Towards Zero Energy Buildings: the UniZEB case study

Laura Carnieletto[1] , *Milica* Mitrovic[2,3] , *Beatrice* Riccardi[4,5*] , *Umberto* Turrini[2] , *Fabio* Bignucolo[5] , *Michele* De Carli[5]

[1] Università Ca' Foscari, 30100 Venezia (VE), Italy
[2] Università degli Studi di Padova, Dipartimento di Ingegneria Civile, Edile e Ambientale, 35131 Padova (PD), Italy
[3] Scuola Edile di Padova, 35127 Padova (PD), Italy
[4] Istituto Universitario di Studi Superiori IUSS Pavia, 27100 Pavia (PV), Italy
[5] Università degli Studi di Padova, Dipartimento di Ingegneria Industriale, 35131 Padova (PD), Italy

Abstract. Buildings are among the primary contributors to global energy consumption, and reducing their demand is one of the challenges that need to be considered for a sustainable future. Zero Energy Buildings (ZEB) represent one of the most promising strategies in this endeavor, and in this sense, the UniZEB project addresses this issue with an innovative approach. It is a Zero Energy Building Laboratory of the University of Padova, built up from a collaboration between local companies, students, and researchers, featuring high performance HVAC and envelope technologies integrated with renewable energy sources. The present work offers an overview of the project, showing some of the already-faced challenges, as well as future opportunities of research and study. The purpose of the laboratory is indeed to offer the students the possibility to put in practice the knowledge they gain through university, as well as exploring new subjects through recent research topics, e.g., the development of a sensor network for the monitoring of the building, the dynamic model calibration, able to compare expected and current energy demand. The paper aims also to demonstrate the potential of a project like UniZEB, proving how research, innovation, and collaboration can shape the future of sustainable construction.

Key words: Energy efficiency; HVAC systems; Dynamic Energy Models; Living Lab; Innovation in building technologies.

1. Introduction

The concept of Zero Energy Building (ZEB) has been present in the academic and building environment for several years, with its origins dating back to the early 1970s, when the increased price of oil lead to the search for energy-saving solutions [1]. In the last fifty

* Corresponding author: beatrice.riccardi.1@studenti.unipd.it , beatrice.riccardi@iusspavia.it

years, technology advanced forward, towards the definition of a zero energy building. It consists of a highly energy-efficient structure designed to produce as much energy as it consumes over the course of a year, ideally achieving an energy balance of zero. This type of building reflects the building sector's recognition of its impact on global carbon dioxide emissions, highlighting the need for sustainable and environmentally conscious solutions. The European Directive 2010/31/EU [2], commonly referred to as the Energy Performance of Buildings Directive (EPBD), focuses on improving the energy performance of buildings by introducing the concept of nearly-Zero Energy Building (NZEBs). The definition provided by the EPBD referred to a building for which "nearly zero or very low of amount of energy required should be extensively covered by renewable sources produced on-site or nearby" (Energy Performance of Buildings Directive, 2010). Numerous studies and writings have explored the subject of NZEB. For instance, [3] compared the technical and economical limits encountered when building NZEBs, using data from seven case studies in Southern Europe. [4] focused instead on how the climate change is influencing the performance of NZEBs; similarly, [5] found how current climate trends, in the short term analysis, are responsible of higher energy requirement for space cooling, rather than space heating – and will continue to do so. [6] discuss the gap between forecast and actual consumption, and how this is fundamental in improving the energy efficiency on a wider scale.

Despite being extremely efficient buildings, their realization tackles with several technical and economic challenges, as thoroughly studied in the work by [7] and [8]. In fact, while the ideal goal is to achieve a complete energy neutrality, a perfect balance between supply and demand may be challenging, as in some cases, there may be a surplus of energy which is not required from the users, and, on the other hand, it may be necessary to draw from the grid when energy from renewable sources is not available. Despite that, the 2023 revision of the EPBD aims for all new buildings to be Zero Emission Buildings by 2028, while existing buildings should achieve zero emissions by 2050, thus having significant effects on the built environment. This is especially true for a country like Italy, where a significant fraction of the residential building stock predates 1991 [9], when the first Italian law regulating building energy consumptions for building was actuated. At the same time, the transition from NZEB to ZEB necessitates a comprehensive integration of technologies, systems, and building design. The present work aims to study and analyze the performance of a case study and explore possible solutions that could allow its transition. The building presented is the prototype of the University of Padova's project, UniZEB. It consists of a zero energy building laboratory, in which a collaboration between students, professors, and local companies is allowing the construction of its first prototype building. [10], show the success encountered from the collaboration between university and industry in the construction of the KTH Live-In-Lab, as, similarly to the UniZEB case, it offers the chance of creating a community where both industrial organizations and research groups can grow and where discussion and sharing can thrive. More specifically, the paper presents the innovative solutions installed in the building, and analyzes its performance through a dynamic model, developed with the dynamic simulation software TRNSYS.[1] It is important to underline that this study represents a preliminary version of the TRNSYS model, which will be implemented more in detail once the construction phase (in progress at the moment) is completed. The main goal objective is to have an overview energy consumption level through a first model setup. As construction advances, the model will be refined accordingly. This iterative process provide hints for conservative actions during the construction, allows the improvement of regulation setup and the definition of a complete monitoring system. Regarding the structure of this work, section 2 describes the UniZEB case study and the properties of the building prototype and Section 3 presents the TRNSYS model integrating

[1] https://www.trnsys.com/ (last seen: 19/12/2023)

the photovoltaic system and the domestic hot water production. After this, the final section explains the main outcomes that lead to many possible future research topics, followed by the conclusion.

2 Description of UniZEB and the case study

The UniZEB project is the Zero Energy Building Laboratory founded by University of Padova, which involves collaborative efforts among students belonging to multidisciplinary university courses. Professors and local companies are also involved in the project design and realization, currently counting around 30 students and several companies that are actively contributing to the project's development. The design phase started in 2015 with a group of energy engineering students, whose main goal concerned the construction and monitoring of the prototype building; data gathered during the operational phase can indeed provide valuable feedback that can be useful both for researchers and involved companies. Following the completion of the building, three students will be living inside for short periods, facilitating the assessment and operation of installed technologies in a real environment. The monitoring system will gather data regarding building envelope, HVAC system, energy demand for space heating, cooling, and domestic hot water (DHW) production, indoor environmental quality, waste management, life cycle analysis (LCA), and other related research areas. Beyond the immediate practical goals, UniZEB also emphasizes the educational aspect for the participating students, as the project serves, indeed, as a platform for students to apply their background knowledge gained from university lectures into practical challenges.

The prototype building is located in the industrial area of Padova, about 20 minutes away from the city center. Covering an area of 80 m^2, the building is designed to accommodate at most three individuals and is organized into three separate zones: the day zone, including the living room and kitchen, the night zone with two bedrooms, and a filter zone including the bathroom, data room, technical room, and hallway. Figure 1 shows the plant of the building.

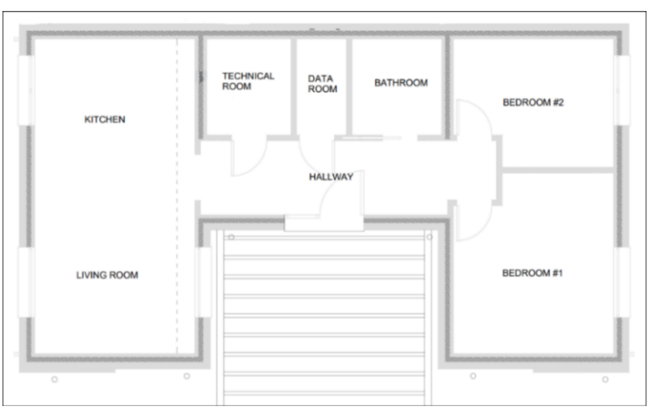

Fig. 1. Map of the prototype.

The unconventional use of cross laminated timber (CLT) in a humid climate represents an architectural challenge. Most of the building's envelope is made of 16 cm of external insulation; the South-facing walls have been divided to enable a comparative study between a ventilated façade and a traditional insulation system. Similarly, the roof is divided into three segments, with gravel covering the night zone, vegetation on top of the day zone and a floated pavement covering the filter zone. This solution has been adopted to test if the efficiency of the PV system would be affected by a different temperature under the panels, as it is expected to be lower in the vegetation side of the roof. To achieve self-sufficiency, the prototype integrates a PV system with a storage battery boasting a peak power of 6 kW, supported by external lithium batteries with a 10 kWh capacitance. PV panels, strategically positioned on the south-facing roof at a 30° inclination, are connected to an inverter with an optimization system deciding if storing the battery system or supplying the actual electrical demands within the house. The electric load produce allows the operation of a reversible ground source heat pump combined with a borehole heat exchanger 100 m deep and coupled with a chilled ceiling for space heating and cooling. The borehole heat exchanger was sized using the ASHRAE method (ASHRAE Handbook, 2007), which requires the calculation of the borehole length for space heating and cooling separately. Using the tool proposed by [12], it was possible to calculate the proper size of the borehole heat exchanger, using as input the available information of the systems currently available for the real case study. From this analysis the necessary length to supply the cooling energy need requirement is about 54 m, while the length required for space heating and domestic hot water is around80 m. As already mentioned, the borehole chosen for the installation will be 100 m deep, to be conservative considering the preliminary early-stage nature of the study while avoiding thermal drift and subsidence of the ground; this result is further confirmed by the tool, since the penalty temperature obtained is lower than 1°C. Furthermore, due to the interdisciplinary nature of the UniZEB project, extensive testing will be conducted on the borehole heat exchanger.

A mechanical ventilation system with an air handling unit (AHU) ensures optimal air quality, humidity control, and sufficient air exchange rates. This system incorporates a heat recovery unit, filters, and a chiller dedicated to de-humidification processes, allowing the extraction of warm air from active rooms, such as the kitchen and the bathroom, in order to pre-heat fresh air before it is supplied to bedrooms and the living room. The exhaust air from the technical room, is then brought to the data room before the expulsion, where servers and computers work consistently.

3 Description of TRNSYS model

3.1 Description of the base model

As the aim of this study is to propose a preliminary analysis of the case study, estimating the main energy consumption, it is fundamental to study the dynamic behavior of the building. However, given the ongoing construction status and the fact that it has yet to be occupied, an analysis of its energy consumption - thus, the overall system performance - cannot be done from bills or sensor data. Therefore, a dynamic simulation model has been carried out with the software TRNSYS. The model simulates the complex interaction of several parameters affecting the energy performance. The starting model refers to the work by [12] and [13], although with different purposes, as the model developed in the former was used for the design of the HVAC systems, while in the latter a simplified version was used to carry out a global sensitivity analysis. In this work, the model is used to set a baseline for more detailed dynamic simulation models, in order to achieve an initial overview on the building behavior.

After the implementation of the geometry and construction layers' properties, the modelling process focused on other important characteristics that influence the behavior of the building. Among these, internal loads represent both sensible and latent heat contributions caused by the presence of people, lighting, electrical and/or mechanical appliances, excluding those from systems or external sources. The value of each internal load is specified in terms of power or water vapor flow rate, assigned to specific types regulating the actual operation of these loads through tailored-made schedules. Table 1 shows in detail which values were used to account for the internal loads.

Table 1. Values of the internal loads.

Internal loads			
Occupancy	70 W	With schedules	- Day zone - Night zone
	50 g_v/h		
Lighting	5 W/m^2	With schedules	- Day zone - Night zone
Appliances	42 W	Constant	
Computer	230 W	Constant	
Kitchen appliances	30 W	Constant	
	10 W and 200 g_v/h	For each meal	
Bathroom	110 W	With schedule	- One person in the morning - Three people in the evening
	200 g_v/h		

In addition, two key parameters should be investigated for thermal comfort evaluation: the basal metabolic rate (BMR) and the clothing resistance. BMR is the rate of energy expenditure per unit time by all endothermic animals, including humans. It is defined through the unit «met»: 1 met = 58.2 W/m^2, 1 met being the rate of energy produced per unit surface area of an average person seated at rest. It varies throughout the day based on the user activity; for this case study, a value of 1.2 met was assumed during the day (sedentary activity) and 0.8 met for the night (lying down to sleep). The clothing resistance takes into account the different thermal conductivity of the fabrics worn. The insulation effect of clothing can be expressed by another value, «clo», corresponding to the equation 1 clo = 0.155 (m^{2}K)/W. Typical values range from 1.0 clo in heating conditions, to 0.3 clo during the summer season. In the present model, it was assumed to vary with seasons, as shown in Table 2.

Table 2. Values of clothing resistance**.**

Values of clothing resistance [clo] throughout the year[2]	
January – February – March	1
April	0.7
May – June	0.5
July – August	0.3
September	0.5
October	0.7
November – December	1

[2] An additional 0.2 clo was added during the nighttime to account for the use of blankets.

Moving to the implementation of the radiant ceiling a partially pre-compiled chilled ceiling layer is available within TRNSYS libraries. It requires the knowledge of specific thermal and structural panel parameters, which remain constant throughout the simulations: pipe spacing (0.074 m); pipe internal diameter (0.008 m); specific power at (250 kJ/m$^{2)}$; thermal heat exchanger coefficient between the water within the pipes and the drywall layer of the ceiling panel, at 60 kJ/(h·m^2·K). These inputs have been defined according to the available datasheet. The convective heat exchange coefficient (α_{conv}) has been considered as a function of the temperature difference between the surface ($T_{sup,avg}$) and the air (T_a), by means of a proportionality constant:

$$\alpha_{conv} = const \cdot (|T_{sup,avg} - T_a|)^n \tag{1}$$

The values used for α_{conv} and n are shown in Table 3.

Table 3. Parameters for the heat transfer coefficient calculation.

Parameters for internal calculation of heat transfer coefficients		
Constant heated ceiling, if ($T_{surf,ceiling}$-$T_{air,ceiling}$) > 0	9	kJ/(h·m^2·K)
Exponent heated ceiling, if ($T_{surf,ceiling}$-$T_{air,ceiling}$) > 0	0	-
Constant chilled ceiling, if ($T_{surf,ceiling}$-$T_{air,ceiling}$) < 0	29	kJ/(h·m^2·K)
Exponent chilled ceiling, if ($T_{surf,ceiling}$-$T_{air,ceiling}$) < 0	0.21	-

The inlet temperature has been set at 30°C during winter and 18°C during summer, as agreed after the sizing of the whole system, which considered the worst-case scenario for each type of regime, paying attention to the requirement of maintaining an inlet-outlet temperature difference at 3°C, for both the heating and cooling season. The water flowrates (m_{tot}) have been calculated considering the following equation:

$$P_{rad} = m_{tot} \cdot c_{p,w} \cdot \Delta T_w \tag{2}$$

where P_{rad} is the power that must be provided to the panels (separately for heating and cooling season) [kW]; $c_{p,w}$ is the specific heat of water (equal to 4.186 kJ/(kg·K)); and ΔT_w is the water temperature difference between inlet and outlet (equal to 3°C). Isolating the flowrate, the values are shown in Table 4, and remain the same for both cases.

Table 4. Values of the flowrates.

Values of flowrates for the radiant system					
	Day Zone	Bathroom	Hallway	Room #1	Room #2
[kg/h]	240	94	74	114	78

After setting the parameters in the TRNBuild active layer, Type 56 requires as input values the flow rates and temperature for the chilled ceiling, which has been provided in Simulation Studio with a calculator. The ceiling operation is regulated by an input text file which simulates the functioning of the panels throughout a year (more in detailed: heating regime from October 15th until April 15th and cooling regime from June 1st until August 31st). Finally, to ensure a proper operation of the radiant system through a typical day, a differential control system with a 2°C dead band is applied to the chilled ceiling, following the regulation setup of the installed panels, which include a sensor per room with on/off signal sent to the interception valves. The temperature setpoints are set at 20°C in winter and 26°C in summer for most rooms, with the bathroom set at 24°C during winter (the technical room and data room lack radiant panels and therefore remain unconditioned and unheated). The differential control modulates the signal (γ_o) between 0 and 1 based on the room temperature and the control signal of the previous timestep, as better explained by Figure 2. More in detail, the key parameter for the switch of the signal is the current room temperature, which is compared with the absolute temperature difference between the setpoint and measured value (ΔT_{ms}), and the value assumed by the signal in the previous timestep (γ_i).

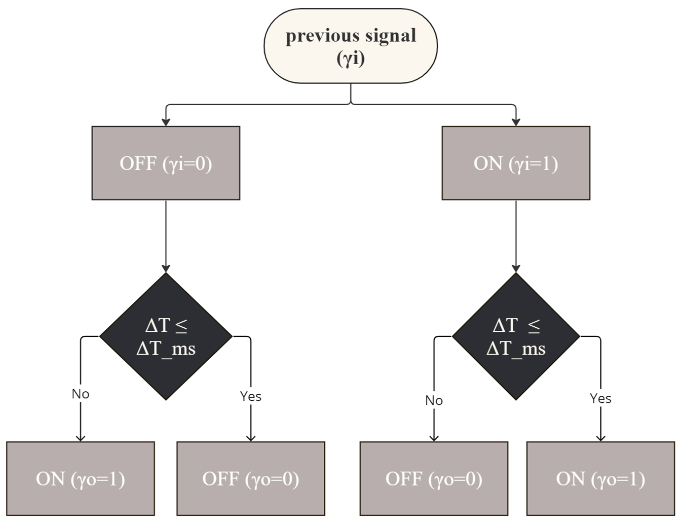

Fig. 2. Flowchart of the differential control.

After completing the radiant system modelling, the focus moved to the ventilation system, for which there is a limitation regarding the extraction of exhaust air. Contrarily to the chilled ceiling, Type 56 does not have an embedded modellable ventilation system; therefore, it was necessary to implement it in the system by using a calculator. After the assessment of the supply air conditions for the specific nodes, maintaining uniform inlet conditions across the rooms (temperature and absolute humidity), the supply air flow is managed by a calculator attached with specific text files. Mass flow rates are calculated based on room occupancy, following a specific schedule. The system can operate either in the regular way, or in the free-cooling mode, when the temperatures range between 18°C and 24°C. Additionally, temperature control relies on external conditions and recovery temperatures from the extraction side. This aspect is managed by the extraction plenum and extraction fan, utilizing temperatures from the building type (Type 56) for extraction flow rates and providing the calculator with the required recovery temperature. Figure 3 shows the layout of the model described.

3.2 Domestic hot water

The heat pump includes an internal 200-liter technical water storage tank as heat accumulator, while a plate heat exchanger is connected externally for the instantaneous production of hot water.

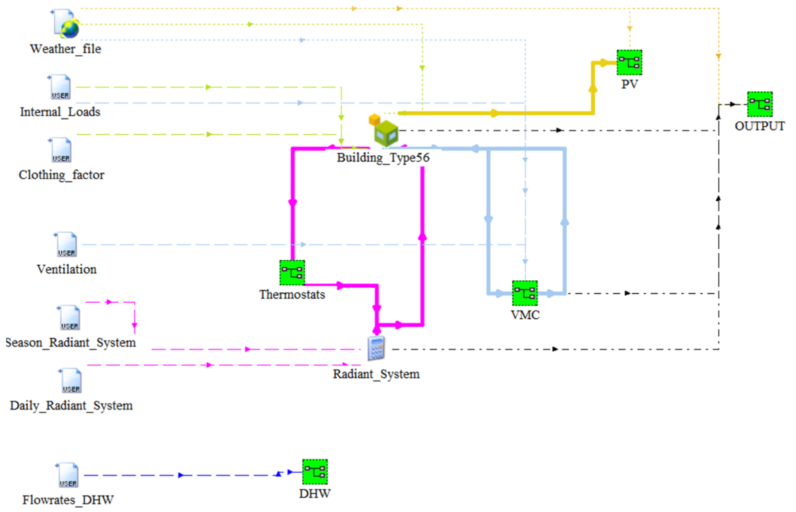

Fig. 3. Basic model of the UniZEB prototype in the TRNSYS interface Simulation Studio.

Type 4 was selected to add the DHW module, representing a cylindrical tank that considers temperature stratification, modeled by dividing the tank into 5 nodes. The cylindrical tank, with a height (L) of 1.5 m, an internal radius (r_i) of 20 cm, and insulated with 4 cm of plastic material (so the external radius r_e is of 24 cm) and a thermal conductivity of $\lambda = 0.033$ W/(m·K), had its heat loss coefficient calculated K based on these parameters:

$$K = 1/\{[(2\cdot\pi \cdot L \cdot\lambda)/ln(re/ri)]+Rsi\} \quad (3)$$

R_{si} stands for the external surface resistance of the tank, set to 0.125 W/(m²·K). The model of the tank includes not only the envelope losses, but also the water mass rate and the energy balance between incoming water and exiting water, as well as the stratification inside the tank. Downstream, a diverter thermostatic valve and a mixing valve redirect a fraction of the incoming flow for recirculation to obtain the set point temperature of the water supplied to the sanitary fixtures, fixed at 45°C. A differential thermostat controls the temperature of the highest node of the tank, which is the hottest one due to stratification. It commands the system to start heating when it drops below 45°C, ceasing as soon as it reaches 54°C.

The input flowrate coming from the aqueduct and entering the diverter valve is calculated using the program “DHW calc”. As explained by [15] this program allows the creation of a quite realistic DHW-load profile, for domestic application. The energy input for DHW has been calculated using the formula available from the standard UNI 11300-2 as:

$$E_{DHW} = \rho_w \cdot c_{p,w} \cdot \Sigma_i V_{w,i} \cdot (T_{er,i} - T_o) \cdot D \quad (4)$$

where ρ_w and $c_{p,w}$ are respectively the water density (1000 kg/m^3) and specific heat ($1.162\cdot10^{-3}$ kWh/(kg·K)); $V_{w,i}$ is the daily water volume required for each activity or service, and is measured in [l/day]. This volume is calculated differently according to the type of building and total useful surface S_u, according to specific parameters that are present in the normative and is equal to 120 l/day. Furthermore, $T_{er,i}$ and T_o are respectively the delivered water temperature, set at 45°C, and the aqueduct water temperature, at 10°C. Finally, D is the number of days considered, in this case 365 days. With all these parameters, the yearly energy requirement for the DHW production is about 1750 kWh, which corresponds to a specific energy requirement of 23 kWh/m^2 per year.

Starting from a daily consumption of 120 L/day, the program generates a daily profile, taking account of the different uses of the domestic hot water, such as hands-washing, taking a shower, or hand-washing some laundry. Figure 4 shows the section of the TRNSYS model dedicated to the DHW production. On the other hand, the control system has the aim to maintain 45°C as outgoing temperature from the mixing valve. When the DHW is required the heat pump provides heating to the water tank, as priority.

3.3 Integration with the PV system

The system installed has a peak power of 6 kW and an energy storage battery with a capacity of 10 kWh, which was later added to the existing model. The electrical load profile is provided as text input file, considering per each timestep heating, cooling (which comprehends dehumidification) and domestic hot water electric energy, and the remaining electrical loads of a typical residential building. In particular, the COP considered for space heating is 5.19 and for the DHW production is equal to 2.85. The EER for space cooling is

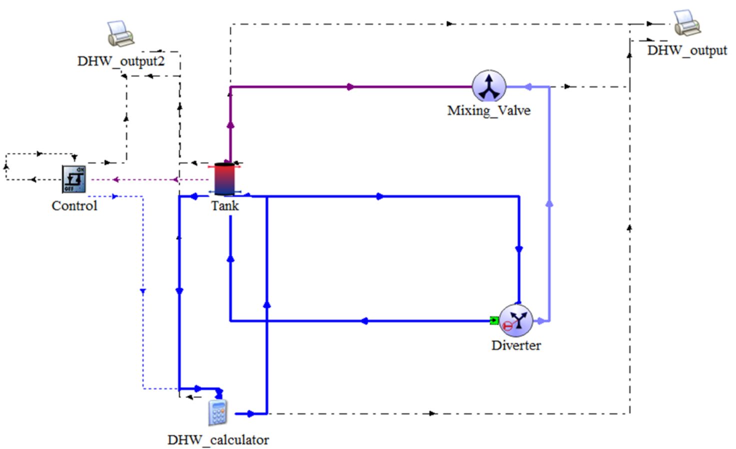

Fig. 4. DHW generation in the TRNSYS model.

instead equal to 5.43, while the EER for the dehumidification demand is 3.5 (all these values were taken from the technical sheet of the heat pump that will be installed). Equipment loads have been estimated based on the available technical datasheet of typical residential appliances:

- Refrigerator: constant functioning at 22 W;
- Washing machine: 3 hours washing program per evening at 140 W;
- Dishwasher: 4 hours program per evening at 205 W;
- Induction hob: 1 kW for one hour, for each lunch and dinner;
- Lighting: average values for each led stripe at 8W, which follow the same schedules of the internal gains seen priorly.

Figure 5 shows the TRNSYS model of the PV system.

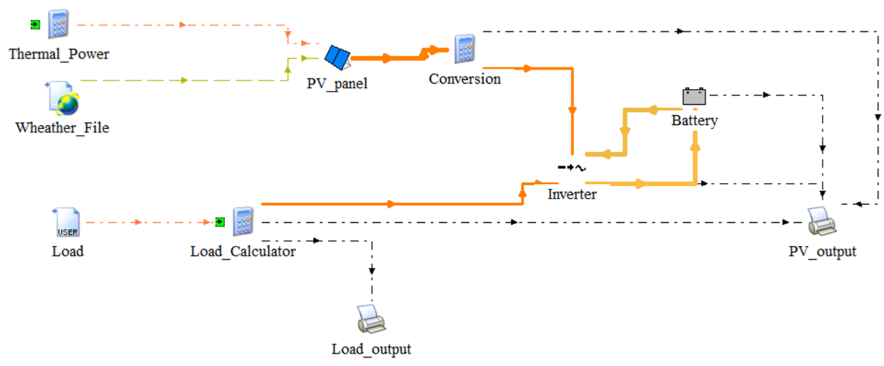

Fig. 5. Section of the TRNSYS model of the implementation of the photovoltaic system.

4 Results

4.1 Thermal energy requirement of the building

With a one-hour timestep, the sensible power needed to heat or cool down the building is shown in in Table 5, while the variation throughout the year is displayed in Figure 6.

Table 5. Energy requirement of the building for space heating and cooling

Energy requirement per year[kWh]		
	Space Heating	*Space Cooling*
Double Bedroom	226.2	434.9
Single Bedroom	173.6	357.2
Bathroom	120.5	-
Hallway	61.9	644.7
Living Room and Kitchen	319.7	2089.7
Total	901.7	3526.5
Specific energy requirement [kWh/(m² y)]	11.3	44.1

According to the guidelines of the EPBD, it is important to refer to the primary energy demand when looking at the overall energy used by the building. The values shown in Table 5 were converted firstly into final energy by considering the heat pump performance (through COP and EER). Finally, the conversion into primary energy used specific conversion factors that consider the losses for each energy carrier. In the present case, as the thermal energy requirement is satisfied by the heat pump connected to the photovoltaic system, the conversion factor ($f_{P,\,TOT}$) is equal to the sum of two other factors, accounting for the use of renewable energy (from the photovoltaic system, $f_{P,\,REN}$) and for the electric energy coming from the grid ($f_{P,\,NREN}$).

$$f_{P,\,TOT} = f_{P,\,NREN} + f_{P,\,REN} = 1.95 + 0.47 = 2.42 \tag{5}$$

The values shown in Equation 6 are taken from the Italian legislative decree 3/03/2011, n.28. Primary energy values are shown in Table 6.

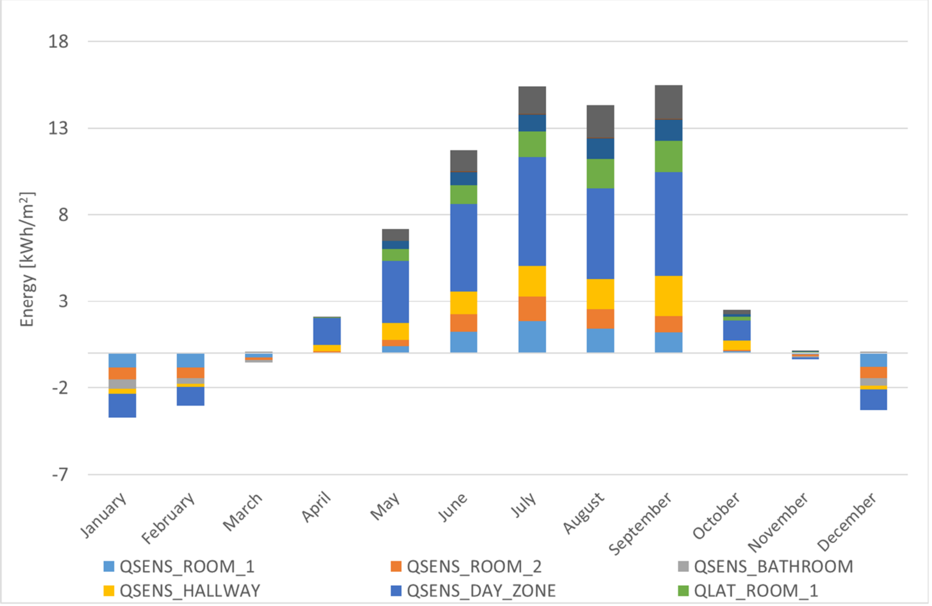

Fig. 6. Monthly variation of the specific energy requirement for space heating and cooling.

Table 6. Primary energy requirement of the building.

Primary energy requirement per year[kWh]				
	Space Heating	Space Cooling	Dehumidification	DHW production
Annual primary energy [kWh/y]	420.45	1571.66	165.50	849.22
Specific primary energy [kWh/(m² y)]	5.25	19.64	2.07	10.62

The values shown are higher than ZEB requirements; however, as UniZEB is not a common building, but a Zero Energy Building Laboratory, it has many sets of standards to fulfil. Among these, the necessity of testing different technical solution which might tackle the overall performance, such as the different envelope insulation techniques, or the different type of roof covering.

4.2 Integration with the PV system

The TRNSYS model allows the calculation of the power produced by the installed PV system considering the load from the building, as shown in Figure 7. The yearly energy produced by the photovoltaic system is about 6890 kWh.

Following the example set by [16], the total electric profile of the building can be compared on an hourly base to the energy produced by the photovoltaic system by means of two indicators: the self-sufficiency (SS) and the self-consumption (SC). Both depend on another parameter, the self-used energy, defined in Equation 7 as:

$$\textit{Self Used Energy} = \textit{Energy Consumed} - \textit{Energy supplied from the grid}\ [\text{kWh}] \quad (6)$$

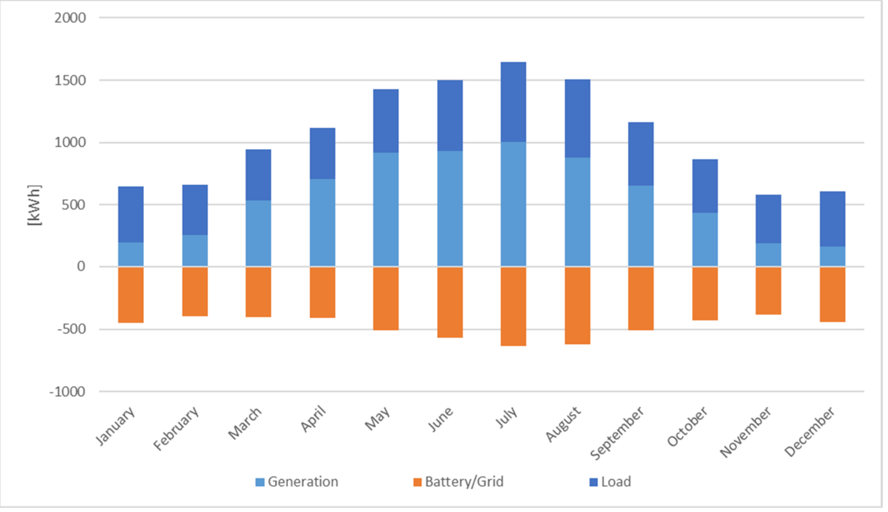

Fig. 7. Generation and load of the PV system.

Self-sufficiency is defined as the ratio between the self-used energy and the total energy consumed. Therefore, it corresponds to the percentage of energy consumed which is produced by the installed PV system. On the other hand, self-consumption is defined as the ratio between the self-used energy and the total energy produced by the PV system, representing the percentage of solar energy produced and consumed in the building compared to the total amount of solar energy produced. These key performance indicators have been calculated based on TRNSYS outputs, as shown in Table 7. The outcomes are coherent with a typical residential end use.

Table 7. Calculation of the two indicators.

Calculation of the self-sufficiency indicator (SS) and self-consumption (SC)	
Load	4200.3 kWh
Battery/grid	2693.1 kWh
Total generated energy	6886.1 kWh
Self-used energy	**1514.9 kWh**
Self -sufficiency	**36 %**
Self-consumption	**22 %**

5 Conclusions

The UniZEB project presented in this work aims at realizing the principles set by the EPBD, as it contributes to the creation of a sustainable, energy-efficient prototype including innovative design and technology integration. The TRNSYS simulation model investigates the energy performance of the building based on the dynamic operation of combined HVAC systems including a ground source heat exchanger properly regulated to maximize the energy

production and the system efficiency. The definition of human comfort parameters to be achieved and internal loads lead to a model close to reality; several challenges in modeling radiant systems and ventilation are addressed, showcasing the complexity of simulating real-world building dynamics. The model presented showed the challenge of achieving a perfect energy balance, thus the complexities occurred when transitioning towards a ZEB.
Although some data are still based on research assumptions, the main outcomes evidence how a neutral energy balance can be achieved by considering not only the energy requirement (which is equal to 11.3 kWh/m^2 in space heating and 44.1 kWh/m^2 in space cooling, yearly), but also the energy produced by the photovoltaic system (or any installed renewable source), through the evaluation of specific indicators, such as the self-sufficiency, as expected from the definition of a ZEB building. Furtehrmore, the regulation of the chilled ceiling is also presented using a draft version of the thermostats that will be installed in the building, which will be properly set on site once available. Therefore, future research topics include the integration of the state-of-the-art model with updated data and the calibration with monitored variables, supported by a sensitive analysis. This will lead to the creation of a highly detailed model that can be then used for many different purposes, according to the interest of the researchers involved. One of the possibilities is to follow the example set by [17], who managed to gather information about the controls of the HVAC systems towards the creation of digital twins. These can be used for fault detection and diagnosis, as well as performance gap analysis during the operational phase. Finally, it is important enhance the educational role of the project. The collaborative efforts between students, professors, and local companies create a platform for applying theoretical knowledge to practical challenges. This unique situation is an opportunity to improve personal and social skills, as well as working experience in a real building site teamwork.

References

1. F. Bazzoli e D. Chiaroni, nearly Zero-Energy Buildings (nZEBs), Master Thesis, Politecnico di Milano, 2015.
2. European Parliament. 2009. Directive 2009/28/EC of The European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the European Union.
3. S. Attia et al., Overview and future challenges of nearly zero energy buildings (nZEB) design in Southern Europe, Energy and Buildings, **155**, 439–458 (2017). https://doi.org/10.1016/j.enbuild.2017.09.043
4. F. Ascione, R. F. De Masi, A. Gigante, e G. P. Vanoli, Resilience to the climate change of nearly zero energy-building designed according to the EPBD recast: Monitoring, calibrated energy models and perspective simulations of a Mediterranean nZEB living lab, Energy and Buildings, **262**, 112004 (2022). https://doi.org/10.1016/j.enbuild.2022.112004
5. D. D'Agostino, D. Parker, I. Epifani, D. Crawley, e L. Lawrie, How will future climate impact the design and performance of nearly zero energy buildings (NZEBs)?, Energy, **240**, 122479 (2022). https://doi.org/10.1016/j.energy.2021.122479
6. N. Aste et al., nZEB: bridging the gap between design forecast and actual performance data, Energy and Built Environment, **3**, 1, 16–29 (2022), https://doi: 10.1016/j.enbenv.2020.10.001

7. T. Wilberforce, A. G. Olabi, E. T. Sayed, K. Elsaid, H. M. Maghrabie, e M. A. Abdelkareem, A review on zero energy buildings – Pros and cons, Energy and Built Environment, **4**, 1, 25–38 (2023). https://doi.org/10.1016/j.enbenv.2021.06.002
8. F. S. Hafez et al., Energy Efficiency in Sustainable Buildings: A Systematic Review with Taxonomy, Challenges, Motivations, Methodological Aspects, Recommendations, and Pathways for Future Research, Energy Strategy Reviews, **45**, 101013 (2023). https://doi.org/10.1016/j.esr.2022.101013
9. Legge 9 gennaio 1991, n.10. Norme per l'attuazione del Piano energetico nazionale in materia d'uso razionale dell'energia, di risparmio energetico e di sviluppo delle fonti rinnovabili di energia. S.O. n.6 della Gazzetta Ufficiale n.13 del 16/01/1991.
10. M. Molinari, J. Anund Vogel, D. Rolando, e P. Lundqvist, Using living labs to tackle innovation bottlenecks: the KTH Live-In Lab case study, Applied Energy, **338**, 120877 (2023). https://doi.org/10.1016/j.apenergy.2023.120877
11. A. Handbook, HVAC applications, ASHRAE Handbook, Fundamentals, 2007.
12. M. De Carli, L. Carnieletto, G. Emmi, D. Menegazzo, M. Mitrovic, U. Turrini, A. Zarrella, A. Di Bella, A computational capacity resistance model (CaRM) for vertical ground-coupled heat exchangers, Renewable Energy, **35**, 1537–1550 (2010). https://doi.org/10.1016/j.renene.2009.11.034
13. B. Riccardi, M. De Carli, L. Carnieletto, M. Rampazzo, E. Sisti, Global Sensitivity Analysis applied to a dynamic energy simulation model: the case study of UniZEB prototype building. International Institute of Refrigeration (IIR). Paris, France, August 21-23 (2023). https://doi.org/10.18462/IIR.ICR.2023.0732.
14. D. Menegazzo, M. De Carli, Gestione e progettazione degli impianti HVAC dell'edificio pilota UniZEB, Master Thesis, Università degli Studi di Padova, 2019.
15 U. Jordan e K. Vajen, Influence Of The DHW Load Profile On The Fractional Energy Savings: A Case Study Of A Solar Combi-System With TRNSYS Simulations, Solar Energy, **69**, 197–208 (2001). https://doi.org/10.1016/S0038-092X(00)00154-7
16. L. Carnieletto, A. D. Bella, D. Quaggiotto, G. Emmi, A. Bernardi, e M. De Carli, Potential of GSHP coupled with PV systems for retrofitting urban areas in different European climates based on archetypes definition, Energy and Built Environment, **5**, fasc. 3, 374–392 (2024). https://doi.org/10.1016/j.enbenv.2022.11.005
17. K. Walther, M. Molinari, e K. Voss, The role of HVAC controls in building Digital Twins: lessons learned from demonstration buildings with an application to air handling units, 18th IBPSA Conference on Building Simulation, BS 2023, Shanghai, China, September 4-6 (2023).