dynamic simulation method allow to put in evidence different effects of solar energy, such as the contribution of the solar greenhouse whose behaviour is analysed in detail during

the winter season. In the summer season, the possibility of using the greenhouse structure to protect the façade with reflective white curtains and the possibility of opening the vertical glazed sections of the greenhouse (sliding) cancels any potentially negative effects of overheating.

The heat pump operation, supported by the PV system, is analysed in detail in relation to the internal/external temperatures of the months of July and August. The analysis of the data collected by the photovoltaic system allows to confirm, as foreseen by the project, the total coverage of the building's energy needs at an annual cycle and to highlight the surplus of energy produced which would allow the building to be classified as PEB to represent a pole in the distribution of renewable energy produced in excess.

Finally, some possibilities are described for realizing a better project or any interventions on the current one, through better management (Section 5). Potential design and technical systems management variants are therefore analysed. Among these, only the most relevant and promising results for a potential increase in energy performance or for an increase in internal comfort are highlighted, obtained by considering the following aspects:

- At the plant management level, actions on the regulation of the internal temperature, with possible variations to the current setting of the room temperature set points.
- At the design level, evaluation of the actual need of the solar greenhouse, which, analysed through dynamic simulation, turns out to be a very important element in terms of energy savings in winter conditions, also in relation to the intelligent management of the air flow rates from it to internal environments.
- Evaluation of the possibility of energy storage in batteries.
- Opportunity to use a biomass heat generator to support the heat pump, in periods when the PV system does not produce enough energy to meet the needs.

## 2. Literature Review

Some aspects related to the current European NZEB energy model towards its future positive energy implementation, its concrete methods of application through technologies and studies for new optimized materials, and the importance of an integrated design between building envelope and systems are presented briefly.

### 2.1. The New Energy Performance Target

Some notes on the NZEB model are here summarised as it currently represents the target to reach for the new buildings and for the restoration, when possible. The introduction of the NZEB (Nearly Zero Energy Building) model in 2010 represents a further development of the particular focus on energy consumption of the building stock since 2002 [1]. The construction sector continues to be under observation, as underlined by the European Commission Recommendation (2019) [2], which indicates the buildings, responsible for almost the 40% of final energy consumption, at the heart of the Union's energy efficiency policy. Therefore, the NZEB objective, initially conceived for new buildings, begins to be extended to existing buildings, in a long-term renovation strategy (Directive 2018/844/EU [3]).

The peculiarity of a NZEB compared to other buildings is the zero (or almost) energy balance between energy demand compared to the generation of energy from renewable sources [4]. Attention is also paid to the quality conditions of the indoor environments (IEQ-Indoor Environmental Quality). In fact, a NZEB should guarantee not only a very low energy consumption, largely covered by RES, but also a good level in terms of thermohygrometric comfort and air healthiness, as well as visual and acoustic comfort.

Another important aspect is the efficient integration of the building into a "smart grid". This transition can be supported by the insertion of control mechanisms (BCS—building control system) and the management (BMS—building management system) of the plant subsystems, for which the building can interact with the occupants and the electricity grid, for keeping the required

internal conditions unchanged and limiting energy consumption. The smart grid would allow the integrated management of individual NZEBs, to realize an energy distribution network and, therefore, the organization of entire neighbourhoods in which some buildings could be identified as PEB (Positive Energy Building), buildings designed and sized to produce more energy than that necessary for their sustenance [5,6]. The current limited diffusion of this model could be attributed to two main reasons: absence of indications on the PEB targets, which should be formulated by the European Commission, and need for extensive adaptation of existing urban networks, to be ready to accept exchanges between the energy produced by the PEB and the user request. Anyway, in recent years, the PEB model has begun to be considered as a possible evolution of the NZEB target, jointly with the PED (Positive Energy District) one. With this last model, energy-independent districts could be built, where energy flows are exchanged between high-performance buildings and others unable to autonomously provide for their own energy support.

## 2.2. Technologies and Strategies to Support the NZEB Target

The most recent studies take into account both consolidate and innovative solutions for building envelope and systems: heavy structures, materials, plant systems already on the market used in an innovative way, increase in the use of plant regulation. However, it is difficult to generalize methods and approaches to outline indications on the use of advanced materials and of sustainable energy generation systems: indications both on materials and systems must be carefully evaluated according to the climate and the architectural characteristics of the building linked to the urban context in which it is located [5].

Often, well-known technologies are re-proposed in an innovative version and adapted to new needs, as they can be very useful for making the most appropriate choices. For example, a well-known technology, such as that of the Trombe wall, represents a passive solution for building envelopes that can lead to high-level energy performance [7].

Innovative wall configurations can limit the thermal losses whilst increasing solar heat gains to the heated spaces, also in cold climates [8]. The combination between the Trombe wall and the PCM thermal storage properties can allow obtaining good results to reduce thermal losses effectively.

The possibility of using sustainable materials in new buildings is particularly interesting. For example, the use of wood could find wider diffusion. However, technologies that provide for an important use of wood are not very well established, especially in areas where the wall thermal inertia is important for reducing the effects of solar radiation. Although the requirements of new buildings in the Mediterranean area appear particularly binding for multi-storey buildings with a massive employment of wooden materials, this technology can help to reach good results [9]. From dynamic simulation, it was assessed that a rational exploitation of the building thermal mass can be obtained by the use of wide dead band thermostats, in addition with triple pane glass windows, to obtain a good compromise between thermal losses and solar gains, and heat pumps coupled with a PV generator.

In all cases where a more accurate and in-depth analysis of energy performance is required, the use of dynamic simulation software appears indispensable, as it allows the analysis, in detail, of the behaviour of the structures and the possibility of heat storage in the daily cycle or in wider intervals. Furthermore, for a more adequate formulation and an accurate knowledge of the choices to be made to obtain the best energy performance of a building, it is necessary to proceed with cost assessments in parallel with the energy calculations and to perform combined analyses on energy-economic aspects.

The selection of the most appropriate simulation method is essential to limit uncertainty in the results and guarantee their accuracy. Usually the use of simplified models, instead of dynamic simulation, does not allow the analysis, in detail, of changes in internal conditions and to describe the thermal comfort conditions.

This problem becomes of particular importance when the aim is the management potential of the energy produced for achieving positive energy performance. In this case, parametric analyses can

be useful [10] to identify the optimum combination of technologies through suitable technical and financial criteria, for example, based on:

- Fabric energy efficiency, by means of wall insulation and high performance windows;
- Low temperature heating (district heating and cooling network);
- Heat pumps, mainly geothermal units; and
- PV panels and battery storage

The technical analysis must be performed by means of the most appropriate software to determine the energy flows at the building and district level and key performance indicators, such as energy self-supply level by RES, emissions reduction and payback period can be calculated.

An element of comparison that still seems problematic is the value of the reference parameters for NZEB. From a wide investigation on 34 NZEB case study (with only two residential buildings) in hot and humid climates [11], the problem of the heterogeneous definition of the references for NZEB was highlighted: in some cases, the NZEB target can be achieved even just by a large use of renewable energy resources, despite a high EUI (energy use intensity) value. In fact, in a few cases the EUI was found higher than 200 kWh/(m<sup>2</sup>y), even if a reference value, used for the comparisons, was the one considered by the New Building Institute (NBI) in the United States, EUI = 56.8 kWh/(m<sup>2</sup>y). However, in general, energy efficiency should be a priority for a true NZEB, therefore referred to a low EUI, properly supported by renewable energy.

To deepen the knowledge of the NZEB effective functioning, extensive experimentation is required. In the literature, there are still few cases monitored, at least in the Mediterranean climate. The monitoring carried out on case studies usually is mainly used for dynamic simulation tools validation rather than for comparing design and real energy performance results.

A contribution to the energy data monitoring on district scale was given by the ECO-Life Project, cofounded by the EU Commission in the period 2010–2016, referred to urban districts, including new and existing refurbished buildings. From the real consumption data, in this case, a difference attributed to the occupants' behaviour was put into evidence [12,13]. The obtained data were normalized in order to compare different projects, at different periods, with different weather conditions, etc., and to analyse variations in a building's energy use. The calculations and results were based on monthly data, referring to the simplified quasi-steady state approach of the EPBD-calculation method. From the analyses, a large energy saving potential was put in evidence, concerning occupant behaviour and average energy use in new dwellings higher than expected from calculations. The use of a good management of technical systems can effectively solve some of the causes of high energy use.

### 2.3. Contributions to the NZEB Design

Among the different elements to consider in the design and management of a NZEB, the present research intends to highlight two important aspects, represented by both the microclimatic control, and the regulation of the building technical systems. It is important that, in the design phase, utmost care is taken to respect the objectives not only of energy saving and high energy performance but also of environmental comfort. Therefore, the project, although accurate and respectful of the NZEB objectives, should put the greatest attention to the continuous control that supports or replaces the user's behaviour and its building management.

An accurate design of the envelope and technical building systems associated with a smart management of the control systems and the setting of the set points, for the optimal operation of the systems, represent elements that need to be considered closely related.

Such integrated design can lead to a good coverage of the energy use for system operation by renewable energy that can be higher than 80%, as tested in the Czech Republic. An energy system for space heating and domestic hot water preparation in a family house, supported by a combination of PV photovoltaic system with a heat pump and a ground heat storage under the house, was designed

and monitored for two years [14]: its management results support the belief that the NZEB target is not that distant and ambitious.

Combined energy systems seem promising to provide complete, optimized and achievable, cost-effective and sustainable solutions that will be increasingly needed in the near future. It is important to mention the importance of the design optimization that requires suitable methods to solve the design problems by means of multi-objective analyses [15].

The design of the energy systems should be analysed through a wide numbers of point of views, including the grid interaction, and different design alternatives such as fuel cells and renewable energy generation systems. The collected information can help for similar buildings [16]. In most cases, even if the overall PV energy yearly generation surpasses the electricity consumption and is fed into the grid, the building has to import from the grid a large energy amount and, therefore, it is not independent from the grid. Therefore, the evaluation of on-site energy storage systems is useful to improve the flexibility of the building to adapt to the load, reducing the dependence on the grid in low-generation times.

### 3. Materials and Methods

The software tools used for the analyses, the characteristics of the case study in relation to the envelope and systems and the climatic context in which it is located, and the input data of the calculations are described below.

#### 3.1. Energy Simulation Tools

The dynamic energy simulation allows to acquire greater awareness of the detailed behaviour of the building structures, of the possibility of exploiting the thermal accumulation, depending on the climatic conditions and of the impact of solar radiation, all elements variable in the day-night, weekly, monthly cycle, seasonal. Above all, it is thus possible to obtain more in-depth information on the plant regulation and on the definition of the set points for their operation, in relation to internal needs and external climatic conditions. Moreover, contributions of elements such as the solar greenhouse can be evaluated taking into account the air flow and its temperature, from this space to the indoor environment.

Usually, the building design process uses simulation tools based on quasi-stationary models to determine the energy performance in summer and winter conditions and, therefore, to evaluate the energy needs of the building in the annual cycle and to verify the compliance with national regulations. The temperatures, the internal contributions, the expected consumptions refer to monthly balance and the calculations are therefore simplified.

It may be useful here to compare the results of the building simulation conducted during the design phase with these simplified models in a semi-stationary regime, with the one used for this study, which is based on a dynamic simulation model. Differences are expected, as indicated in several researches. Comparisons between steady-state calculation and dynamic simulation for energy efficiency have evidenced differences mainly due to temperature and solar radiation variations that can vary from 16 to 44% in cold zones [17].

The limits of the quasi-steady-state method, represented by the overestimation of thermal losses, are a recognized problem affecting the low energy consumption buildings and particularly NZEBs. In studies developed on buildings located in Mediterranean areas [18], the gap between models was found to be around 10% for heating energy needs, and lower for cooling energy needs.

The energy performance assessment is here developed following national and international indications, as required by the European Directive [1] and summarised in [19,20]. The software used for the dynamic hourly simulation of buildings sets the calculations in accordance with the EN ISO 52016-1: 2018 standard [21,22], and allows calculations for:

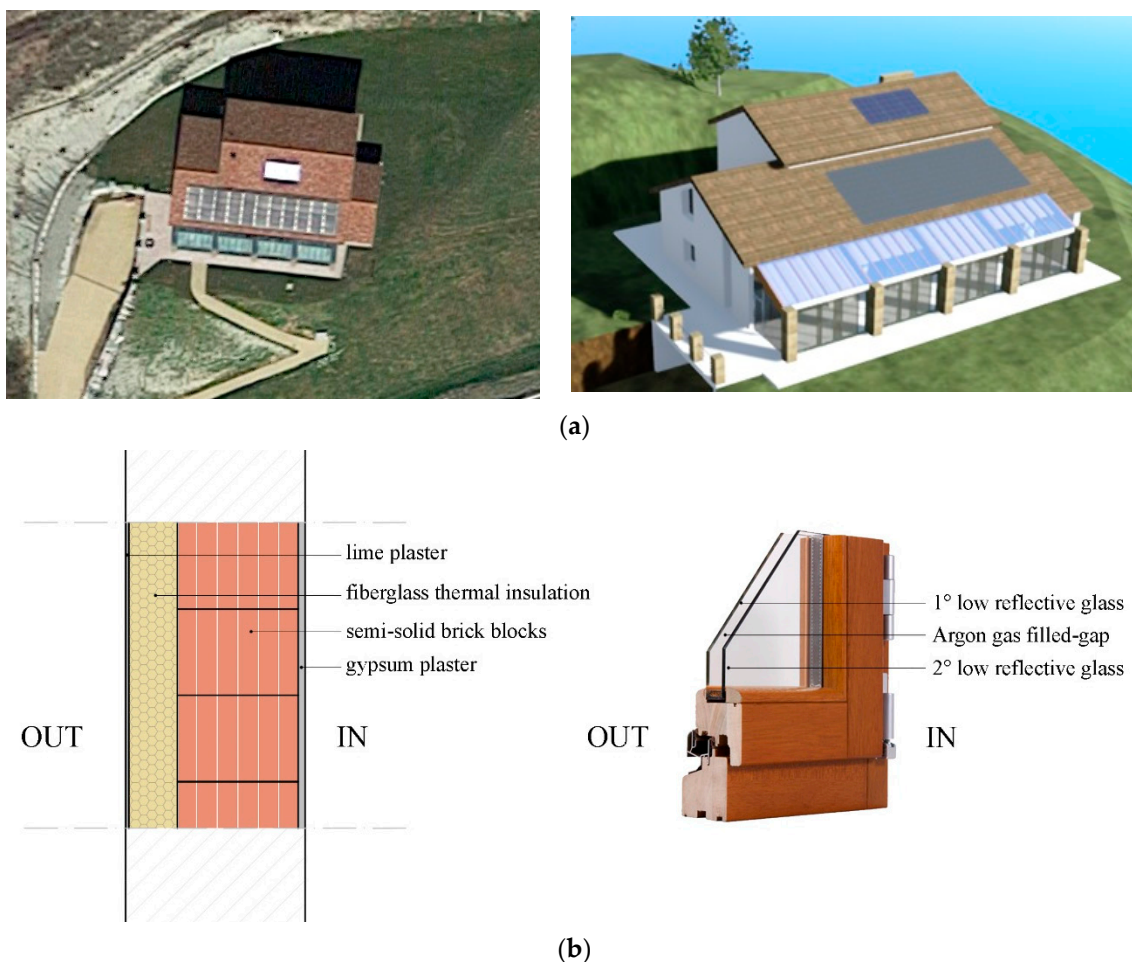
- Dynamic energy needs of the building for heating and cooling services;

- Analysis of summer comfort in free cooling conditions or with the systems support;
- Evaluation of the energy required to maintain the design temperatures for heating and cooling;
- Study of the contribution of a solar greenhouse for the energy needs reduction;
- Analysis of the night ventilation effectiveness; and
- Design and validation of fixed shields.

The results of the simulations will also be compared with the data collected from long-term monitoring both to confirm the possibility of describing thermal behaviour by means of simulation methods and to verify whether the regulation techniques adopted in practice in building energy management allow better exploitation of energy resources.

### 3.2. Case Study—Building Features

The case study is represented by a single-family residential building, built in 2013 in Northern Italy, characterized by a traditional architectural form, congruent with the hilly context in which it is inserted (Figure 1).



**Figure 1.** (a) Investigated building: overview from Google Maps (left) and lateral view (right); (b) stratigraphy of the main building envelope: perimeter wall (left) and low-emission double glazing (right).

The building, chosen as case-study, has attracted attention, not only at a regional level, by winning a regional call for its construction, but also nationally. It has been included in the census of the national NZEB through a summary and descriptive card produced by the “National Observatory of almost zero energy buildings” [23], promoted by the National Agency for New Technologies, Energy and

Sustainable Economic Development (ENEA). The building, together with 25 others located in 10 Italian regions, represents an example of good NZEB practices at national level [24], in particular for the energy performance of the building envelope (external insulation, wooden window frames with thermal break and double glazing), the high efficiency of the plant system (heat pump, CMV, air intake system from the solar greenhouse), and for the almost total coverage of consumption from renewable sources (94%).

Two particular aspects can be highlighted: the first concerns the fact that, despite being a high efficiency building, the construction is typical of the rural context in which it is built and is not characterized by modern lines, which would cause great visual impact on the context urban and landscape; the second relates to the fact that the project is prior to the national directives and laws that defined the NZEB model and its performance. However, the building respects this target and has even far better performances that could define it as PEB (positive-energy building).

The building has a useful area of 322.4 m<sup>2</sup> divided on three levels:

1. Basement (cellars, garage, bathroom, the only heated room on the floor, the thermal power plant);
2. Ground floor (living area); a mezzanine floor with two bathrooms and two bedrooms; and
3. First floor (main bedroom, bathroom and dressing room) and a mezzanine.

### 3.2.1. Opaque Elements

The structures used for the case study are mainly represented by 12 elements (structural or dividing walls, floor slabs, inter-floor and roofing). The design thermal transmittance U-values are compared with the reference U-values for NZEB, defined by the DM 26/06/2015 [25] (Table 1). As regards the periodic transmittance  $Y_{IE}$ , verification of the limit value is not necessary as the project site is characterized by an average irradiance value less than 290 W/m<sup>2</sup>, in the month of maximum insolation.

**Table 1.** List of stratigraphic packages with thermal transmittance checks.

	Description	U <sub>design</sub>	U <sub>ref</sub>
		(W/(m <sup>2</sup> K))	(W/(m <sup>2</sup> K))
1	Earth retaining wall (thickness 35 cm)	0.68	0.30
2	Perimeter wall (thickness 52 cm)	0.20	0.30
3	Mezzanine floor partition (thickness 22 cm)	0.58	0.80
4	Partition heated rooms in the basement (thickness 28 cm)	0.31	0.30
5	Internal partition (thickness 10 cm)	2.05	0.80
6	Heated basement slab (thickness 81.3 cm)	0.12	0.30
7	Unheated basement slab (thickness 80.1 cm)	0.12	0.30
8	Ground floor slab (thickness 57 cm)	0.31	0.80
9	Mezzanine floor slab (thickness 52 cm)	2.90	0.80
10	First floor slab (thickness 50 cm)	0.26	0.80
11	Attic slab (thickness 38 cm)	0.24	0.25
12	Roof slab (thickness 33.3 cm)	0.23	0.80

From the comparison of the U values, the only opaque elements that do not meet the transmittance verification are the ones between an unheated environment and the outside (uninsulated masonry against the ground) or vertical and horizontal dividing elements between heated internal environments. Therefore, this failure does not lead to losses for the energy requirement calculations.

### 3.2.2. Transparent Elements

The highly efficient windows are chosen in line with the local architecture: they are composed of low-emission double glazing, with argon gas in the cavity, and thermal break oak frames.

The preferred orientation for natural lighting is the South; from the four large windows of the living area on the ground floor, it is possible to access the solar greenhouse, characterized by sliding

doors in tempered glass with a folding system (open in summer and closed in winter) and a 45% inclined coverage (laminated glass), shielded by white roller blinds, to reduce the risk of summer overheating.

The three openings on the east side are not shielded, as they are protected by an overhang with an extension of 4 m; to the north, the rooms have four openings, which do not require shielding, given the lack of direct solar input; finally, the West side is characterized by three windows, one of which is double height, for which a mobile shielding system with white wooden venetian blinds has been provided, since it is affected by solar radiation in the second part of the day.

All the windows of the building envelope are verified as characterized by a thermal transmittance with a mean value of  $U_w = 1.35 \text{ W}/(\text{m}^2\text{K})$ , lower than the limit equal to  $1.80 \text{ W}/(\text{m}^2\text{K})$  in accordance with the Ministerial Decree 26/06/2015 [25].

A large glazed element built on the south-facing façade on the ground floor is represented by a large solar greenhouse. During the heating period, the white roller blinds, which shield the roof of the greenhouse, are rewound to promote maximum irradiation and the sliding windows, made of tempered glass, are closed to allow airtightness. The environment represents a passive indirect-gain solar system: the accumulated heat is used for heating the internal rooms through an air intake system from the greenhouse, which, by means of two  $100 \text{ m}^3/\text{h}$  fans, introduces into the area the air of the greenhouse when its temperature is  $5 \text{ }^\circ\text{C}$  higher than the temperature of the indoor environment.

### 3.3. Case Study—Technical Systems

In the thermal power plant of the basement, there are almost all the systems, represented by:

- An air-water electric heat pump, with a useful thermal power of 13.1 kW and ON-OFF operation, which covers the role of generation system both for the radiant heating and cooling system and for production domestic hot water;
- A controlled mechanical ventilation (CMV) system, equipped with a heat recovery unit (90% efficiency), represented by an enthalpy exchanger operating continuously with an air flow that varies between  $50 \text{ m}^3/\text{h}$  and  $550 \text{ m}^3/\text{h}$ ;
- A dehumidifier, which starts if the internal humidity conditions are such as to create discomfort (set-up value  $\text{RH} = 50\%$ ); it happens especially in summer, due to the high vapour content of the air which is cooled by the radiant system;
- A water storage tank (500 L), used to collect the hot water from the solar thermal system: the domestic hot water is heated by the heat pump only in cases where the solar thermal collectors are not able to work, due to lack of solar radiation.

In addition, on the ground floor, there is a secondary ventilation system that allows to transfer an air flow of  $200 \text{ m}^3/\text{h}$  from the solar greenhouse to the internal environment. A summary of the plant components, in a schematic representation of the most significant sections of the plant is reported in Figure 2. Although the solar greenhouse is not actually part of the plant system, it is included, as it plays a role in supporting the radiant heating system. The only system for generating the entire system is the heat pump, which exchange energy with the other components. For calculating the energy requirement in a semi-stationary regime, the building has been divided into five heated thermal zones, and three unheated zones (Figure 3, Table 2). Table 3 summarizes the characteristics of the radiant system (heating period: 15 October–15 April, 8.00–16.00, cooling period: 1 July–31 August, 8.00–16.00, CMV active 24 h a day throughout the year).



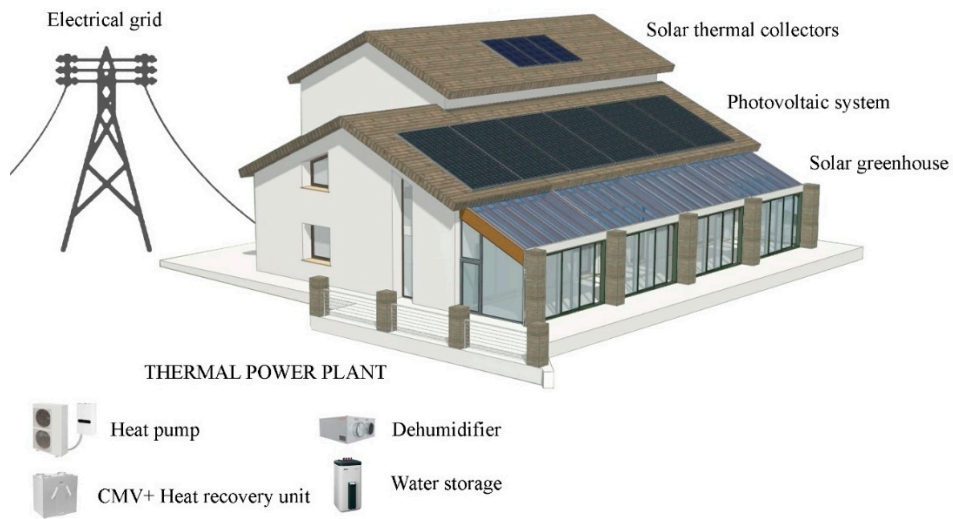


Figure 2. Schematic representation of the case study's systems.

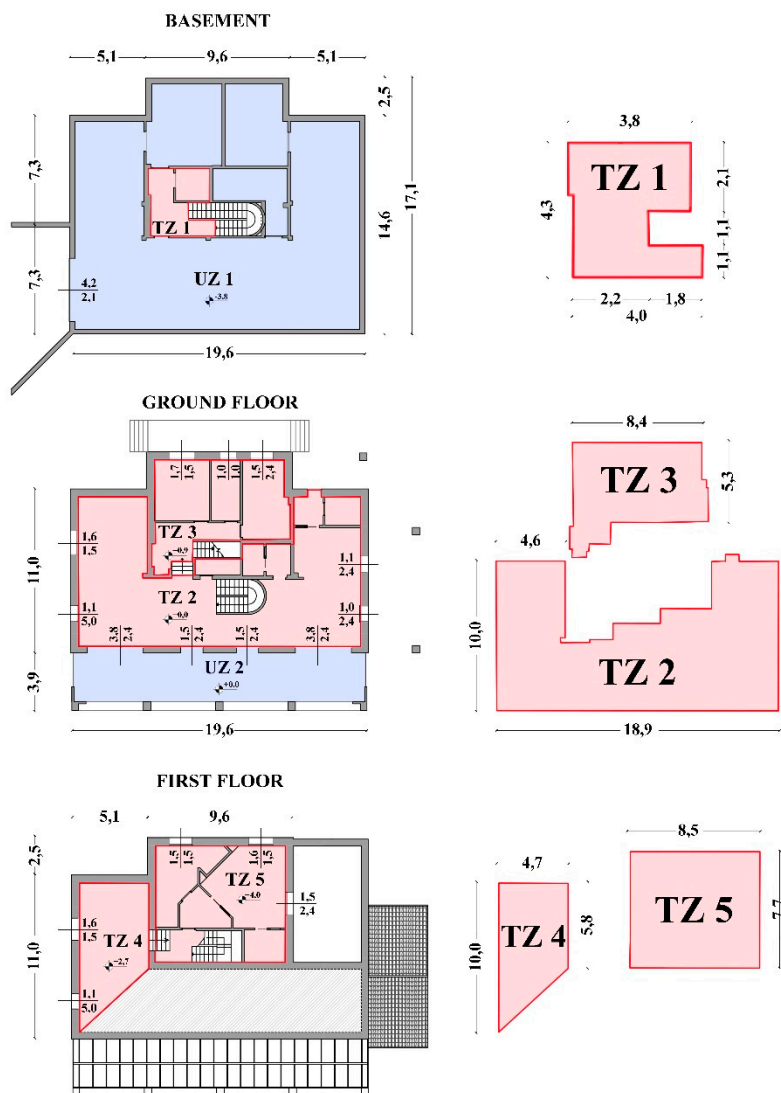


Figure 3. Heated thermal zones (TZ) (in red) and unheated zones (UZ) (in blue) (left: external opaque wall dimensions and windows; right: internal dimensions of the thermal zones).

**Table 2.** Subdivision of the building into heated thermal zones and unheated zones. (A = net surface; V = net volume).

Code	Heated Thermal Zones	A (m <sup>2</sup> )	V (m <sup>3</sup> )	Code	Unheated Zones	Area (m <sup>2</sup> )	V (m <sup>3</sup> )
TZ1	Bathroom (basement)	16.1	53.1	UZ1	Garage (basement)	252	875
TZ2	Living area (ground floor)	132.8	543.5	UZ2	Solar greenhouse (ground floor)	63.4	190.2
TZ3	Sleeping area (mezzanine floor)	38.8	104.8	UZ3	Attic (second floor)	68.3	93.6
TZ4	Loft (first floor)	36.6	84.6				
TZ5	Sleeping area (first floor)	51.7	139.6				

**Table 3.** Plants serving heated thermal zones (TZ) and location of radiant panels (floor/ceiling); CMV: I = immission, E = extraction.

	Heating-Cooling with Radiant Panels	DHW	CMV	CMV Flow (m <sup>3</sup> /h)
TZ 1	1.3 kW (ceiling)	yes	E	50
TZ 2	6.6 kW (floor)	yes	I/E	200
TZ 3	3.1 kW (ceiling)	yes	I/E	100
TZ 4	4.0 kW (ceiling)	no	I/E	100
TZ 5	4.1 kW (ceiling)	yes	I	100 (I), 150 (E)

The contribution of renewable sources is represented by a photovoltaic system (about 79.5 m<sup>2</sup>) and a solar thermal system (6.6 m<sup>2</sup>), placed on the 45% inclined surface with respect to the horizontal, with a South orientation. The LED lighting is used both for external and internal use. A recovery rainwater system helps to cover the need for the irrigation of the surrounding garden (2800 m<sup>3</sup>/year).

The design of the building envelope and the technical systems sizing have been set synergistically: the management of the building is entrusted to an appropriate control system (BCS) and management system (BMS), capable of maintaining the required conditions of internal comfort, with reduced energy consumption. A climatic control unit acquires the temperature and humidity data in each room and the ones coming from an external climate probe, located on the north side of the building.

Furthermore, the free-cooling technique is used to control energy consumption in summer: it permits a reduction in the summer night temperature of the rooms. A fan is activated for external temperatures of 24 °C or lower. The external air intake is located near the northeast corner of the building, and the air distribution takes place separately for each environment, thus promoting a decrease in the internal temperature of up to 4 °C.

### 3.4. Case Study—Environmental Design Data

The following data were used in the calculation:

- Degree days: 2631 DD;
- Italian climatic zone E (heating period. 183 days);
- Minimum design temperature for heating system: −9.2 °C;
- Internal conditions—heating period: Temperature = 20 °C, Relative Humidity = 50%; and
- Internal conditions—cooling period: Temperature = 26 °C, Relative Humidity = 50%.

Monthly mean temperature (T), relative humidity (RH) and irradiation values for each orientation are resumed in Table 4.

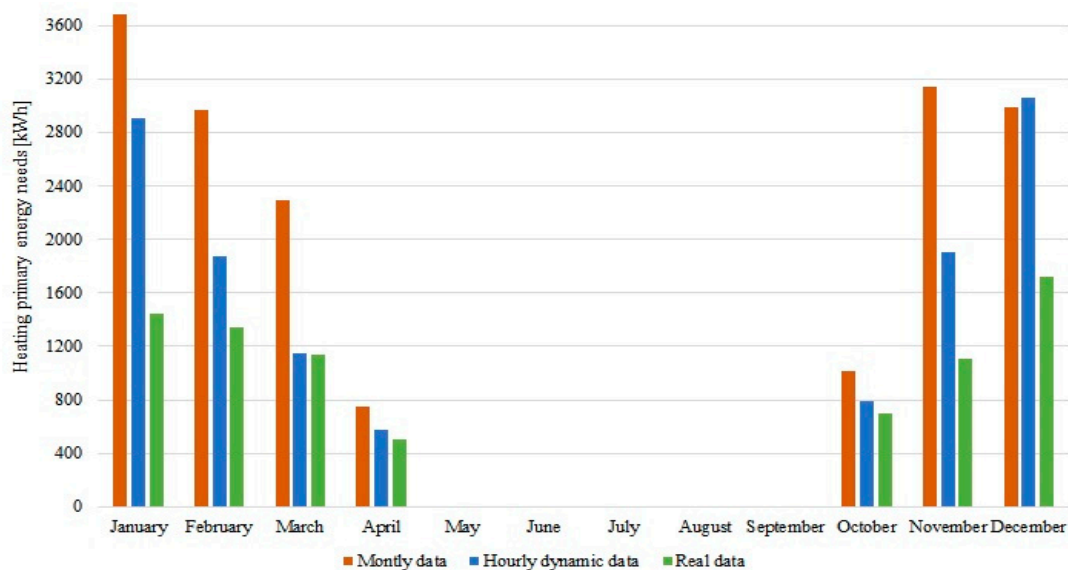
**Table 4.** Climatic data: solar irradiation.

	T (°C)	RH (%)	Monthly Mean Irradiation (MJ/day)								
			N	NE	E	SE	S	SW	W	NW	Oriz.
January	6.5	79.4	1.7	1.9	4.1	7.1	9.1	7.1	4.1	1.9	5
February	7.5	79.2	2.6	3.2	6.1	9.1	10.9	9.1	6.1	3.2	7.9
March	10.2	71.2	3.7	5.4	8.8	11.1	11.7	11.1	8.8	5.4	12.1
April	13.3	69.9	5.3	8.1	11.3	11.9	10.7	11.9	11.3	8.1	16.4
May	16.4	71	7.5	10.4	12.9	11.9	9.6	11.9	12.9	10.4	19.6
June	20.5	68.4	9.1	11.9	14	12.1	9.4	12.1	14	11.9	21.7
July	23.1	65.6	9	12.7	15.6	13.7	10.5	13.7	15.6	12.7	23.8
August	23.2	66.7	6.3	9.8	13.2	13.1	11.1	13.1	13.2	9.8	19.4
September	20.9	74	4.2	6.7	10.4	12.2	12.1	12.2	10.4	6.7	14.5
October	15.7	77.6	2.9	3.9	7.3	10.4	12.1	10.4	7.3	3.9	9.6
November	11.5	80.5	1.9	2.2	4.5	7.5	9.4	7.5	4.5	2.2	5.6
December	7.9	82.5	1.5	1.7	3.9	7.2	9.4	7.2	3.9	1.7	4.6

## 4. Results

### 4.1. Heating: Quasi-Static and Dynamic Simulation vs. Real Energy Consumption

Figure 4 shows the difference between the primary energy requirement for heating, calculated using the semi-stationary method with monthly balances, deriving from the calculation in the hourly dynamic regime. The energy consumption data obtained from the monitored data are also reported. These are, overall, 35% lower than the estimate carried out by hourly dynamic simulation: the dynamic model was calibrated on the basis of the ventilation data recorded by the building monitoring system.



**Figure 4.** Hourly dynamic, monthly semi-stationary calculated data and real primary energy needs.

As already highlighted in several studies, the results obtained through quasi-stationary simulation models are different from those that can be obtained from a more detailed study through dynamic simulation models. The difference may be due to a more or less accurate knowledge of the characteristics of materials, construction techniques and systems. Furthermore, it is usually difficult to provide a precise description of the operating and management conditions of the system set points.

A comparison between different models [26] has shown that the quasi-steady state approach and the dynamic simulation methods can give differences in energy need calculations for heating in winter months up to 25.8%. Reasons of these discrepancies can be found considering some elements that

are not always well known, such as occupant behaviour, ventilation, temperature set point, but also calculation methods and simplifications. Depending on climatic conditions, the differences between methods and real consumption data can be positive or negative: solar gains, for example, can determine opposite effects causing underestimation or overestimation of the energy needs [27].

The results of the semi-stationary simulation (which significantly overestimates real consumption) of the case-study, compared with the reference values by national rules, are indicated in Tables 5 and 6. The comparison between design values and reference values highlight the excellent performance of the building, better than the NZEB target. In the Energy Performance Certificate, energy class A4 (the maximum rate) and the NZEB status are attributed to the building.

**Table 5.** Geometric parameters and energy performance indices.

Parameters	Design Values	Reference Values [25]	Difference
Gross dispersing surface S	370.8 m <sup>2</sup>		
Building heated volume V	1450.5 m <sup>3</sup>		
Shape ratio S/V	0.26 m <sup>-1</sup>		
Global average heat transfer coefficient H <sub>T</sub>	0.25 W/(m <sup>2</sup> K)	0.75 W/(m <sup>2</sup> K)	67%
Equivalent solar area/Floor area A <sub>sol</sub> /A <sub>f</sub>	0.029	0.030	3%
Energy performance indicator for heating EP <sub>H,nd</sub>	46.32 kWh/(m <sup>2</sup> y)	50.37 kWh/(m <sup>2</sup> y)	8%
Energy performance indicator for cooling EP <sub>C,nd</sub>	12.56 kWh/(m <sup>2</sup> y)	16.34 kWh/m <sup>2</sup> y)	23%
Global non-renewable energy performance index of the building EP <sub>gl,nren</sub>	1.00 kWh/(m <sup>2</sup> y)	36.12 kWh/m <sup>2</sup> y)	97%
Total energy performance index of the building EP <sub>gl,tot</sub>	47.69 kWh/(m <sup>2</sup> y)	100.05 kWh/m <sup>2</sup> y)	52%

**Table 6.** Efficiency parameters.

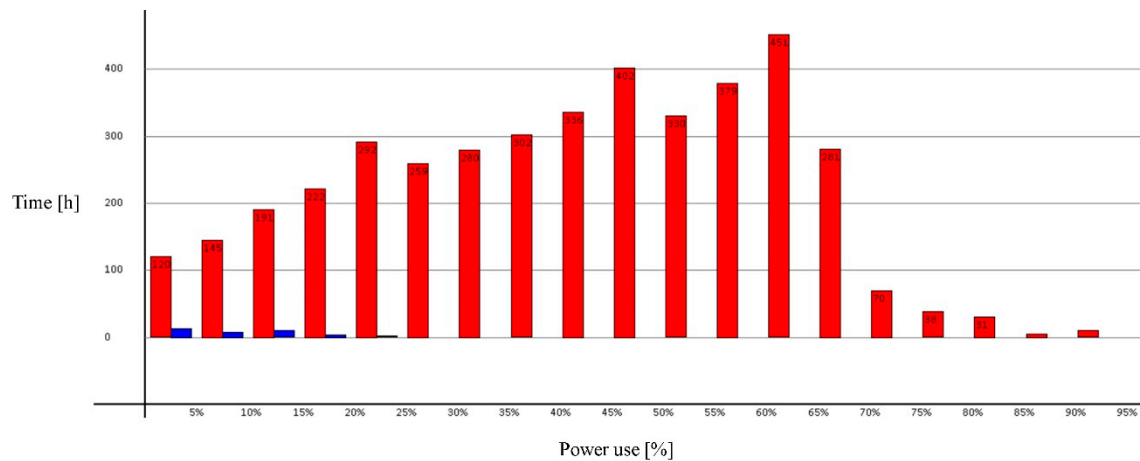
Parameters—Renewable Energy	Design Values	Reference Values
Share of total renewable energy QR total	98%	50%
Share of renewable energy destined for the production of domestic hot water QR DHW	99.4%	50%
Photovoltaic system power	10.33 kW	7.61 kW
Parameters—Global average seasonal performance	Design Values	Reference Values
Heating performance $\eta_{gl,H}$	91.9%	70.6%
Cooling performance $\eta_{gl,C}$	325.4%	202.5%
DHW performance $\eta_{gl,W}$	96.7%	68.5%

#### 4.2. Dynamic Simulation—Energy Performance

The main data used in the model are the following: set point temperatures for the heating and cooling periods, geometric parameters, an accurate description of the shading of the windows and the definition of hourly profiles for internal contributions, the ventilation flows, and the powers provided by the heating and cooling.

During the heating period, and even more for the cooling period, only a small amount of the power available from the radiant system is actually used, as it is not necessary for reaching the set point temperature. The living area (TZ2) is the only thermal zone for which up to 92% of the available thermal power has been used, given its large volume and useful surface.

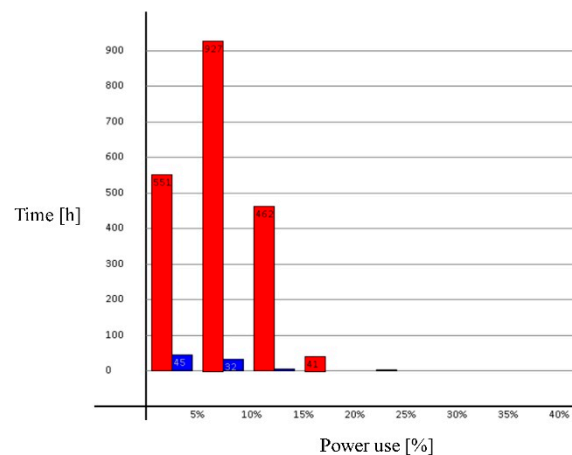
It may be useful to highlight the percentage distribution of power (Figure 5), used for heating (in red) and cooling (in blue): the heating system mainly operates for powers ranging from 20% to 70%, while it never works for 100% of the available power, as the minimum site design temperature (−9.2 °C) is rarely reached.



**Figure 5.** Percentage distribution of power used by the heating and cooling systems in the living area.

The heating system works with the available power of 65% (which corresponds to the maximum number of operating hours, or 451) only for 19 days out of the 183 that make up the heating season. The cooling system, on the other hand, operates with available powers of the order of 10%, confirming the fact that the thermal zone does not require much cooling energy to reach or maintain the summer set point temperature.

The sleeping area on the first floor (TZ5) requires much less energy than the living area by using about 10% of the available power most of the time (Figure 6).



**Figure 6.** Percentage distribution of the power used for heating and cooling systems in the sleeping area on the first floor.

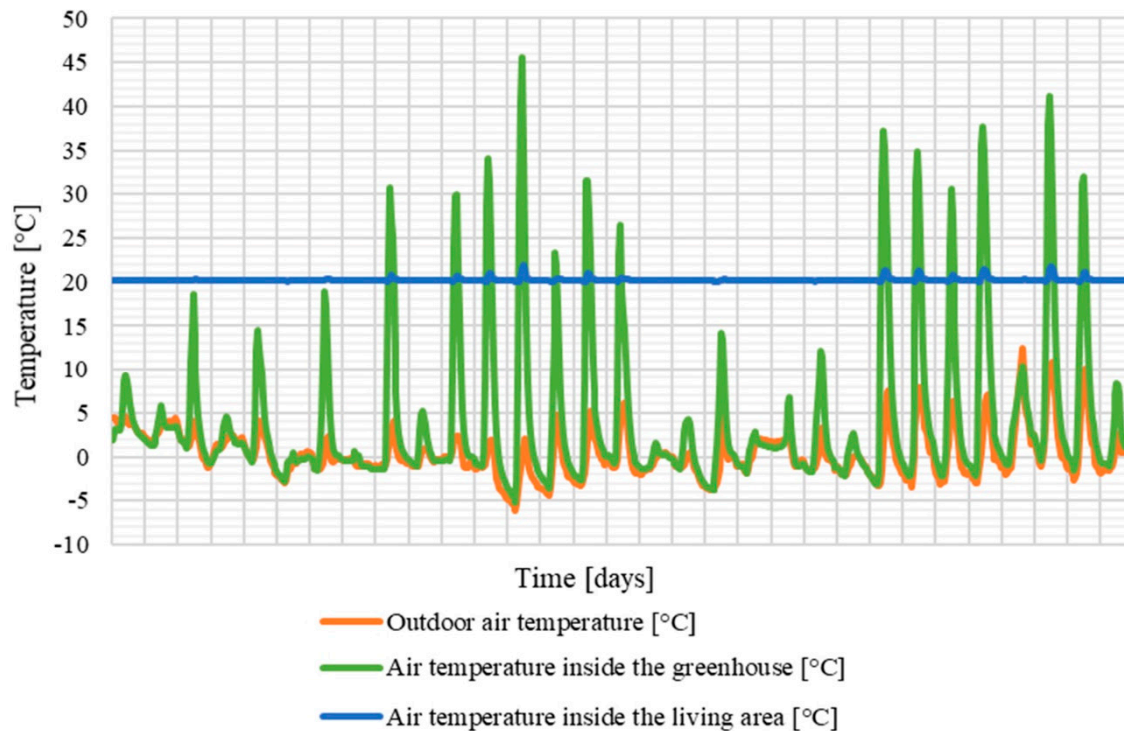
#### 4.3. Solar Greenhouse: Simulation and Temperature Analysis

The solar greenhouse is a very important element in winter, as it allows a reduction in the thermal load of the space heating system. To maximize its efficiency, numerous elements must be considered in its design and management, such as exposure, optical properties and thermal capacity of the opaque surfaces, the amount of ventilation and of the shading devices [28]. The same elements are considered particularly important in the conclusions of a research developed through simulation models and experimentation on a prototype [29]. In fact, the need to avoid any summer overheating, to carry out in-depth calculations on the effects of thermal inertia and to provide for the control of microclimatic conditions through intelligent management of the CMV is highlighted.

The case study building uses the solar greenhouse during the heating period, from 15 October to 15 April, as support for the radiant heating system of the living area, with which it is in direct

communication. The air intake system from the greenhouse to the internal environment is active from 11.00 to 14.00, when the temperature of the air inside the greenhouse reaches at least a temperature of 25 °C, i.e., when it exceeds by 5 °C the design temperature of the air inside the living area (winter set point of 20 °C).

It may be interesting to analyse the behaviour of the greenhouse as a function of time. Hourly data of indoor and greenhouse temperatures were simulated depending on external temperature. The results have been examined monthly. The detailed results for January are indicated in Figure 7, while a synthesis is presented for the other periods.



**Figure 7.** Trend of outdoor air temperatures (orange), inside the living area (blue) and the greenhouse (green) for the month of January.

In the hottest hours, indicatively from 11.00 to 13.00, solar radiation causes an increase in the temperature of the greenhouse with peaks up to 45 °C. The temperature of the internal environment (set point = 20 °C) remains constant for most of the time, allowing the reduction of the operating time of the heat pump and in some cases there is an increase that remains contained inside appropriate values to maintain comfort conditions in the indoor environment.

It may be interesting to observe how long the temperature remains around a certain value in the greenhouse: it is observed that the recurrent temperature is 0 °C (Figure 8), for 21% of the time. The fan that transfers the air from the solar greenhouse to the internal environment works when the temperature of the greenhouse reaches 25 °C and this occurs 15% of the time (37 h).

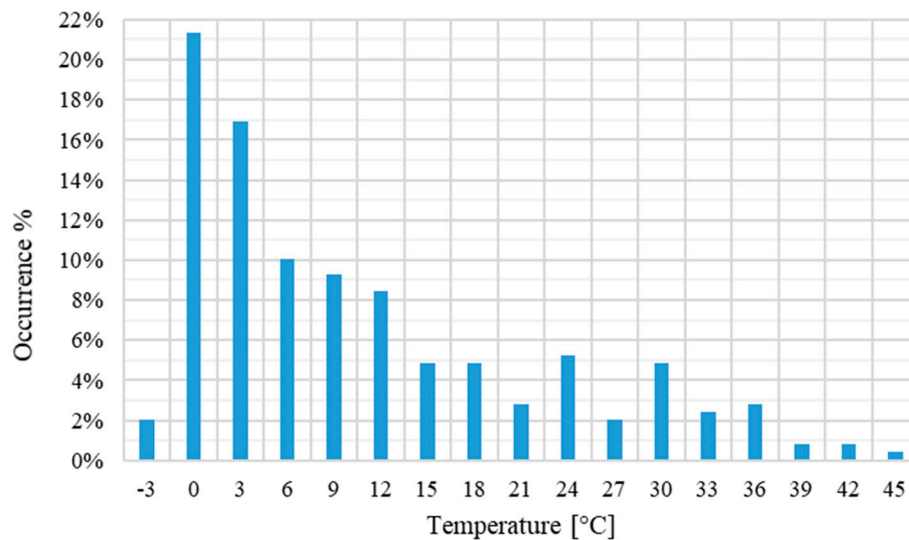


Figure 8. Percentage of time a certain temperature occurs in the greenhouse.

The results obtained for the complete heating period are summarized in Table 7, which shows the maximum and minimum values of the external temperature and of the greenhouse for each winter month. The following columns for each month indicate the percentage of time in which:

- (A) The temperature remains around the most recurrent value outside;
- (B) The most recurrent temperature value in the greenhouse occurs; and
- (C) The air intake system from the greenhouse is activated.

Table 7. Analysis of the contribution of the greenhouse during the heating season.

Month	Temperature (°C)				Temperature Occurrence (%)							
	Outdoor		Greenhouse		(A) Outdoor		(B) Greenhouse		(C) Greenhouse		(D) Greenhouse	
	min	max	min	max	(°C)	(%)	(°C)	(%)	(h)	(%)	(h)	(%)
January	−6	12	−3	45.5	0	21	32	14	37	15	54	22
February	−6	15	−2	46.5	3	12	26	11	75	28	106	39
March	−3	21	0	47	18	10	34	9	151	42	193	54
April	0	20	2	42.5	24	11	39	10	82	44	111	59
October	1	21	4	46	18	12	27	11	62	37	89	54
November	−2	17	−1	39	9	18	32	17	36	15	56	23
December	−11	10	−7	38	6	16	32	16	31	13	46	20

(A) Outdoor: Temperature inside the greenhouse for the most recurrent interval [Tmin; Tmax]; (B) Greenhouse: Temperature inside the greenhouse for the most recurrent interval [26 °C; Tmax]; (C) Greenhouse: Operation of the air intake system from the greenhouse for the interval [26 °C; Tmax]; (D) Greenhouse: Operation of the air intake system from the greenhouse for the interval [21 °C; Tmax].

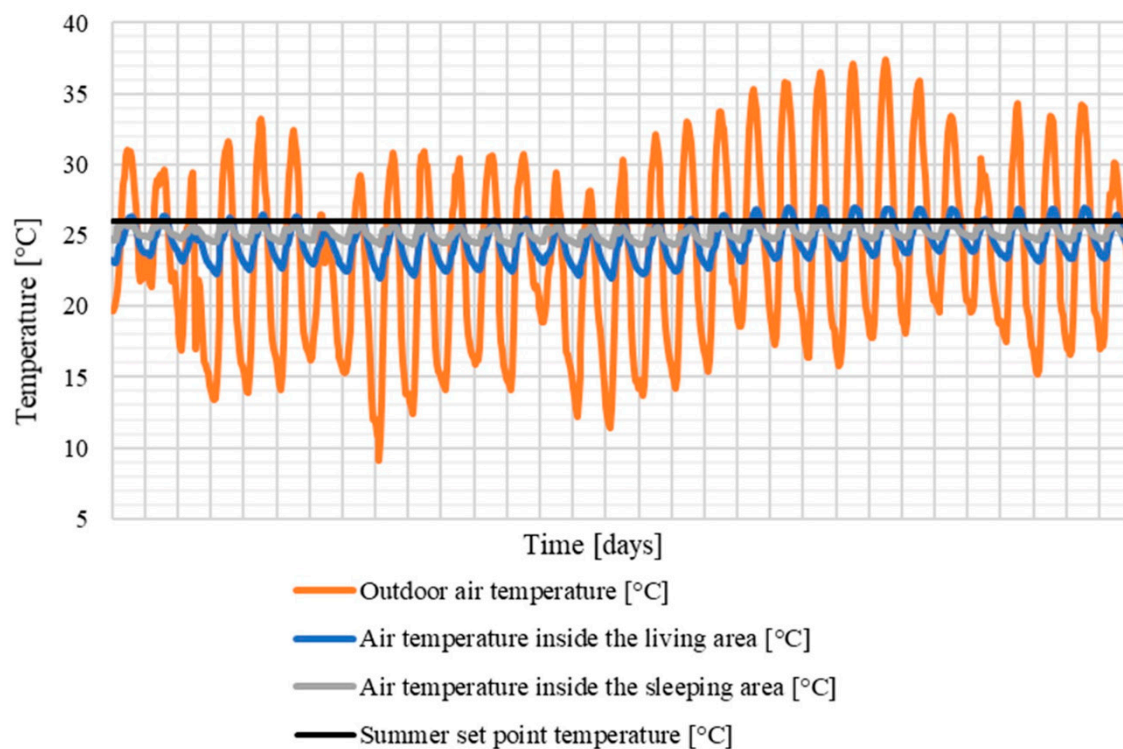
Furthermore, in the last section (D) the hypothesis of changing the set point for activating ventilation from the greenhouse is considered, bringing it to  $T = 20$  °C. The suction of air from the greenhouse would therefore be activated when the temperature of the greenhouse reaches that of the internal environment. In this way, the hours in which the release of air from the greenhouse is activated would go from 474 to 655, with an increase of 38%. This solution could allow a further reduction in consumption due to the presence of the solar greenhouse and the circulation of heated air in the internal environment.

#### 4.4. Analysis of the Heat Pump Operation

The operation of the heat pump, supported by the PV system, is analysed in relation to the internal/external temperatures of the summer months in which it is used for cooling (July/August). The heat pump allows cooling the water that is circulated in the radiant panels with a flow temperature of 18 °C. The return temperature is 25 °C. The goal of the system in the summer season is to maintain an air set point temperature in the environments of 26 °C.

The study focuses on the results of the hourly dynamic simulation of the living area (TZ2) and the sleeping area on the first floor (TZ5) during the two months of activation of the cooling system (July and August). In particular, the temperatures of the external, internal air and that of the external envelope surfaces (perimeter walls and windows) are compared.

From the trend of the external and internal temperatures of the two thermal zones for the month of July (Figure 9), it is noted that the external temperature exceeds the summer set point (26 °C) for 282 h out of 744 total hours, with peaks up to at 37.5 °C.



**Figure 9.** Trend in outdoor air temperatures, inside the living and sleeping areas in July.

Analysing in detail the temperature trends of the TZ2 and TZ5, it is observed that the set point temperature is exceeded in TZ2 for 111 h, while it is never exceeded in TZ5. Therefore, it can be said that the heat pump, which is activated for  $T \geq 26$  °C, worked for 111 h in July (about 5 h a day): in fact, it can be seen from the graph that the set temperature point is exceeded for 21 days out of 31 total. In this period, the cooling energy supplied by the heat pump is 350 kWh: the corresponding cooling power used (3.2 kW) can be compared with the useful cooling power of the heat pump (13.1 kW). From the comparison, it can be said that the cooling system in July needed only 24% of the useful power of the heat pump. With the same approach, for the month of August, the power used is 27% of the useful one.

#### 4.5. Photovoltaic System

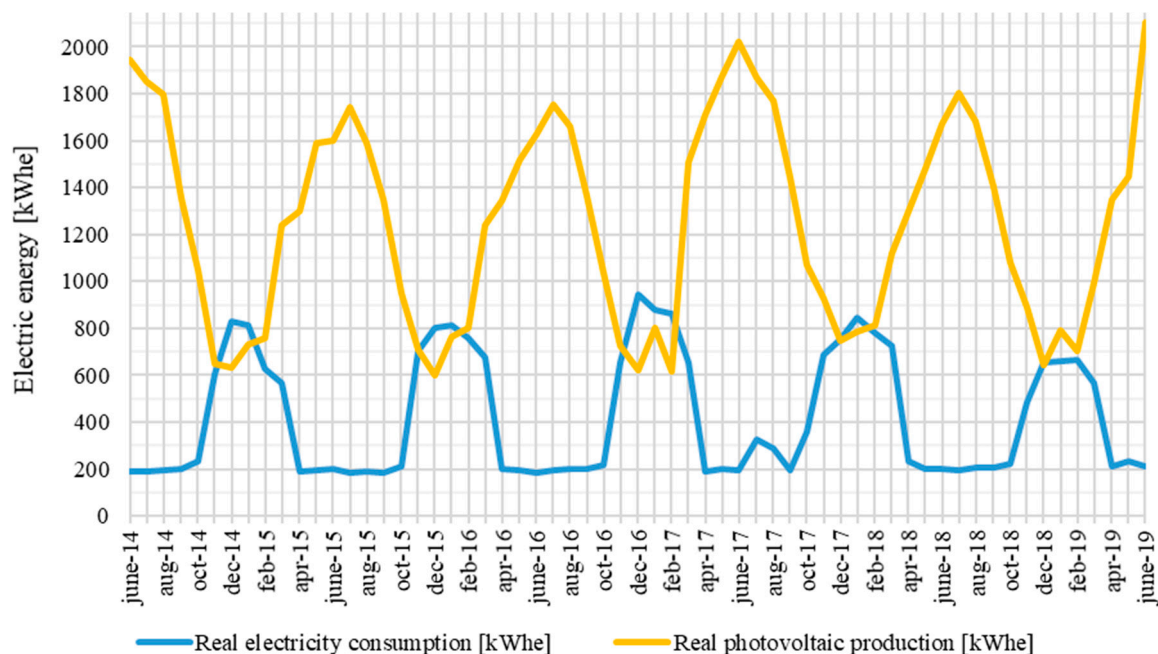
The availability of experimental data provided by the designer made it possible to conduct a comparison, extended for a period of five years (from June 2014 to June 2019), between the electricity



consumed to meet the energy requirement and the production of electricity from the photovoltaic system. In addition, an economic calculation was developed to compare the economic cost of the energy required from the network with the profit obtained from the sale to the network of the energy surplus not intended for self-consumption.

Starting from 2011 with the publication of Legislative Decree n. 28 [30], attention was paid to promoting the use of energy from renewable sources. In fact, national indications require that at least 50% of the demand for domestic hot water, heating and cooling must be satisfied using renewable energy sources.

In compliance with the decree, the building under study has a photovoltaic system integrated into the lower pitch of the roof, with a net surface area occupied by the modules of 79.46 m<sup>2</sup>, which produces an overall peak power of 10.33 kW<sub>p</sub>, 30% higher than the required reference power. From the comparison between electricity consumed and produced (Figure 10) it is clear that the electrical coverage by photovoltaics is guaranteed for almost the whole year, except for the winter months (December and January), for which it is necessary to obtain a modest amount of electricity to the grid (up to 320 kWh). The surplus of energy produced is transferred to the grid.



**Figure 10.** Comparison between real electricity consumption and photovoltaic production for the period June 2014–June 2019.

The comparison between the demand and the sale of energy is conducted considering the costs of electricity requested from the network in the winter months and the share sold to the network, when the plant produces more than it consumes. Reference is made to the following economic costs:

- Electricity drawn from the network: 0.1917 euro/kWh; and
- Electricity fed into the grid: 0.543 euro/kWh (all-inclusive tariff paid in 2013 to integrated photovoltaic systems with innovative features)

Table 8 shows the values of electricity consumed and produced for the five years analysed. From the comparison of the overall share of electricity consumed with that produced by the photovoltaic system, it can be said that only 34% of the energy available from photovoltaics was used for self-consumption.

**Table 8.** Energy data on electricity consumption and photovoltaic (PV) production for five years (June 2014–June 2019).

Year n.	Electricity Consumed	Electricity Produced by PV System	Surplus of Electricity Fed into the Grid		Electricity Purchased from the Grid	
	(kWh)	(kWh)	(kWh)	(€)	(kWh)	(€)
1	4.833	14.907	10.352	5.621	278	53
2	5.123	14.212	9.338	5.071	249	48
3	5.378	15.296	10.558	5.734	640	123
4	5.596	15.344	9.808	5.326	60	12
5	4.723	16.563	11.854	6.437	14	3
Tot.	25.653	76.322	51.910	28.188	1.241	239

Consequently, the amount of energy surplus is obtained from the difference between the third and second columns of the table. This surplus can also be estimated at an economic level: the economic return determined by the sale of electricity during the five years appears clearly higher than the small expenditure during the winter months in which the plant is not subject to adequate solar radiation to cover the energy needs.

## 5. Design Improvements Analyses

Building systems management and regulation have been analysed by means of simulation and monitoring data. The results highlight the good energy performance due to a smart design of both building envelope and systems and depending on an accurate management of the thermal systems operation. Some aspects of the project are evaluated below to highlight any further improvement opportunities. This procedure should be included in each project to evaluate the possibilities of obtaining more ambitious results than the target NZEB achieved.

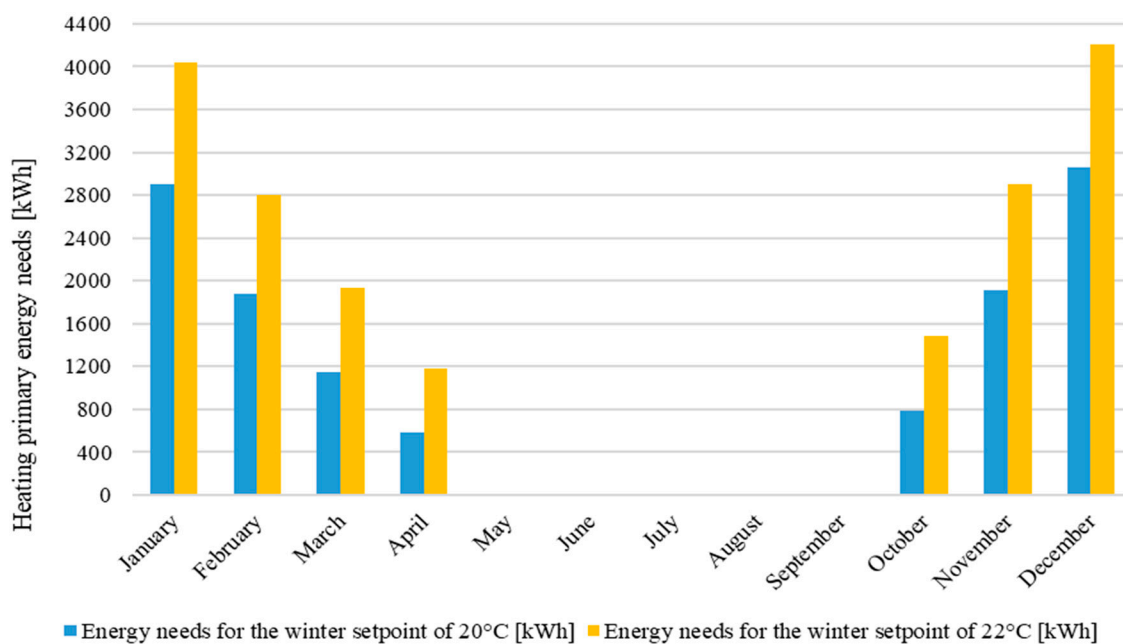
Some features of the project are discussed below to highlight any further improvement opportunities. This procedure should be included in each project, to evaluate the possibilities of obtaining more ambitious results than the target NZEB achieved. Obviously, the peculiarities of each project mean that there are no indications generally applicable to everyone, but that more suitable alternatives must be identified case-by-case. In the analysed case study, different variants have been taken into consideration and only those considered most significant are discussed.

### 5.1. Improving Environmental Comfort

Three significant parameters for environmental comfort can be managed by a building technical system: temperature, humidity, and velocity of the air [31].

As indicated, the system has control of the temperature ( $t$ ) and relative humidity (RH) in each zone with set points respectively set at  $t = 20\text{ °C}$  and  $\text{RH} = 50\%$  in winter and  $t = 26\text{ °C}$  and  $\text{RH} = 50\%$  in summer. The temperature in winter conditions may not be completely satisfactory in terms of comfort. For this reason, a comparison was made between the current conditions and those that would be achieved for a winter set point temperature set at  $22\text{ °C}$ , both in terms of energy consumption and comfort. The evaluations were carried out assuming to maintain the constant temperature in the day-night cycle, and considering a maximum deviation of  $\pm 0.5\text{ °C}$  for the calculation of the deviation from the comfort conditions [32].

The comparison between the simulation results provides a 15% increase in the maximum power used which goes from 7.3 kW to 8.6 kW and a 36% increase in the energy used for heating, corresponding to approximately 7000 kWh. The monthly energy requirement that varies mainly as a function of the external temperature and solar contributions (Figure 11) shows a higher percentage increase in the less cold months.



**Figure 11.** Comparison between the monthly heating primary energy needs for a set point of 20 °C (blue) and 22 °C (yellow).

The overproduction of energy from the photovoltaic system during these months, which are characterized by a greater availability of solar energy (March, April, October and November), can be used to power the heat pump and, therefore, to compensate for the greater energy requirement. During the other months of the heating season (January, February, and December), the photovoltaic system is not, however, able to cover the electricity needs, which, therefore, must be requested from the grid. The increase in demand entails an increase in costs, which, however, can be well compensated in the annual budget.

As regards the improvement of internal comfort, the difference between the two conditions in terms of deviation from the comfort condition can be assessed. From the dynamic energy simulation, the time in which the internal temperature underwent variations outside a range set at ±0.5 °C was calculated for each thermal zone (Table 9).

**Table 9.** Comfort hours for 20 °C and 22 °C temperature set point, in each thermal zone (TZ) referred to in Figure 3 (Δt = temperature difference).

Thermal Zone	Set Point	Time [h] Comfort		Time [h] Discomfort (Cold)		Mean Δt (Discomfort, Cold)	Time [h] Discomfort (Hot)		Mean Δt (Discomfort, Hot)
	(°C)	(h)	(%)	(h)	(%)	(°C)	(h)	(%)	(°C)
TZ1 Bathroom	20	6391	73	2363	27	1.4	0	0	0
	22	7176	82	1584	18	1.2	0	0	0
TZ2 Living area	20	723	8	8037	92	1.4	0	0	0
	22	6405	73	2355	27	0.8	0	0	0
TZ3 Sleeping area	20	4936	56	3823	43	0.8	1	0	0.3
	22	8246	94	490	6	0.5	24	0.3	0.3
TZ4 Loft	20	2714	31	6046	69	1.1	0	0	0
	22	7922	90	838	10	0.6	0	0	0
TZ5 Sleeping area	20	3497	40	5258	60	1.2	5	0.1	0.2
	22	8205	94	535	6	0.5	20	0.2	0.3

In the living area (TZ2), the hours of comfort go from 8% to 73%, while, for the two sleeping areas (TZ3 and TZ5), an even better condition is reached (94%) as regards the feeling of cold, while the

number of hours in which the temperature is above the defined interval increases; even if in percentage terms it remains a negligible value.

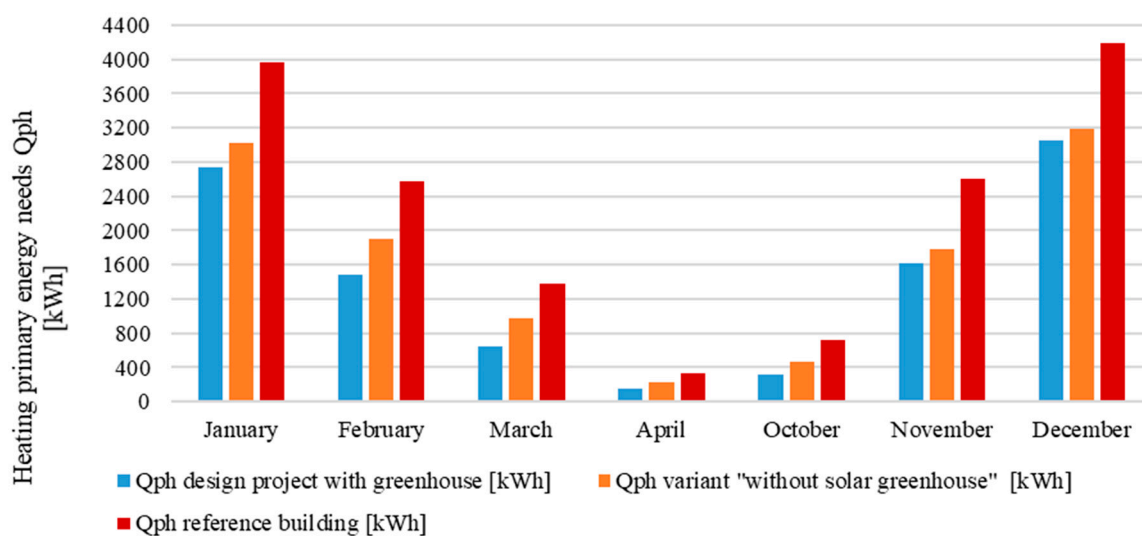
The simulation was conducted assuming a fixed day-night set point and, from what has been observed in terms of comfort, the possibility of a different day-night set point could be considered, at least in areas TZ3 and TZ5 to improve comfort. This choice would also help to reduce the corresponding energy consumption.

## 5.2. Impact of the Solar Greenhouse

A peculiarity that makes the architectural form of the building homogeneous and uniform to the context is the solar greenhouse, a characteristic element of the biocompatible architecture, characterized by a glass envelope both on the wall and on the roof and by an optimal south exposure for capturing solar radiation.

The main goal of the solar greenhouse is to provide heat to the indoor environment in winter to reduce energy needs. The comparison between the energy requirements, calculated in the current configuration (with greenhouse) and without, highlights the importance of its contribution. In addition, the results are compared with those referring to the reference building corresponding to the NZEB standard for this building.

The presence of the solar greenhouse offers a positive contribution from an energy point of view (Figure 12), resulting in an overall decrease of 13% of the primary energy for heating compared to the configuration without the greenhouse, corresponding to a saving of 1550 kWh.



**Figure 12.** Comparison between the heating primary energy needs of the design building equipped with a solar greenhouse with the variant “without solar greenhouse” and the reference building.

For each month, the percentage reduction of the energy requirement of the project configuration compared to the variant is indicated. However, it can be observed that the energy requirement of the building without a greenhouse is always below the corresponding requirement of the reference building. Thus, even in the absence of a solar greenhouse the building would have been classified as NZEB.

The presence of the solar greenhouse leads to a decrease in the thermal performance index useful for heating, thanks to the free supply of heat offered by the thermal storage in winter: with reference to the main energy performance indices [25], the percentage difference between the configuration with the solar greenhouse and the one without can be calculated (Table 10).

**Table 10.** Energy performance indices of the configuration with solar greenhouse compared in percentage with those of the variant without solar greenhouse.

Parameters	% Difference between Configurations with and without Solar Greenhouse
Energy performance index of the envelope $EP_{H,nd}$	−11%
Global non-renewable energy performance index of the building $EP_{gl,nren}$	−17%
Total energy performance index of the building $EP_{gl,tot}$	−4%

### 5.3. PV Energy Storage System

Since, for a limited period of time in winter, the building needs electricity from the grid, the possibility of realizing the complete autonomy of the building and, therefore, making it stand-alone rather than grid-connected was evaluated through the use of an energy storage system.

It is assumed to use stored energy for an operating time of 3 h of the heat pump at full capacity during the winter months of photovoltaic underproduction (15 kWh). The cost of the system was estimated at around €10,000 in relation to the current market offer.

To assess how long the cost of the investment could be recovered, Year 3 (Table 8) is taken as a reference for consumption, as it is the period in which the greatest demand for electricity was detected. In December, January and February the electricity consumed (2682 kWh) exceeded the energy produced by the system (2042 kWh) for 640 kWh, which was taken from the network and which, in this case, is considered to be supplied from the energy storage system.

It is assumed that the storage batteries must supply energy for a period of 30 days (distributed 15 days in December 5 in January and 10 in February), for 3 h a day (from 19.00 to 21.00). This estimate was made considering in that time interval the absence of solar radiation, and the possibility of exploiting at other times both the contribution of the solar greenhouse and the energy from PV to recharge the accumulation for 749 h (248 in January, 269 in February and 232 in December).

The calculations show that the investment is not favourable in this context, due to the high energy performance of the building which ultimately requires energy from the network with an annual cost of approximately €120. The cost of storage does not seem reasonable, at least in the current context, also taking into account the battery life due to the charging and discharging cycles.

As an alternative to the energy storage system, it would be interesting to consider making high thermal capacity radiant screeds from the design stage: thanks to the high coefficient of thermal conductivity, this system could optimize the performance of the entire heating/cooling system with flooring favouring a homogeneous and gradual transmission of heat in the indoor environment.

### 5.4. Opportunity to Cover Part of the Winter Energy Needs with a Biomass Heat Generator

Another possibility of making the building autonomous from the network, the insertion of a solid biomass boiler (pellet), to support the heat pump, is analysed, referring to the coldest winter period, in which the PV system does not completely cover the need for hot water for both the radiant heating system and for sanitary use (Year 3).

The analysis of the heat generator systems led to the choice of an automatic loading biomass heat generator with a nominal useful power of 9 kW, to be installed in the basement, where the remaining part of the equipment is located.

For this type of heat generator, an automated system is provided, which allows the continuous and autonomous supply of fuel without the intervention of an operator. Indicatively, it can be estimated that the cost of a boiler of this type is around €4000, excluding costs for the chimney and for the electrical connections, which may be absorbed in construction costs.

The demand for electric energy from the network, equal to 640 kWh, assuming a performance coefficient of 2.5, corresponds to a need for thermal energy equal to 1600 kWh. In the event of a

generation efficiency of 0.75, and the calorific value of the pellet equal to 4.9 kWh/kg, 435 kg of biomass (pellets) would be required, corresponding to an indicative cost of €116.

This estimate shows that the annual fuel expenses would be slightly lower than the annual cost of electricity required on the grid during the months of underproduction of the photovoltaic system. However, it is necessary to take into account the initial cost of the generator, the periodic maintenance costs (cleaning, smoke analysis), which have not been analysed as in any case they would not be recovered in an adequate time.

Although it is not convenient, from the economic point of view, to face the investment in a biomass generation system, in support of the heat pump, this solution would still be more advantageous than the previous one, as it is economically more convenient and better manageable, even in conditions other than those assumed.

The integration would be interesting to pursue the building's objective of energy autonomy from existing urban networks, with a better management possibility than that assessed for the electricity storage system. The system would, in any case, receive a contribution from renewable sources and, therefore, have minimal impact on the environment.

## 6. Discussion

Some considerations have been summarized here, deriving both from the study of the current conditions of the building, through simulation and monitoring, and from the evaluation of the proposed design alternatives:

1. The calculations carried out through semi-stationary simulation, according to national and international regulations, have shown that the building has the NZEB energy classification. These data, compared with those obtained from the dynamic simulation, highlighted, as expected, differences that in some months were also significant (about 45%). Only in December, the dynamic simulation gave higher consumption, probably caused by the hourly variation of temperatures. The comparison with the actual consumption data indicates that, although the model was calibrated according to the actual ventilation rates, the dynamic calculation was able to accurately describe the situation with an error more evident in the two coldest months. Probably the thermal inertia of the structures and the contribution of the solar greenhouse played more important roles in keeping the internal environment at the set temperature.
2. The use of dynamic simulation made it possible to analyse in detail the power used over time and verify that the system has been correctly sized for each thermal zone. Furthermore, the hourly description of the behaviour of the solar greenhouse made it possible to evaluate the opportunity to change the temperature set point for activating the fan between the greenhouse and the internal environment. In this way it is possible to obtain greater advantages in terms of the solar energy use for heating indoor air in the winter months. The importance of the solar greenhouse is also demonstrated through the comparison between the configuration without and with its presence.
3. The comparison between the data of energy consumption and energy produced by the photovoltaic system shows that the electrical coverage by photovoltaics is guaranteed for almost the whole year. Only in two months of the year is it necessary to use electricity from the grid, but overall electricity consumption represents only 34% of the energy produced over the whole year. Currently, in the absence of an energy storage system, the energy surplus by the photovoltaic system is reintroduced into existing urban networks. It would be interesting in the future to consider the possibility of connecting the building to a local smart grid, capable of redistributing the surplus of energy to other buildings connected to the system, to cover an energy requirement corresponding to about four times that of the case study.
4. The analysis of the internal thermohygro-metric conditions indicates that the internal comfort can be improved in winter by setting an internal set point temperature of 22 °C instead of 20 °C. Even if the increase in energy consumption is equal to 36% for heating, it can be largely covered

by the summer overproduction in the annual budget. A good level of comfort is maintained for a much longer time, especially in the living area, but also in the two sleeping areas.

5. In the analysis of the building project, two aspects that deserve further attention emerged and, therefore, were subject to verification: the possibility of energy storage was calculated by demonstrating that in the specific context the solution is not economically convenient. The support of a biomass generator to cover the winter needs, when the heat pump powered by photovoltaic energy is not sufficient, is equally not convenient from an economic point of view.

## 7. Conclusions

Some peculiar elements in the design and management of a NZEB have been analysed, mainly represented by microclimatic control, technical systems management, and regulation. Through the dynamic simulation, some exemplary results have been highlighted, considering the following aspects:

- The management system of the solar greenhouse and its energy contribution in winter;
- the operation of the heat pump, supported by the PV system, in summer;
- the almost total coverage of the building's energy needs in the annual cycle, thanks to the production of energy from the photovoltaic system;
- the potential PEB qualification of the building thanks to the surplus of energy produced which is fed into the network;
- the effective advantages, in terms of environmental comfort, due to the regulation of the internal set point temperature, with a consequent extra consumption, limited and covered by the overproduction of PV energy;
- the winter energy supply of the solar greenhouse, in relation to a smart management of the air flows from it to the internal environment and possible operating alternatives;
- the use of storage batteries for the energy produced by the PV system; and
- the use of a biomass heat generator to support the heat pump during the winter season to recover energy from the electricity grid.

The analysis of the case study is emblematic of an integrated approach, to be applied for all new buildings, which must take into account multiple aspects and alternatives to allow maximum effort to reduce energy consumption, avoiding unjustified extra costs and optimizing the integration of RES. It should represent the method to apply in every NZEB project to obtain optimal results.

The NZEB design, however, should not represent the goal, but the starting point: in fact, this model tends to create highly efficient buildings, but isolated from the urban context in which they are located, mainly characterized by existing buildings with a dispersing building envelope and an inefficient plant system. The further step forward, represented by PEB, could be evaluated technically and economically, to share its energy surplus to other buildings through the connection to a distribution network of a smart energy grid.

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## References

1. European Union. Directive 2010/31/EU of the European Parliament and of Council of 19 May 2010 on The Energy Performance of Building (EPBD Recast). *Off. J. Eur. Union* **2010**, *18*, 2010.

2. European Union. Commission Recommendation (EU) 2019/786 of 8 May 2019 on Building Renovation, C (2019) 3352, 16.5.2019. *Off. J. Eur. Union* **2019**, *127*, 37–79.
3. European Union. Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the Energy Performance of Buildings and Directive 2012/27/EU on Energy Efficiency, 19.6.2018. *Off. J. Eur. Union* **2018**, *156*, 75–91.
4. Cao, X.; Dai, X.; Liu, J. Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. *Energy Build.* **2016**, *128*, 198–213. [[CrossRef](#)]
5. Magrini, A.; Lentini, G.; Cuman, S.; Bodrato, A.; Marengo, L. From nearly zero energy buildings (NZEB) to positive energy buildings (PEB): The next challenge—The most recent European trends with some notes on the energy analysis of a forerunner PEB example. *Dev. Built Environ.* **2020**, *3*, 100019. [[CrossRef](#)]
6. Kolokotsa, D.; Rovas, D.; Kalaitzakis, K.; Kosmatopoulos, E. A roadmap towards intelligent net zero- and positive-energy buildings. *Sol. Energy* **2011**, *85*, 3067–3084. [[CrossRef](#)]
7. Bevilacqua, P.; Benevento, F.; Bruno, R.; Arcuri, N. Are Trombe walls suitable passive systems for the reduction of the yearly building energy requirements? *Energy* **2019**, *185*, 554–566. [[CrossRef](#)]
8. Szyszka, J.; Bevilacqua, P.; Bruno, R. An Innovative Trombe Wall for Winter Use: The Thermo-Diode Trombe Wall. *Energies* **2020**, *13*, 2188. [[CrossRef](#)]
9. Bruno, R.; Bevilacqua, P.; Cuconati, T.; Arcuri, N. Energy evaluations of an innovative multi-storey wooden near Zero Energy Building designed for Mediterranean areas. *Appl. Energy* **2019**, *238*, 929–941. [[CrossRef](#)]
10. Sougkakis, V.; Lymperopoulos, K.; Nikolopoulos, N.; Margaritis, N.; Giourka, P.; Angelakoglou, K. An Investigation on the Feasibility of Near-Zero and Positive Energy Communities in the Greek Context. *Smart Cities* **2020**, *3*, 362–384. [[CrossRef](#)]
11. Feng, W.; Zhang, Q.; Ji, H.; Wang, R.; Zhou, N.; Ye, Q.; Hao, B.; Li, Y.; Luo, D.; Lau, S.S.Y. A review of net zero energy buildings in hot and humid climates: Experience learned from 34 case study buildings, Renewable and Sustainable. *Energy Rev.* **2019**, *114*, 109303. [[CrossRef](#)]
12. Himpe, E.; Janssens, A.; Vaillant Rebollar, J.E. Energy and comfort performance assessment of monitored low energy buildings connected to low-temperature district heating. *Energy Procedia* **2015**, *78*, 3465–3470. [[CrossRef](#)]
13. Van de Putte, S.; Bracke, W.; Delghust, M.; Steeman, M.; Janssens, A. Comparison of the actual and theoretical energy use in nZEB renovations of multi-family buildings using in situ monitoring. *E3S Web Conf.* **2020**, *172*, 22007. [[CrossRef](#)]
14. Matuska, T.; Sourek, B.; Broum, M. Energy system for nearly zero energy family buildings—Experience from operation. *Energy Rep.* **2020**, *6* (Suppl. S3), 117–123. [[CrossRef](#)]
15. Xu, Y.; Yan, C.; Liu, H.; Wang, J.; Yang, Z.; Jiang, Y. Smart energy systems: A critical review on design and operation optimization. *Sustain. Cities Soc.* **2020**, *62*, 102369. [[CrossRef](#)]
16. Tumminia, G.; Guarino, F.; Longo, S.; Aloisio, D.; Cellura, S.; Sergi, F.; Brunaccini, G.; Antonucci, V.; Ferraro, M. Grid interaction and environmental impact of a net zero energy building. *Energy Convers. Manag.* **2020**, *203*, 112228. [[CrossRef](#)]
17. Zhang, S.; Liu, Y.; Yang, L.; Liu, J.; Hou, L. Applicability of different energy efficiency calculation methods of residential buildings in severe cold and cold zones of China. *E ES* **2019**, *238*, 012029. [[CrossRef](#)]
18. Ballarini, I.; Primo, E.; Corrado, V. On the limits of the quasi-steady-state method to predict the energy performance of low-energy buildings. *Therm. Sci.* **2018**, *22* (Suppl. S4), 1117–1127. [[CrossRef](#)]
19. Magrini, A. *Building Refurbishment for Energy Performance—A Global Approach*; Springer: Cham, Switzerland, 2014; ISBN 978-3-319-03073-9.
20. Magrini, A.; Lazzari, S.; Marengo, L. Energy retrofitting of buildings and hygrothermal performance of building components. Application of the assessment methodology to a case study of social housing. *Int. J. Heat Technol.* **2017**, *35*, S205–S213. [[CrossRef](#)]
21. Available online: <https://www.anit.it/software-anit/icaro/> (accessed on 31 August 2020). (In Italian)
22. European Committee for Standardization. *Energy Performance of Buildings—Energy Needs for Heating and Cooling, Internal Temperatures and Sensible and Latent Heat Loads—Part 1: Calculation Procedures (ISO 52016-1:2017)*; European Committee for Standardization: Brussels, Belgium, 2017.
23. ENEA. *Annual Report 2019—Energy Efficiency—Analysis and Results of Our Country’s Energy Efficiency Policies*; ENEA: Rome, Italy, 2019; p. 312, ISBN 978-88-8286-382-1. Available online: <https://www.enea.it/it/seguici/pubblicazioni/edizioni-enea/2019/rapporto-annuale-efficienza-energetica-2019> (accessed on 31 August 2020).



24. Mutani, G.; Pascali, F.; Martino, M.; Nuvoli, G. Nearly zero energy buildings: Analysis on monitoring energy consumptions for residential buildings in Piedmont Region (IT). In Proceedings of the 2017 IEEE International Telecommunications Energy Conference (INTELEC), Broadbeach, Australia, 22–26 October 2017; pp. 233–240, ISBN 978-1-5386-1019-0.
25. Ministry of Economic Development. *Applicazione delle Metodologie di Calcolo delle Prestazioni Energetiche e Definizione delle Prescrizioni e dei Requisiti Minimi Degli Edifici (Application of the Energy Performance Calculation Methodologies and Definition of Dispositions and Minimum Requirements for Buildings)*; OJ of The Italian Republic: Rome, Italy, 2015. (In Italian)
26. Zavrl, M.S.; Stegnar, G. Comparison of Simulated and Monitored Energy Performance. Indicators on NZEB case study Eco Silver House. *Procedia Environ. Sci.* **2017**, *38*, 52–59. [[CrossRef](#)]
27. Di Giuseppe, E.; Ulpiani, G.; Summa, S.; Tarabelli, L.; Di Perna, C.; D’Orazio, M. Hourly dynamic and monthly semi-stationary calculation methods applied to nZEBs: Impacts on energy and comfort. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *609*, 072008. [[CrossRef](#)]
28. Oliveti, G.; Arcuri, N.; De Simone, M.; Bruno, R. Solar heat gains and operative temperature in attached sunspaces. *Renew. Energy* **2012**, *39*, 241–249. [[CrossRef](#)]
29. Ulpiani, G.; Giuliani, D.; Romagnoli, A.; di Perna, C. Experimental monitoring of a sunspace applied to a NZEB mock-up: Assessing and comparing the energy benefits of different configurations. *Energy Build.* **2017**, *152*, 194–215. [[CrossRef](#)]
30. Italian Government. *Legislative Decree 3 March 2011, n.28. Attuazione della Direttiva 2009/28/CE sulla Promozione Dell’uso Dell’energia da Fonti Rinnovabili. (Implementation of Directive 2009/28/EC on the Promotion of the Use of Energy from Renewable Sources)*; OJ of The Italian Republic: Rome, Italy, 2011. (In Italian)
31. European Committee for Standardization. *Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort*; (CEN) EN ISO 7730; ISO: Rome, Italy, 2005.
32. European Committee for Standardization. *Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics*; (CEN) EN 15251; European Committee for Standardization: Brussels, Belgium, 2007.



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