

The role of UniZEB living lab to promote a sustainable and user-centred building sector

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Abstract. Living labs represent a promising approach to the development of innovative solutions in real-world environments, particularly within the building sector. As it continues to contribute significantly to the growing global energy consumption, the application of living labs in this context is crucial. They indeed help develop dynamic and user-centred ideas, thanks to the collaborative effort of the involved stakeholders. The UniZEB project is the first living lab developed at the University of Padova, using this approach to address the challenge of creating sustainable solutions for buildings. The initiative brought together local companies, students, and researchers to build the first prototype in the industrial area of Padova. The building integrates high-performance HVAC systems, innovative building envelope technologies, and renewable energy sources, thus creating an interactive learning environment in a Zero Energy Building. This work presents in detail the design and construction process of the UniZEB living lab including the dynamic simulation model developed in TRNSYS to validate the building's potential and performance, showing a considerably low energy requirement for both heating and cooling (14.8 and 5.4 kWh/(m² y), respectively). Considering the future issues related to climate change and the ongoing need to reduce fossil fuel consumption, this project highlights the benefits and potential of living labs in shaping the future of sustainable construction.

Keywords: Living Labs, Sustainable building, User-Centred design, Innovation, Energy efficiency.

1 Introduction

The building sector plays a crucial role in the transition to a sustainable and low-carbon future, as it accounts for nearly 30% of global CO₂ emissions and over 40% of total energy consumption worldwide [1]. The increasing urgency of climate change highlighted the need for innovative approaches to design and manage energy-efficient buildings. Within this context, Living Labs become powerful tools for research and innovation, becoming testbed facilities to investigate sustainable construction methods, smart technologies, and user-centred building design. Furthermore, Living Labs offer a form of experimental learning in engineering education, providing interesting case studies for the people involved.

Living labs can be defined as interactive, collaborative and dynamic environments that involve multiple stakeholders, from manufacturers and researchers to the end-users, with the dual purpose of research and learning [2]. More specifically, as added by [3], a Living Lab is a dual-purpose facility, as it can be both an occupied building (e.g. housing, office space), and a hands-on learning and research facility where new technologies can be tested to ensure they are practical, scalable, and adaptable to real-world needs [4].

Several examples of Living Labs can be found worldwide. A first example of is the MIT PlaceLab, which is an apartment building with advanced technologies to study occupant's wellness [5]. Another example is in Chalmers University (Sweden), called HSB Living Lab, presented in [6]. It is a multi-family residential building comprising 29 apartments within the university. As underlined by [7], this follows within the recent trend of developing university campus as Living Lab to actively involve students and researchers. Similarly, the KTH Live-In Lab (Sweden) presented by [8] and [9] allows students and researchers to experiment with flexible building design and smart energy management systems in real living conditions.

Following this global trend, the UniZEB project represents the first Living Lab for sustainable construction at the University of Padova. Established in 2015 as a student-led initiative, UniZEB has evolved into a multidisciplinary platform, integrating education, research, and industry collaboration to develop and test Zero Energy Building (ZEB) solutions. The learning-by-doing approach applied follows the key characteristic of living labs, the user involvement. Students collaborate through the design, construction, and real-time performance evaluation of the building, ensuring that UniZEB is not only sustainable but also adaptable to human needs. Collaborating with five academic departments, 50 local companies, and 15 professors, UniZEB has created a bridge between academia and industry.

This paper provides a comprehensive analysis of the UniZEB Living Lab, focusing on the design, construction, and technological innovations that make it an exemplary model of user-centered design and sustainable building. Additionally, it presents the dynamic simulation model developed in TRNSYS, which evaluates the building's thermal performance. By placing UniZEB within the broader framework of Living Labs, this study underscores the crucial role of real-world experimental

environments in shaping the future of energy-efficient and user-centered building design.

2 UniZEB: the living lab concept

UniZEB started in 2015 from the idea of a group of Energy Engineering students aiming to tackle the urgent challenges of climatic change, recognizing that the building sector is responsible for approximately 30% of the global CO₂ emissions. Starting from these objectives, the group of students and professors developed the concept of a Living Lab for the University of Padova, thus setting a model for sustainable and innovative building practices. Over the past decade, the project moved from the conceptual design phase to the onsite construction of the first prototype, which was inaugurated in May 2024. The building is designed to be a Zero Energy Building, including many technological innovations and integrating renewable energies, as will be better explained in the following sections.

This remarkable achievement was possible thanks to the various collaborations established, from the network of students and academics to industrial stakeholders. UniZEB benefits from the participation of five departments at the University of Padova with 15 professors actively contributing as mentors and guiding an average of 40 students enrolled each year. Beyond academia, UniZEB extended its impact working with 50 local companies, promoting strong partnerships that connect education, research, and industry. Finally, the construction of the prototype was supported by the Scuola Edile di Padova, which provided the site for the building and played a significant role during the construction phase. Thanks to this network of collaborators, over its 10-year history, UniZEB has evolved into a multi-disciplinary reality, where students can experience the theory learned during class, and to actively contribute both in both the design and construction process of the building, following user-centered and sustainability design strategies.

Following the timeline of the project shown in Figure 1, several steps led to the inauguration of the building. Being a student-driven initiative, the project experienced annual turnover, providing an increasing number of students with the opportunity to contribute to the completion of the house.



Fig. 1: Timeline of UniZEB project

After the conclusion of the construction phase, the building will be used as a Living Lab, hosting three students from the University of Padova selected through an open application process, with a new group rotating on average every six months. Throughout their stay, their behavior will be passively monitored via an extensive sensor network, which will track environmental and energy-related parameters. More specifically, it 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 its primary goal of construction, UniZEB is a research hub, operating as a case study for a wide range of potential research topics involved since the design phase. Figure 2 provides an overview of the research areas involved, from psychology to engineering.



Fig. 2: Research areas that have UniZEB prototype as case study.

3 UniZEB: the building

The prototype building is located within the industrial area of Padova, about 20 minutes away from the city centre. Covering an area of 80 m², it 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 the two bedrooms, and a filter zone including the bathroom, data room, utility room, and hallway. Figure 3 shows pictures of the building including the site plant and two elevation views.

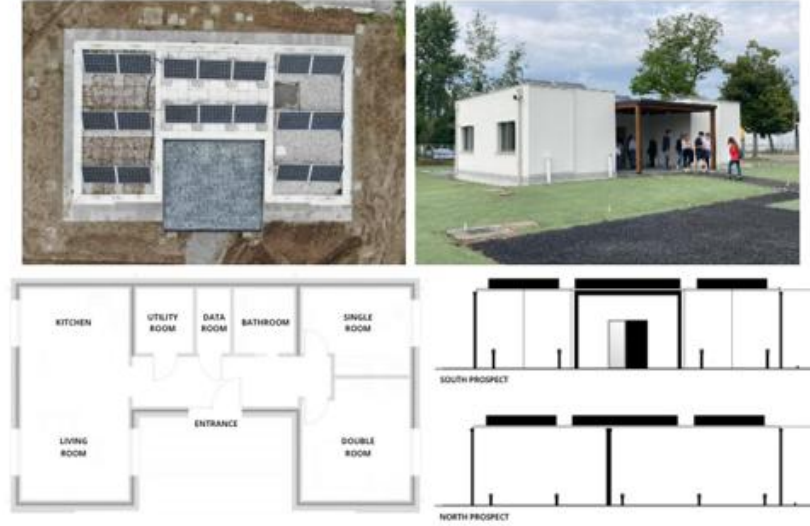


Fig. 3: Plant and prospects of the building.

3.1 Envelope innovations and properties

The wooden structure is quite uncommon in this region due to its peculiar humid climate. However, Cross Laminated Timber (CLT) is an innovative material composed of layers of solid-sawn timber glued together, which has recently gained popularity for its exceptional structural properties, making it a suitable and sustainable choice for this project. The prefabrication of the panels enabled a faster, cost-effective construction process, while the thermal insulation helps stabilize internal temperatures and reduce energy consumption, leading to the achievement of Zero Energy goals. Additionally, the thinner walls maximize interior space, increasing usable area by up to 6%. The panels are also equipped with a layer that slows fire propagation, further enhancing safety.

Envelope insulation is provided by a 16 cm panel of high-performance polyisocyanurate (PIR) that eliminates thermal bridges, protects the structure from temperature fluctuations, and extends its durability. Additionally, the building envelope of the South-facing walls is intentionally divided into two sections, allowing a comparative analysis between a ventilated façade and the typical insulation system technology. In the case of the ventilated façade, an external coating includes an air gap that separates it from the rest of the structure. In this way, natural convection is promoted within the gap, enhancing thermal performance while simultaneously allowing moisture to escape, which is particularly beneficial in humid climates. Table 1 presents properties of the two types of external walls of the building.

Similarly, the roof has been split into three sections: there is a floating pavement on the portion above the night zone, while the portions above the day and filter zones are covered with vegetation and gravel, respectively.

The glazed components of the building incorporate triple-pane glass with argon gas, ensuring exceptional insulation properties, minimizing heat loss and external noise, presenting a U-value of $1.2 \text{ W}/(\text{m}^2\text{K})$.

Finally, the floor is made of an innovative floating system, thus eliminating the need for adhesives or nails by using a height-adjustable support holding the tiles in place. This system was chosen because of the modular design, free of permanent fixings, which allows a quick and easy access to underfloor utilities, simplifying maintenance and inspections. The same choice was made for the floor on the outside patio of the house, for its effectiveness in managing stormwater, as its structure ensures efficient drainage, preventing flooding in areas prone to heavy rainfall. Moreover, the floating floor adapts to structural expansions and movements, minimizing the risk of cracks and damage, which enhances durability and reduces maintenance needs.

Table 1: Stratigraphy of the two types of external walls.

	Material	Width [m]	U-value [$\text{W}/(\text{m}^2\text{K})$]
External CLT with thermal coat (0.356 m)	Internal plaster	0.010	0.113
	Drywall panel	0.025	
	Mineral wool	0.050	
	CLT	0.100	
	Bitumen membrane	0.001	
	Insulation	0.160	
	External plaster	0.001	
External CLT with ventilated fa- çade (0.396 m)	Internal plaster	0.010	0.111
	Drywall panel	0.025	
	Mineral wool	0.050	
	CLT	0.100	
	Bitumen membrane	0.001	
	Insulation layer	0.160	
	Air gap	0.050	
	Drywall panel	0.025	
	External plaster	0.010	

3.2 HVAC systems

To ensure indoor thermal comfort, a ground-coupled heat pump system is used to deliver both heating and cooling through radiant panels installed in the ceiling. Beyond temperature regulation, the heat pump supplies domestic hot water, which is stored in a thermal storage system to ensure a continuous supply. Furthermore, for a healthy indoor environment, a mechanical ventilation system is implemented to ensure proper air ex-change, maintaining air quality and controlling humidity levels.

Ground-coupled heat pump and borehole heat exchanger. The source side of the heat pump is supplied by a 100-meter-deep vertical borehole heat exchanger located within the building entrance. Therefore, the building does not rely on natural gas, reducing fossil fuel dependence. Using water as heat transfer fluid offers several advantages by being natural, non-toxic, non-polluting, and with lower viscosity compared to glycol-based solutions, resulting also in reduced pumping costs. Ground source systems rely on relatively constant year-round ground temperature, leading to more stable Coefficients of Performance (COP) for both heating and cooling. With higher COP values, the energy demand for climate control is significantly reduced, allowing the use of renewable energy for other needs. The dual-use system for both heating and cooling helps minimize long-term temperature fluctuations in the ground, ensuring consistent performance over the years. The heat pump installed in the building presents a SCOP of 6 and SEER of 6.

Radiant ceiling system. The water heated and cooled by the heat pump flows through a chilled ceiling system to provide space heating and cooling. Unlike traditional radiant floor systems, pipes are embedded within several layers that together form a single panel. They are arranged in a counter-ceiling configuration and are placed throughout the building. According to the local climate and the system configuration, the operational water temperatures for the chilled ceiling are set at 30°C for winter and 18°C for summer. The radiant ceiling system ensures efficient heat transfer despite using low-temperature water (typically 35°C is the maximum temperature), possible thanks to the large heat exchange surface. Additionally, the system has low thermal inertia, meaning it can reach the desired temperature quickly, improving its responsiveness. In addition to this, the heat pump's functioning is regulated by an inverter, allowing partial load operating conditions.

Ventilation system. To ensure thermo-hygrometric comfort inside the building, it is essential to incorporate a ventilation system, as the radiant system alone cannot control the humidity levels within the house. [10] Secondly, as the building envelope becomes more insulated and air-tight, the building requires proper air exchange to maintain good air quality. This is achieved through the air handling unit (AHU) that includes a heat recovery system, filters, and a small chiller responsible for dehumidification. It provides fresh air to the living room and bedrooms, which are the most active rooms during a typical day and therefore require ventilation. Exhaust air is extracted from areas prone to unpleasant smells, such as the kitchen, bathroom, and technical room and it is first routed through the data room, where server and computer equipment generate significant internal heat. By doing so, the exhaust air helps to cool the data room before being expelled outside. The heat recovery unit of the AHU takes advantage of the warm exhaust air to preheat the fresh air supplied to the rooms. However, in free-cooling mode, which occurs when the external air temperature is between 18°C and 24°C, the heat recovery unit is by-passed entirely. This is especially useful at night during middle seasons, helping reduce cooling energy demand. In the summer, dehumidification is managed by the small chiller

within the AHU, powered by refrigerant R134a. To prevent discomfort from excessively cold air, the supply air is post-heated before being distributed within the house. The heat required for this post-heating is recovered from the compressor of the chiller, ensuring that the system's energy demand remains unchanged.

3.3 Photovoltaic system

A photovoltaic system has been chosen as the local renewable energy source for electricity generation at the UniZEB building. The system is installed on the flat roof of the building with a 6-kW capacity, achieved with 18 photovoltaic panels arranged in two strings, and tilted at a 30° angle to maximize absorption and capture. This system produces electricity without emitting pollutants, reduces reliance on fossil fuels by utilizing solar energy, and ensures no acoustic pollution. Additionally, the system provides economic savings by enabling self-consumption of electricity, reducing the energy powered from the grid. The three sections of the roof are equipped to verify the different impact of roof materials on temperature, insulation, and electricity production for different operating conditions and technologies. From west to east, the roof compares a green roof, a floating floor roof, and a gravel roof.

4 Dynamic simulation model using TRNSYS

The design phase of the UniZEB Living Lab included a dynamic simulation model carried out using TRNSYS software, as its modular structure allows the combination of various components to represent building zones, HVAC systems, renewable energy installations, and control strategies. The ability to simulate multi-zone buildings with detailed heat transfer, thermal mass effects, and energy flows makes it ideal for analysing complex structures considering varying weather and operational conditions.

Figure 4 shows the model layout in Simulation Studio. Internal loads, including sensible and latent heat from occupants, lighting, and appliances, were modelled with specific values and schedules to regulate their operation.

For the radiant ceiling system, a pre-compiled chilled ceiling layer from TRNSYS was used, requiring specific thermal parameters, such as pipe spacing, diameter, and heat exchanger coefficient. The ventilation modelling operates in regular and free-cooling modes, with temperature control based on external conditions and exhaust recovery temperatures. The extraction plenum and fan, using data from Type 56, manage flow rates and provide recovery temperatures to the calculator. The heat pump is modelled using an Excel macro that, based on the input frequency of the inverter, can calculate the actual electric power and COP/EER using bilinear interpolation from the standard [11] and the data given by the manufacturer at 100% of the load. The results of the simulations demonstrate that the building operates with remarkable energy efficiency. The building energy need is coherent with the Zero Energy Building (ZEB) standards and will be supplied by the photovoltaic system

installed for most of the year. This system is designed to meet most the building's electrical needs, including the energy required to power the heat pump. Table 2 presents the monthly specific thermal demand, while Figure 5 illustrates the building's air temperature throughout the year. Together, these data confirm that the building is not only designed for minimal energy consumption but also ensures a consistently comfortable indoor environment for its occupants. To put the results from Table 2 in perspective, considering a single-family house built in Italy around 2006-2009, the typical energy need for space heating is about 66.4 kWh/m²y, as reported in [12].

Table 2. Energy need of the building for space heating and cooling.

	Space Heating [kWh]	Space Cooling [kWh]
Day Zone	547.9	289.8
Double Room	182.2	36.9
Single Room	44.1	106.1
Bathroom	234.6	-
Hallway	172.1	-
Specific energy need [kWh/m²y]	14.8	5.4

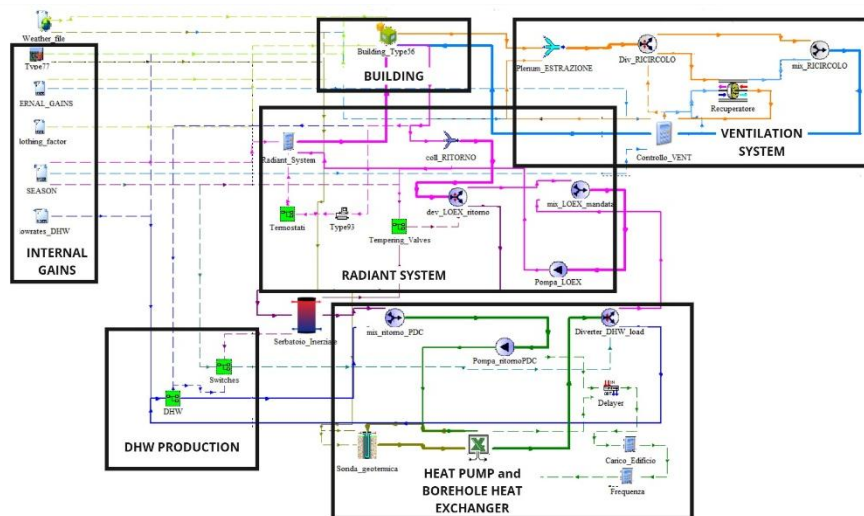


Fig. 4: TRNSYS model

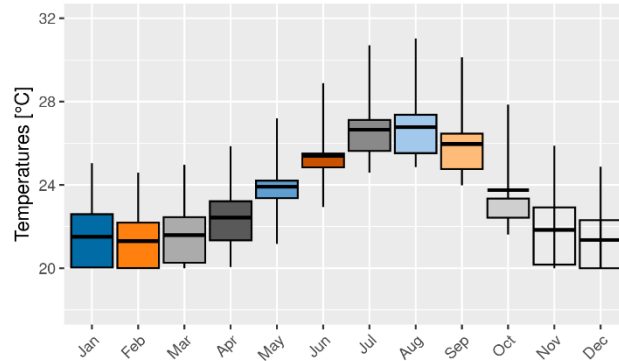


Fig. 5: Air temperatures inside the building throughout the year.

5 Conclusions

Living Labs are essential facilities to accelerate innovation in the building sector, bridging the gap between academia, industry, and society to meet sustainability goals.

UniZEB, the first Living Lab of the University of Padova, integrates experimental learning and multidisciplinary collaboration to address the challenges of sustainable construction and user-centered design. A detailed description of the building has been presented and validated through TRNSYS dynamic simulation results. These findings highlight the building's efficiency, strengthening its role as a valuable case study for energy performance analysis and sustainable design strategies. Future research will focus on validating the dynamic simulation with real monitoring data, providing insights concerning the building energy performance, occupant behavior, and environmental impacts during real-time operation, further refining the design choices. In the meantime, UniZEB will operate as a living educational environment, offering students hands-on opportunities to engage with innovative building technologies and contribute to real-world sustainability solutions.

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