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Experimental evaluation of energy-efficiency in a holistically designed building

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Abstract: Building sector continues to register a significant rise in energy demand and environmental impact, notably in developing countries. A considerable proportion of this energy is required during the operational phase of buildings for interior heating and cooling, leading to a necessity of buildings performance improvement. A holistic approach in building design and construction represents a step further to moderate construction costs in conjunction with a reduced long-term operating cost and low impact on the environment. The present paper presents the experimental evaluation of the energy efficiency of a building under real climate conditions (the building, which represents a holistically designed modular laboratory, is located in a moderate continental temperate climate, characteristic of the southeastern part of the Pannonian Depression, with some sub-Mediterranean influences). Considerations for the holistic design of the building, including multi-object optimization and integrated design with high regard towards technology and operational life are described. The paper provides a genuine overview of the energy efficiency response of the building during six months of operational use through a monitored energy management system. The results showed a reliable thermal response in the behavior of recycled-PET thermal wadding used as insulation material in the building and proper energy efficiency of the holistically designed building.

Keywords: holistic; energy management system; sustainable; building performance; thermal performance; indoor comfort

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1. Introduction

1.1 Context

The built environment with its different forms (residential buildings, workplaces, educational buildings, hospitals, libraries, community centers, and other public buildings) is the largest energy consumer and one of the largest emittent of carbon dioxide (CO_2) in the European Union (EU). Buildings caused 41,3% of the EU27 final energy consumption in the last decade (figure 1), being responsible for ca. 36% of the EU's greenhouse gas emissions [1]. Aiming to help address these issues, the EU has agreed with new rules for the energy performance of buildings directive: in 2010 it has established a legislative framework that includes the Energy Performance of Buildings Directive 2010/31/EU (EPBD) [2] and later, in 2012, the Energy Efficiency Directive 2012/27/EU [3], promoting policies that help to achieve a highly energy-efficient and zero-emission building stock in the EU by 2050, to combat energy poverty, and to encourage more automation and control systems, in order to make buildings operate more efficiently. Later, in 2018 and 2019, both directives were amended, as part of the new energy rulebook called Clean Energy for all Europeans package (2018/844/EU) [4], through which the EU improved its energy policy framework to encourage the migration from fossil fuels to cleaner energy, while also delivering on the EU's Paris Agreement [5] commitments in reducing greenhouse gas emissions and tackling global warming. At the same time, building and renovating is part of the European Green Deal [6] action plan in striving for Europe to be the first carbon-neutral continent.

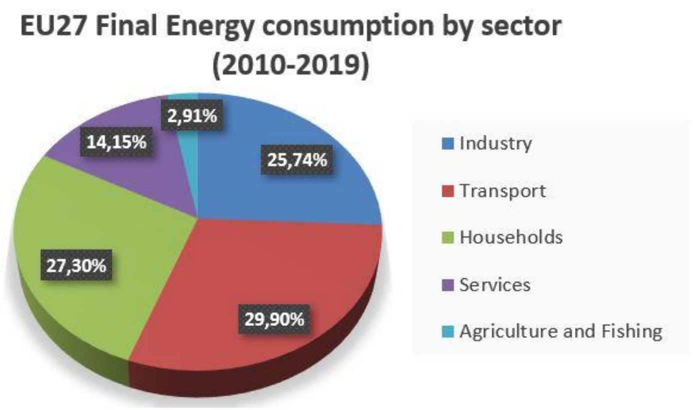


Figure 1. Final Energy consumption by sector in 27 Member States of the European Union (average from final energy consumption registered in 2010-2019) [1].

Two issues need to chime to make Europe's building sector compatible with the Paris Agreement: reducing the energy demand by employing energy efficiency measures alongside increasing the use of renewable energy sources.

Besides the building's envelope, human behavior is also a key factor in defining energy demand in a building. Both intelligent use of building automation technologies and improved awareness-raising contribute to diminished energy consumption [7].

Implementing building automation technologies, adopting renewable energy sources, and providing energy-efficient envelopes are deficient in meeting important sustainability objectives, as long as the design stages of the buildings are contrived successively and independently, leading to an unalterable variable selection starting with the first steps of the design process, which highly shortens the ability to find optimal solutions of a sustainable approach in the end [8]. In consequence, embodying a holistic approach in building design, considering cross-disciplinary analysis and multi-object optimization, is essential in the building sector [9]. By means of this, addressing concerns like embodied GHG emissions (GHG emissions from the energy that is used to extract raw materials, produce and transport materials and components during production and construction phases, as well as the energy used for the maintenance, renovation and building's deconstruction/demolish) and operational GHG emissions (GHG emissions from the energy consumed in buildings during operation phase) are equally important [10].

1.2 Aim of the Research

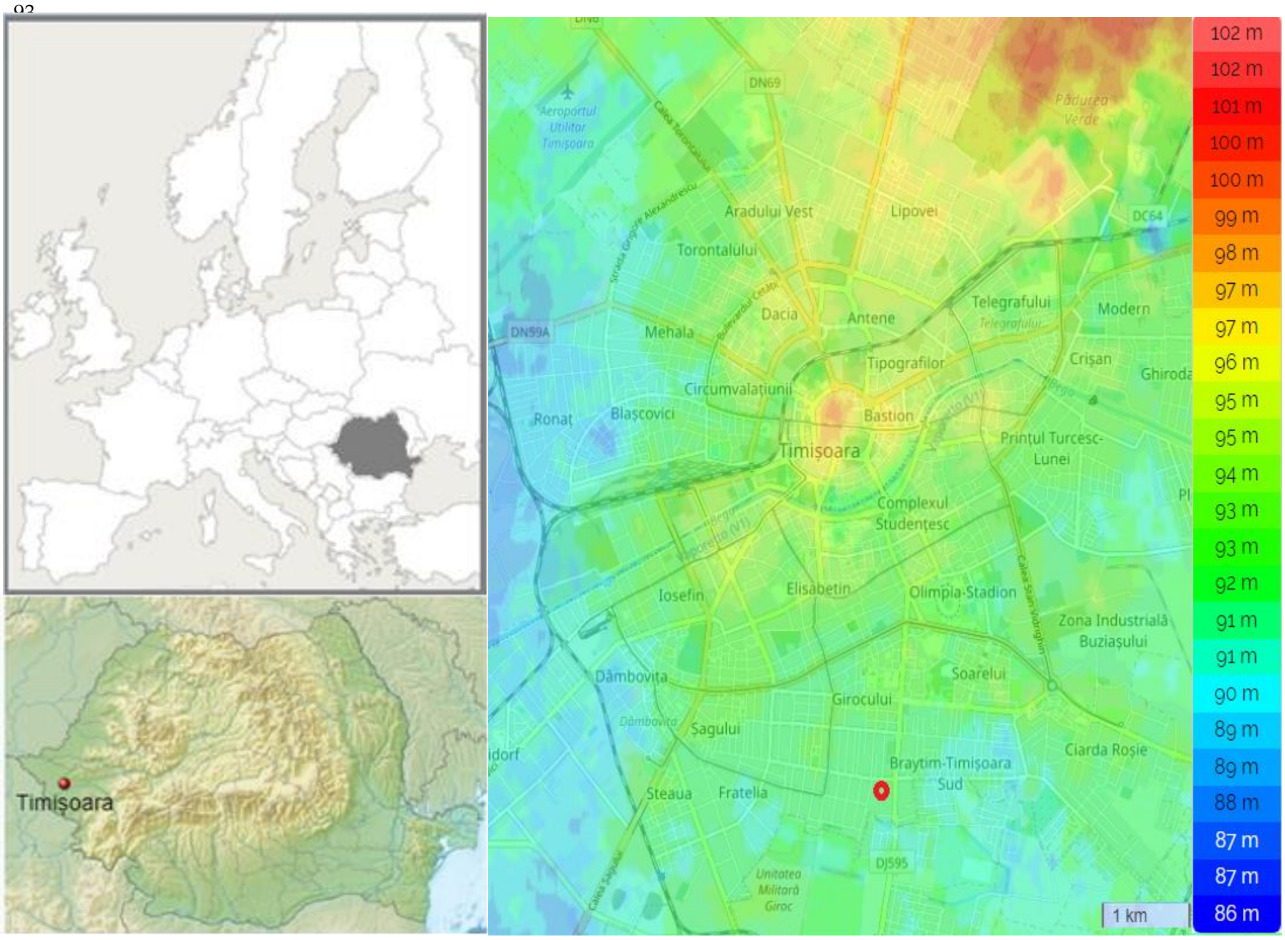
The achievement of energy-efficient buildings requires an integrated design concerning various factors such as climate, occupant behavior, technology, operation and maintenance, etc [11].

The literature review [12], [13] shows that the current body of knowledge leaned its most attention, so far, towards the economic values of sustainable construction and towards case studies (from the methodological point of view), which demands additional research in the environmental and social context of constructions, as well as in the experimental and quantitative research. The present work aims to investigate and confirm multiple sustainable factors gathered in a holistically designed building through an experimental evaluation of the energy efficiency of a modular laboratory.

2. Building and equipment

2.1. Site and Climate

The case study is located in Timişoara, the capital city of Timiş County, western Romania (Figure 2).



a) **b)**

Figure 2. Location of the case study: a) country context, b) Timisoara's urban layout on topographic map and location of the Experimental Module [14].

Located on the Bega River, the city of Timișoara is considered the informal capital of the historical Banat region, being the country's third most populous city, with almost 320,000 inhabitants and close to half a million inhabitants in its metropolitan area [15]. At a geographical level, Timișoara is located at the intersection of the 21st meridian east with the 45th parallel north, being at almost equal distances from the north pole and the equator and in the eastern hemisphere. Timișoara lies at an altitude of 86-102 meters (Figure 2b), on the southeast edge of the Banat Plain which is part of the Pannonian Plain.

According to the Köppen-Geiger climate classification [16], the Banat region exhibits a Cfb Climate, a Marine Climate with mild summers and cool but not cold winters. The average annual temperature in Timișoara is 11.1°C, having the warmest month, on average, in July, with an average temperature of 21.7°C (average high 27.8°C) and the coolest month on average, in January, with an average temperature of -1.7°C (average low -4.8°C) [17], [18]. Figure 3 shows calculated values for the dry bulb temperature ranges for each month and the full year, enclosing the Recorded High and Low Temperature (round dots), the Design High and Low Temperatures (top and bottom of green bars), Average High and Low Temperatures (top and bottom of yellow bars), and Average Temperature (open slot). It can be seen that the majority of the recorded hours are below the comfort zone, both during the warm and cold periods of the year.

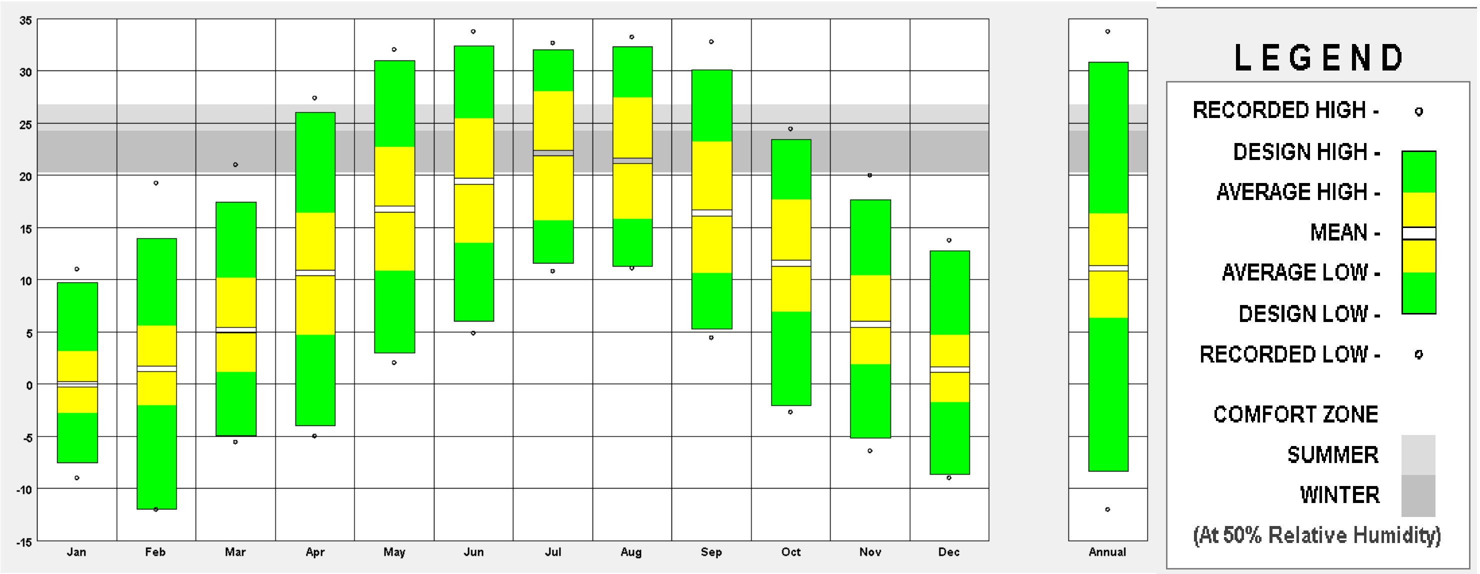


Figure 3. Temperature range for Timișoara (IWEC Data, 152470 WMO Station) [19], [18].

The annual average relative humidity is 80% in Timișoara, where June is the month with the highest rainfall (76mm average rainfall) and February is the driest month (36mm average rainfall) [17]. Figure 4 shows the monthly average relative humidity by the hour, for a non-shaded building, in the city area.

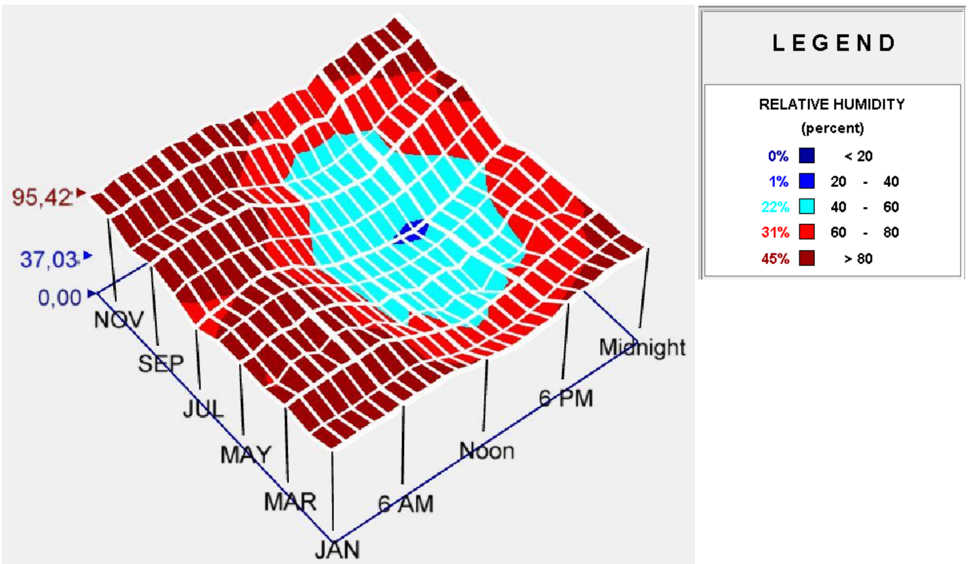


Figure 4. Monthly average annual relative humidity for Timișoara (IWEC Data, 152470 WMO Station).

Recent studies [20], [21], [22] over climate and bioclimatic conditions in Romania show changes in the bioclimatic indices over the period 1961-2016 in terms of frequency of occurrence considering the number of days for each class of bioclimatic indices and in terms of duration of their occurrence period. For the stated period, bioclimatic indices such as the Universal Thermal Climate Index (UTCI), the Effective Temperature (TE), the Equivalent Temperature (TeK), the Temperature-Humidity Index (THI), and the Cooling Power (H) reveal a shift from cold stress conditions to warm and hot conditions, as the climate in the big cities of Romania (Timișoara being among them) became hotter during the warm periods of the year and milder during the cold season. In terms of thermal sensation, it was noticed a general negative trend in the number of comfortable days [21]. Figure 5 displays a psychrometric chart for Timișoara location, based on IWEC weather data [18] and ASHRAE 55 standard [23] and shows that only 14% of the hours (1226 hours) during a year are indoor comfortable hours for a human being when no design strategies (such as cooling, heating, humidification, dehumidification, sun shading of windows, natural ventilation cooling, fan-forced ventilation cooling, etc.) are considered. Every hour of

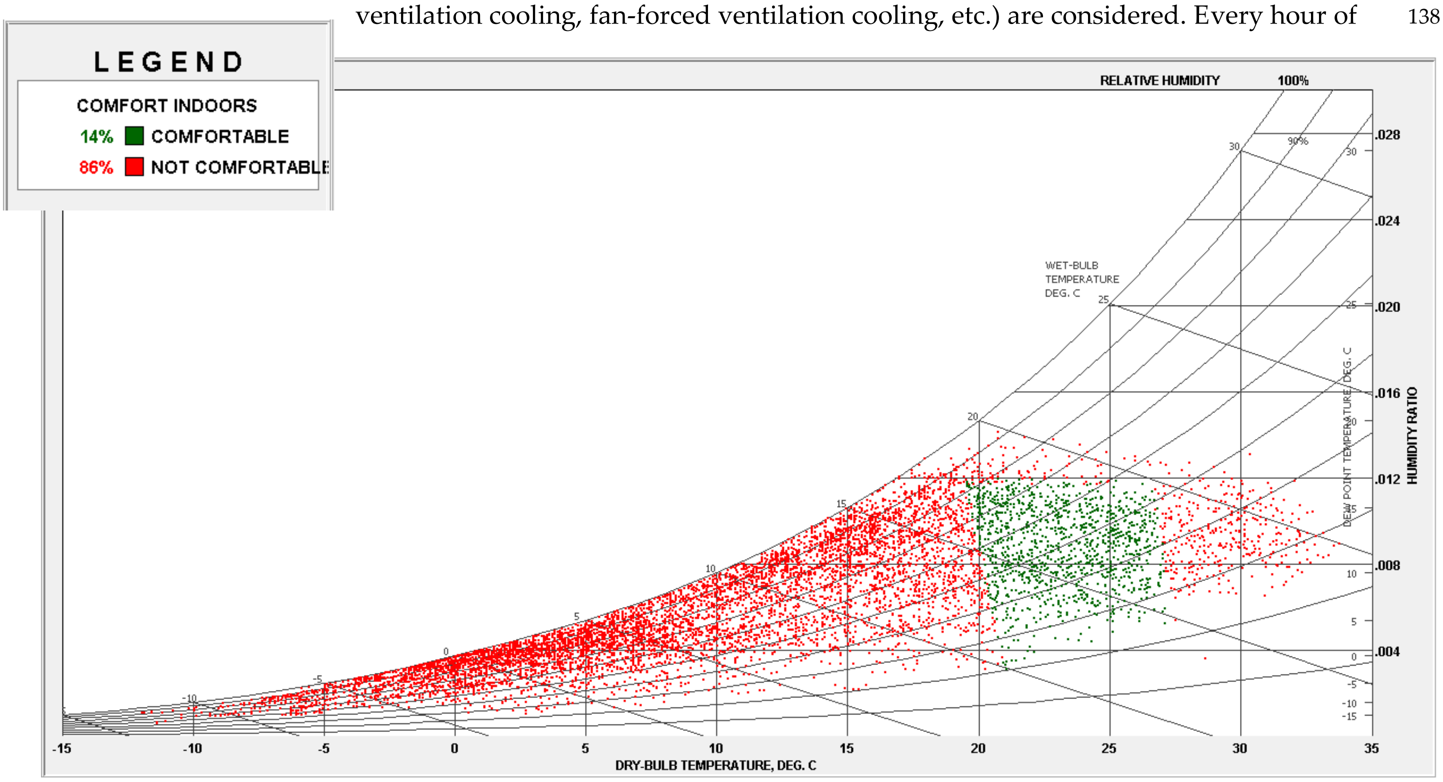


Figure 5. Psychrometric chart for Timișoara location (IWEC Data, 152470 WMO Station): comfort indoors without design strategies[19].

registered climate data is shown as a dot on this chart. The color of each dot represents whether the hour is comfortable (green dots) or uncomfortable (red dots). To reach more than 90% of indoor comfortable hours during a year, one has to consider design strategies such as heating and humidification for 7047 hours (from a total of 8760 hours annually) and cooling along with dehumidification (when needed) for 387 hours annually (figure 6) which leads to significant energy use during the year and for the building's life span. In this specific location, the same achievement of more than 90% of indoor comfortable hours during a year can be reached when integrating holistic and passive design strategies in building design, such as internal heat gain, sun shading of windows, direct gain passive solar, night flushing of high thermal mass, etc. reducing heating and humidification need to 4424 hours annually (almost 38% less heating hours annually) and cooling and dehumidification need to 31 hours annually (92% less cooling hours annually), as shown in figure 7.

Integrating passive design strategies in building design and Concurrent Engineering (CE) overall is the necessary pathway to follow, not only to meet the climate change

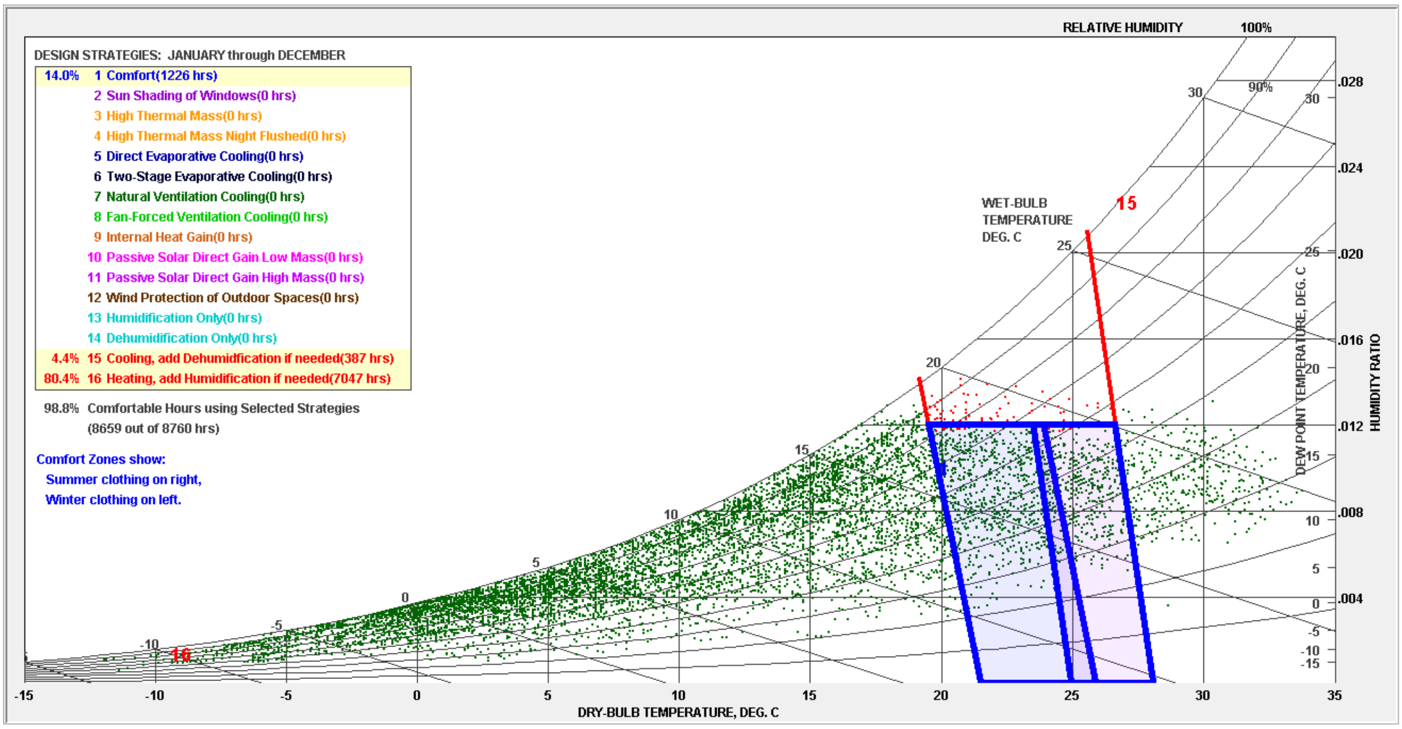


Figure 6. Psychrometric chart for Timișoara location (IWEC Data, 152470 WMO Station): comfort indoors with heating and cooling design strategies [19].

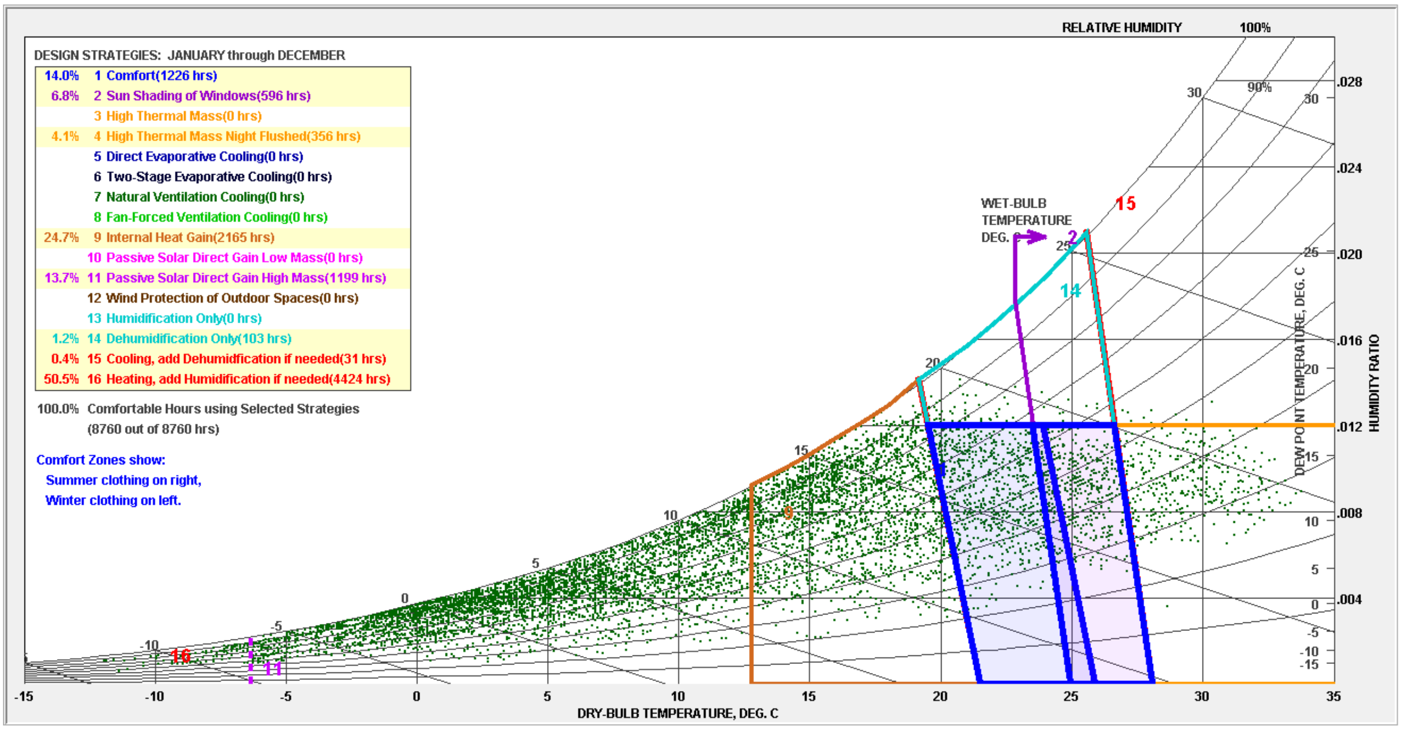


Figure 7. Psychrometric chart for Timișoara location (IWEC Data, 152470 WMO Station): comfortable indoors hours using both active and passive design strategies [19].

milestones related to keeping a global temperature rise for this century well below 2 degrees Celsius and to achieving a climate neutral world by mid-century within zero-carbon solution targets [5] in current bioclimatic conditions and the context of a future weather shift but also to provide a more resilient future for our built environment. Based on IWEC Data [18], the RCP 4.5 [24] emissions scenario (Representative Concentration Pathway of an additional 4.5 W/m2 of heating in 2100 compared to preindustrial conditions representing moderately aggressive mitigation that requires that carbon dioxide (CO2) emissions start declining by approximately 2045) and a warming percentile of 50%, the local weather previsions, over the course of the 21st century due to the impact of climate change, a continuous shift in decreasing the number of colder days in a typical year and increasing the number of hotter days (figure 8). For example, the number of days with an average temperature of 26.9°C will increase from 3, registered at the present, to 10 days by 2035, to 21 days by 2065 and will reach a number of 30 days annually by 2090, while the number of days with an average temperature of -0.2°C will decrease from 70, which are registered at the present, to 57 days by 2035, to 52 days by 2065 and 47 days annually by the year 2090.

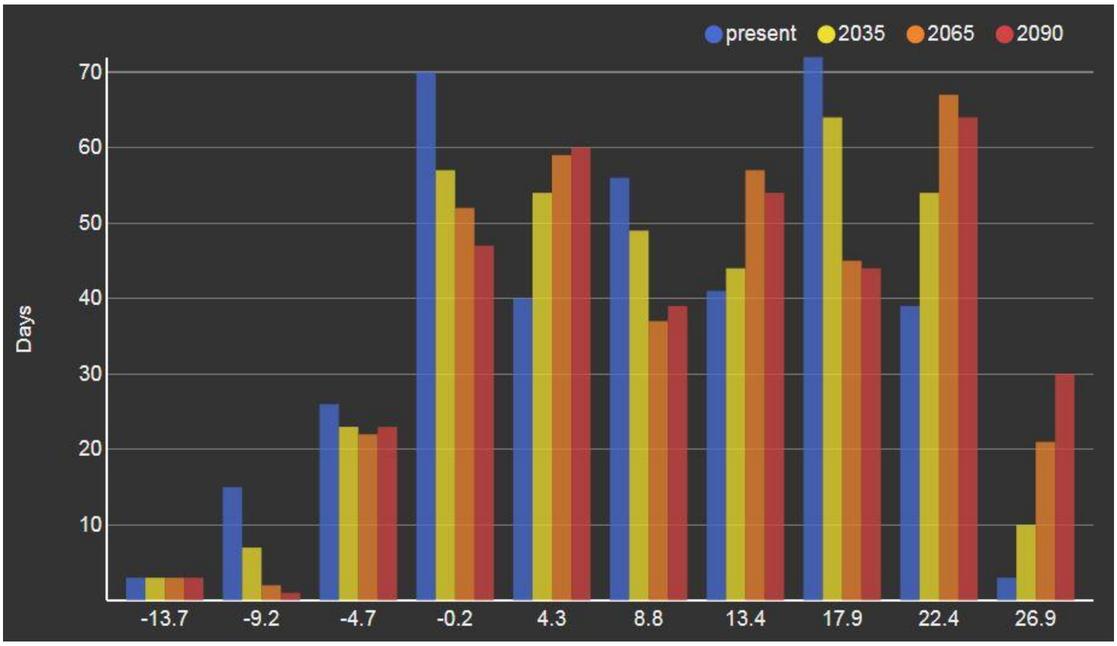


Figure 8. Projected weather data for Timișoara location based on RCP 4.5 and 50% warming percentile representing the shift of the number of days of average daily temperature [25].

As RCP 1.9 is the pathway that limits global warming to below 2°C, as the Paris Agreement specifies, a significant below greenhouse gas concentration trajectory than RCP 4.5, which is considered to be a possible scenario for 2100 (in which global temperature rise between 2°C and 3°C over the 21st century and many plants and animal species will be unable to adapt to its effects) integrating a holistic concept in sustainable building design proves its importance.

2.2. Construction of the Experimental Module

The modular laboratory, illustrated in Figure 9, on which the experimental measurements were performed was constructed based on a selection of structural systems and materials under constituent factors of sustainable building principles, such as material efficiency, resource efficiency, health and well-being or cost-efficiency.

The structure is a lightweight steel-framed (LSF) construction with cold-formed elements. The structural system was chosen on the account of sustainable characteristics of steel, essentially, small weight with high mechanical strength, tremendous potential for recycling, deconstruction and future reuse, onsite reduced severance, speed of construction, flexible structural system for modular design, an economy in transportation and handling, reduced foundation costs, [26], [27], [28]. The LSF structure is a two-stories, modular construction, having a 5 m long span, 5 m long bay, 3.80 m eave height (on the southern side), 6.10 m eave height (on the northern side), and 6.95 m ridge height.

The eastern façade has two 0.76 m x 0.96 m window openings, the southern façade integrates a 3.56 m x 2.73 m glass curtain opening, while the western façade has a 0.76 m x 0.96 m window opening and a 0.97 m x 2.73 m door opening. There are no openings on the northern side of the building. The access to the second floor is ensured by a 1 m × 1 m attic scuttle door.

Figure 9. LSF experimental module.

Using a LSF structure allowed the adoption of a precast wedge foundation system (Figure 10), designed as a "quick foundation system", easy to handle and install, fully recoverable at the End-of-Life of the building and suitable for reuse [29]. The foundations' design was part of the holistic approach design of the experimental module, adopted regarding environmentally conscious design, modular and standardized design, reusable/recyclable element design, life cycle design, waste generation assessment, environment-friendly demolition method, working conditions, safety design and consideration of costs for materials, waste disposal and life cycle[9].

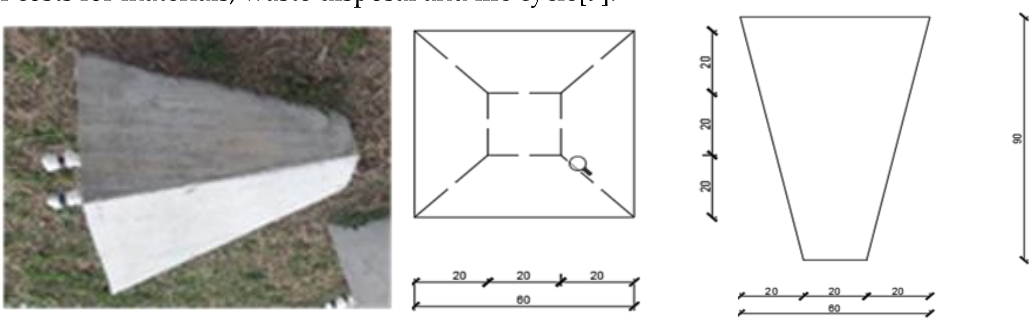


Figure 10. Precast wedge foundation – adapted from [29]: actual singular foundation before installation – left, singular foundation dimensions – middle and right.

The southern side of the roof was designed with a roof pitch of 42°, in the pursuit of gaining an optimal performance of a roof-mounted solar energy system.

The materials used in the experimental module's construction were selected in the same approach of holistic design and ease for deconstruction and future reuse of the components. Table 1 displays the thermal conductivities of the materials used in the LSF experimental module.

Table 1. Thermal conductivity (λ) of the materials used in the LSF experimental module.

Material	λ [(m·K)/W]
Steel profiles (C150/2, C200/1.5)	50.00
OSB [1]	0.130
Recycled-PET[2] thermal wadding	0.048
Wood fiberboard	0.050
Vapor barrier	0.22
Aluminum sheet	160
XPS [3]	0.035
PIR [4] sandwich panel	0.023
Glass (door and windows)	0.024

[1] OSB, oriented strand board; [2] PET, polyethylene terephthalate; [3] XPS, extruded polystyrene; [4] PIR, polyisocyanurate.

The structure is proper for various envelope configurations. The current envelope configuration (schematically illustrated in Figure 11) was carefully selected with consideration for the locally sourcing of building materials to keep transport emissions and associated costs to a minimum.

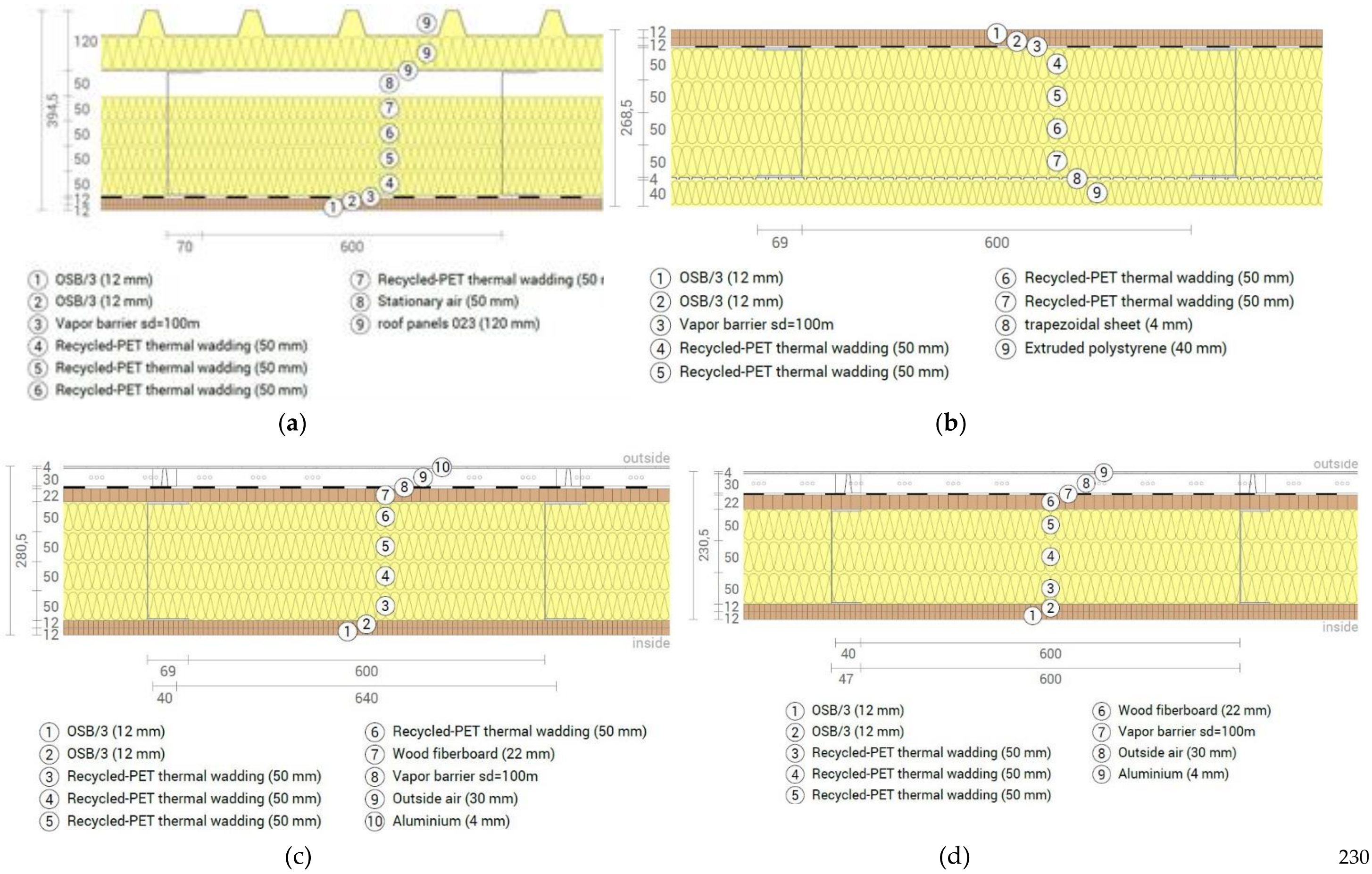


Figure 11. LSF construction elements stratification: (**a**) Roof; (**b**) Floor; (**c**) Northern wall; (**d**) Eastern and Western wall.

As an inner sheathing layer of walls, ceiling, and floor, the LSF experimental module was designed to have oriented strand board (OSB) panels (24 mm thick). In between the steel frame, recycled-PET thermal wadding (150 mm or 200 mm thick, by the case) was used as batt insulation. For walls, the thermal insulation system was completed in the exterior with an overlaid layer of wood fiberboards (22 mm thick) and finished by a layer of rectangular aluminum panels (4 mm thick). In order to avoid moisture from the ground, the floor was 400 mm elevated. In between the steel frame of the floor, it was used also recycled-PET thermal wadding (200 mm thick) as batt insulation. Below the thermal insulation wadding, it was installed a layer consisting of trapezoidal steel sheets (4 mm thick), and beneath, an exterior continuous layer (40 mm) of extruded polystyrene (XPS). Both floor and roof were waterproofed by poly-vinyl chloride (PVC) membranes. On the roof, the thermal insulation system was completed in the exterior with PIR-sandwich panels (120 mm thick).

The LSF envelope elements (materials, thicknesses, number of layers) are displayed in table 2.

Table 2. Materials, thicknesses (d) and thermal transmittances (U) of the experimental module elements.

Element	Material (Layers from inside to outside)	d [mm]	U-value [W/(m²·K)]
Floor	OSB	24	0.272
	Vapor barrier	0.5	
	Recycled-PET thermal wadding	200	
	Steel sheet	4	
	XPS	40	
	Total thickness	268.5	
Walls (North)	OSB	24	0.314
	Recycled-PET thermal wadding	200	
	Wood fiberboard	22	
	Vapor barrier	0.5	
	Rear ventilated level (outside air)	30	
	Aluminum cladding	4	
	Total thickness	280.5	
Walls (East and West)	OSB	24	0.355
	Recycled-PET thermal wadding	150	
	Wood fiberboard	22	
	Vapor barrier	0.5	
	Rear ventilated level (outside air)	30	
	Aluminum cladding	4	
	Total thickness	230.5	
Roof	OSB	24	0.192
	Vapor barrier	0.5	
	Recycled-PET thermal wadding	200	
	Stationary air	50	
	PIR sandwich panel	120	
	Total thickness	394.5	
Door and windows	Glass with argon filling	24	0.880
	PVC casement	92	
Glass Curtain	Glass with argon filling	44	0.740
	PVC casement	92	

2.2.1. Thermal insulation made from recycled post-consumer PET bottles

The thermal insulation layers of the envelope elements (figure 12), consisting of a thermal insulation wadding, are made of polyester fiber, recycled from post-consumer PET (polyethylene terephthalate) bottles. The insulation material is produced entirely from recycled PET bottles, which withholds CO2 emissions and ensures environmental benefits. Besides the significantly low environmental impacts shown by the product [30], the recycled-PET thermal wadding provides high mechanical and physical properties [31], which remain unaffected by the time-passing and ensures acoustic insulation properties as well.

(**a**) (**b**)

Figure 12. Recycled-PET thermal wadding: (a) Installation phase at the construction site; (b) Layers of insulation before installation.

Since there are no chemical or textile agents used in the production process, the product contains no harmful substances for human health [32]. Another property of the recycled-PET thermal wadding is the material circularity: at the End-of-life of the building where it was installed, the product can be recycled in a proportion of 100% and used as a raw material for new thermal insulation wadding. The Eco-efficiency of this specific thermal insulation came also from the proximity of the production place to the construction site of the laboratory: a transportation distance of only 15 km contributed to the created value of the product system, along with other factors aforementioned, like reusing post-consumer PET bottles as a raw material in the production stage, the absence of chemicals in the production process, the lack of wastes resulted from production or installation of the product.

2.3. Experimental Installation and Data Acquisition

The primary function of a building is to provide a suitable, comfortable, inner environment, according to the building's functions. A holistic design of an energy-efficient building regards, besides the installation of renewable energy sources and energy conservation, also an integrated design with regard towards technology, operation, and maintenance. In a building's lifetime, the greatest amount of energy is required during the operational phase, therefore the building's envelope has a pivotal impact on the building's behavior.

2.3.1. Passive design strategies

The holistic design of the building regarded a series of passive strategies for the design of the LSF experimental module. Natural illumination is granted by a 3.56 m x 2.73 m glass curtain, installed on the south façade of the building, which provides also passive solar heating during daylighting. When additional, artificial light is necessary, LED light sources ensure the need. The sun shading of the glass curtain, provided by external photovoltaic shading lamellae, ensures passive cooling of the first floor (not yet installed at the moment of these six months of monitoring).

The renewable sources of energy are based on harvesting solar and wind energy: twelve 250 W polycrystalline cell panels intake solar energy, with an estimated amount of solar energy produced on-site of 1269 kWh/year (the potential production of the installed polycrystalline cell panels under ideal conditions is 3427,29 kWh/year [30]), and a 1 kW vertical wind turbine (not yet installed at the moment of monitoring period).

2.3.2 Monitored energy management system

The design of the LSF experimental module included, in pursuance of having an authentic, factual overview of the building's performance during the operational phase, a monitored energy management system. The LSF experimental module is a non-grid connected building, matching its own energy needs by on-site generation, fully based on renewables. The monitored energy management system consists of an electric power distribution representing a direct current (DC) grid, similar to a "smart nano-grid" (SN). The electric power distribution integrates wind and solar sources of energy, elements for conversion and storage of the electrical energy, and a distributed control and an energy management system through a SCADA system. Common electrical appliances (fridge, TV, PC) are used and adapted for DC supply, in order to reproduce a residential application.

The architecture of the SN, presented in Figure 13, consists of a high voltage DC bus (HVDC), with a value of 350 V, and a low voltage DC bus (LVDC), with a level of 24 V. For alternating current (AC) loads and as a backup solution, the SN owns an AC bus with a voltage of 230VRMS.

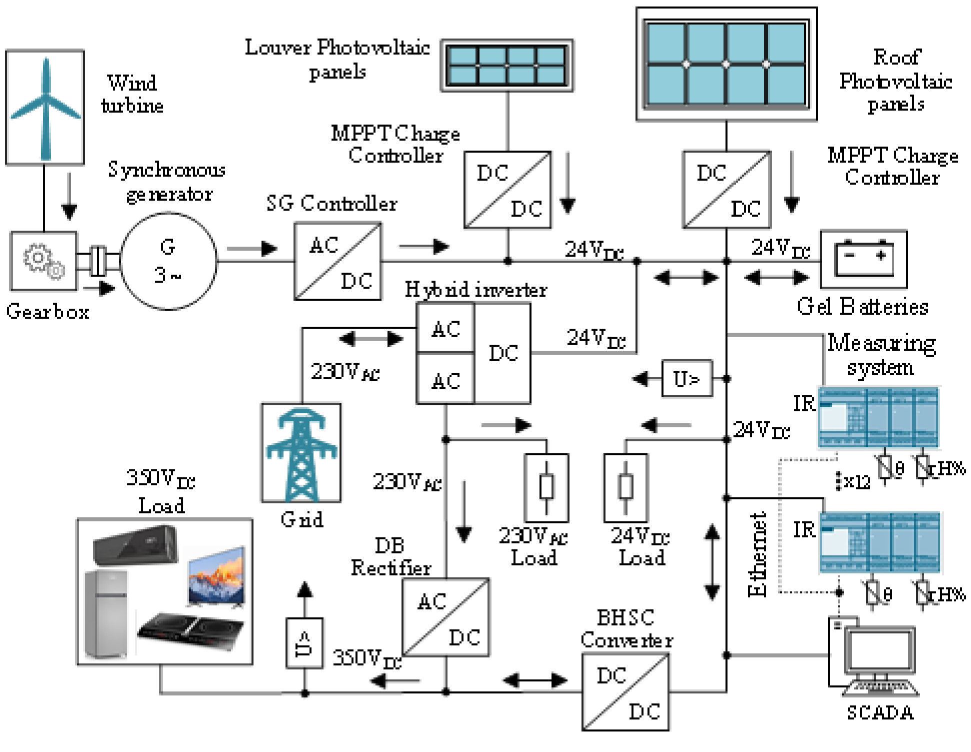


Figure 13. The architecture of the implemented smart nano-grid (adapted from [9]).

A synchronous generator (SG) coupled through a gearbox ensures the harvest of the wind energy from the vertical wind turbine. The electrical power provided by the SG is injected into the LVDC bus using the SG Controller. A maximum power point tracking (MPPT) charge controller through which the LVDC is connected to the photovoltaic panels helps converting solar energy into electrical energy. Also, a smaller MPPT charge controller is used for the louver photovoltaic panels. The energy is stored in four 12 V/220 Ah Valve Regulated Lead-Acid Gel Batteries, which can store 10 kWh of electrical energy, enough for 2-3 days of a usual household operation without recharging. The connection between the HVDC bus and LVDC bus is done through a bidirectional hybrid switched capacitors converter (BHSC) [33].

High efficiency and low cost of high ratio voltage conversion are viable due to the BHSC converter's capabilities. The entire flow of electrical energy is controlled by a SCADA system which ensures the data acquisition of all parameters.

2.3.3. Data acquisition infrastructure

The LSF experimental module's data acquisition infrastructure consists of three CO_2 sensors, 14 humidity sensors and 53 temperature sensors distributed as presented in figure 14. A measuring station, composed from 12 so-called "intelligent relays" (IR) is

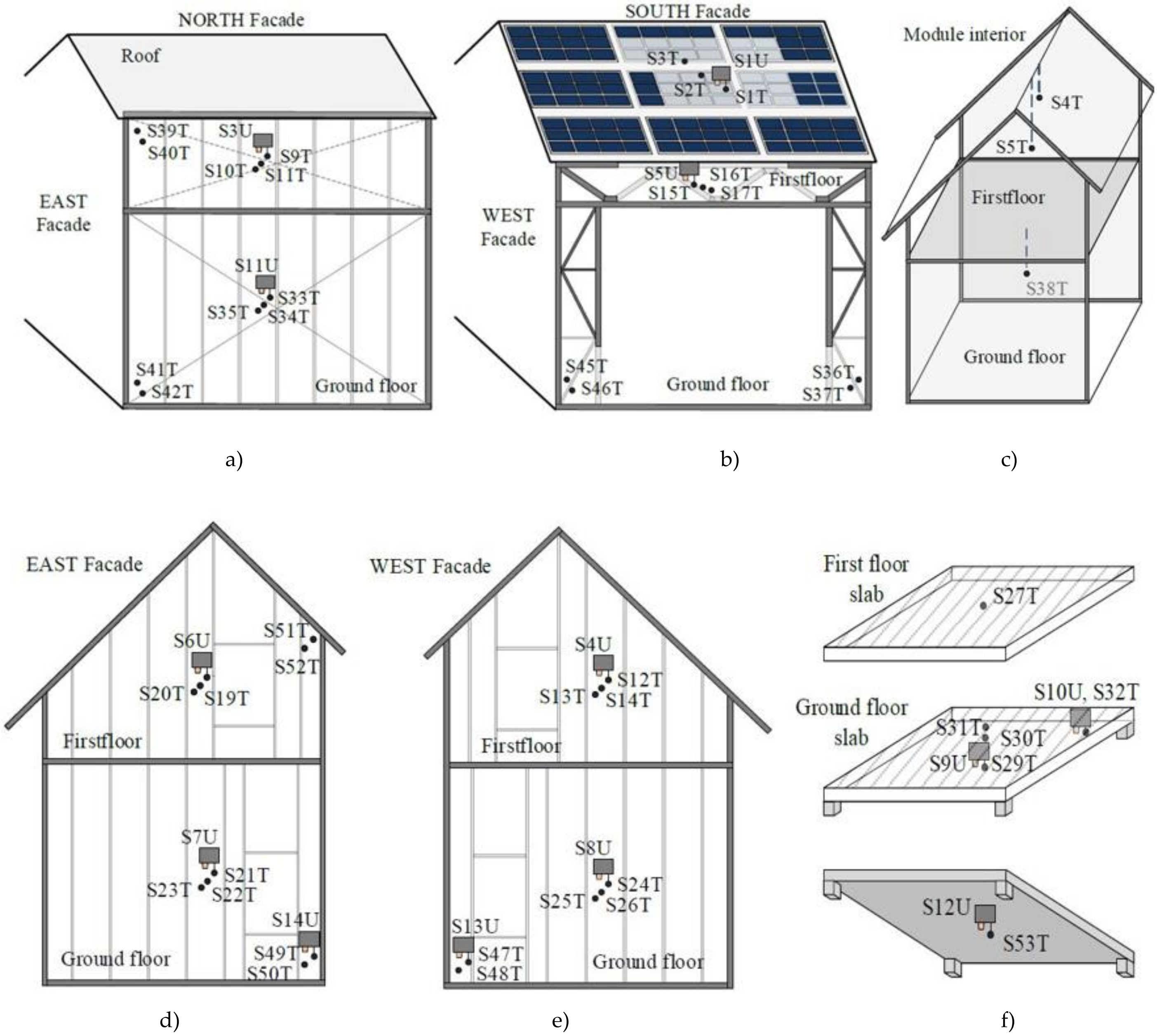
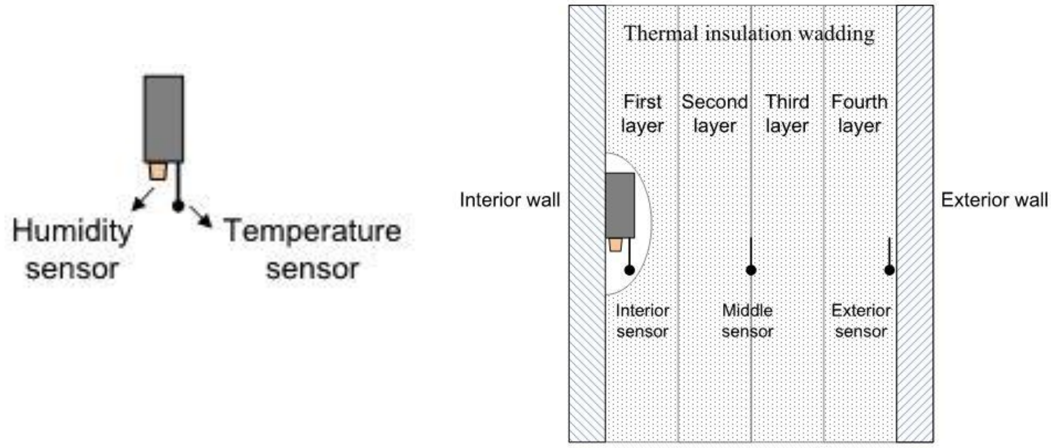


Figure 14. Sensors' distribution on LSF experimental module: a) North Façade b) Southern Façade and Roof c) Interior d) East Façade e) West Façade f) in slabs (adapted from [9]).

used for acquiring the data from the sensors [34], providing digital inputs and outputs, which can be used in small automation such as residential automation [9]. The sensors (figure 15a) distributed on the walls are located on the outer face of the interior walls, between the insulation layers and on the inner face of the exterior walls, as illustrated in figure 15b.



a) b)

Figure 15. a) Humidity and temperature sensor configuration b) Sensors' distribution between thermal insulation layers.

The SCADA interface was designed with the LabView 2021 software development platform provided by National Instrument and it is supported by a dedicated station server. Also, for redundancy, a second SCADA system was designed with Logo Web Editor V1.0 software development platform [34] which is supported by the IR. Unlike other SCADA systems which run over a dedicated station (server or desktop), this second SCADA system is accessible using a web page. The acquired data is stored on the server station and for backup is also stored on the IR which is equipped with a micro-sd card.

3. Results and Discussion

3.1. Thermal monitoring

Figures 16-21, illustrated below, show the information provided by the monitoring management system registered during a supervision interval of six months (December 01, 2020 – May 15, 2021). The recordings transferred from the sensors reveal the behavior of the experimental module's envelope and indoor comfort conditions. In the temperature graphics, data provided from the sensors located on the outer face of the interior walls are shown in yellow, data provided from the sensors located between the insulation layers are shown in blue while data provided from the sensors located on the inner face of the exterior walls are shown in purple. It should be noted that at the time of monitoring the external photo-voltaic shading lamellae were not installed yet, nor any other HVAC sys-

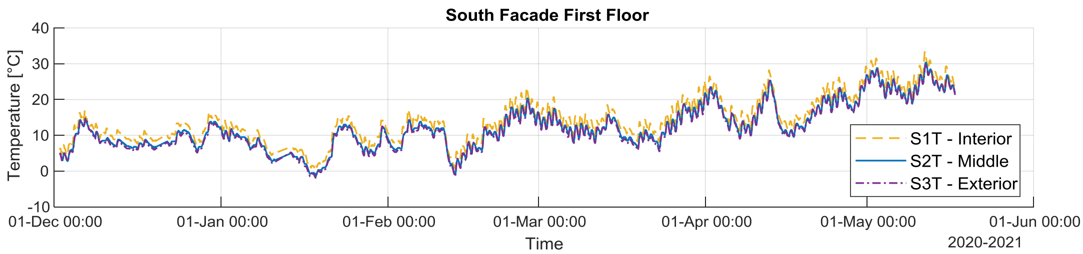


Figure 16. a) Temperature data provided by the sensors for Southern Façade First Floor.

tem, therefore no mechanically cooling, heating or any dehumidification system contributed to the indoor comfort. The interior temperature was influenced only by solar gain, electrical appliances, and human interaction during maintenance and observation interference. 361 362 363 364

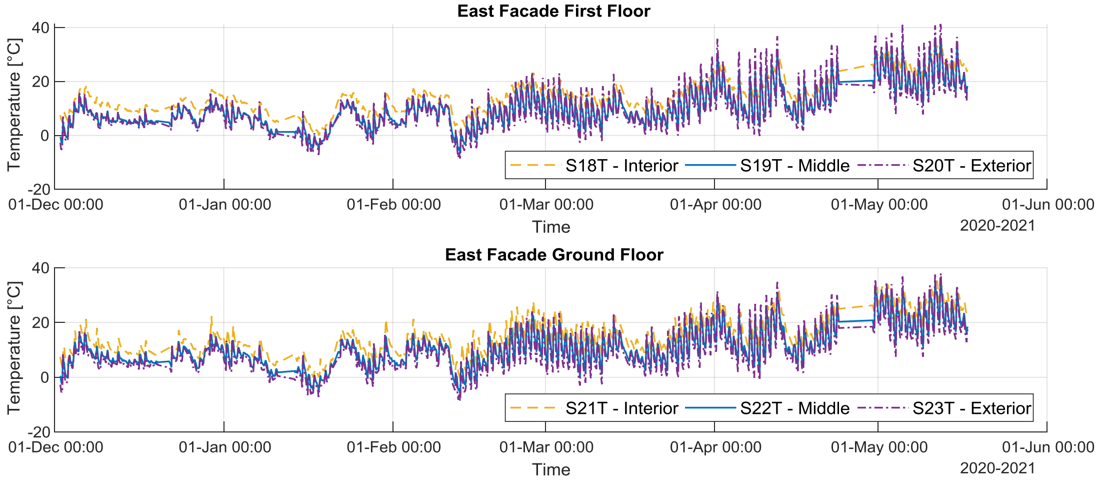


Figure 17. Temperature data provided by the sensors for the Eastern Façade First Floor (above) and Ground Floor (below). 365 366

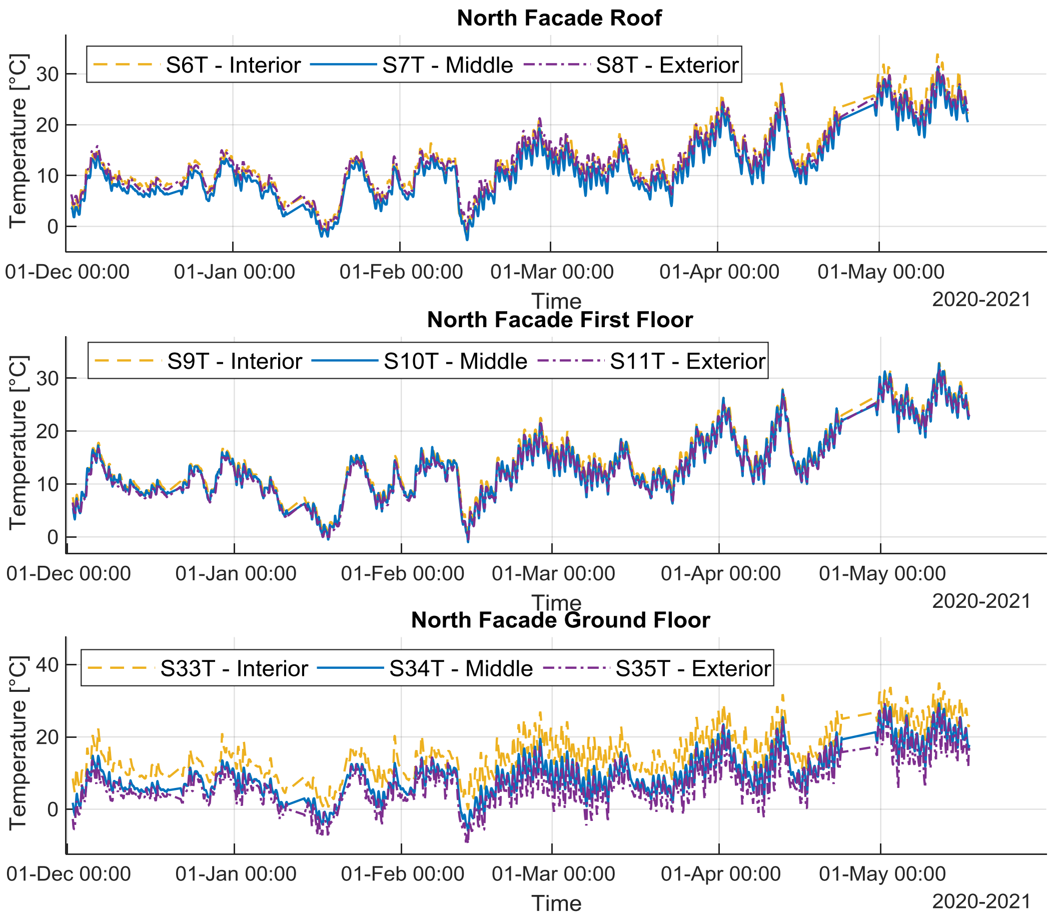


Figure 18. Temperature data provided by the sensors for the Northern side of the building: Roof (above), First Floor Façade (middle), and Ground Floor Façade (below). 367 368

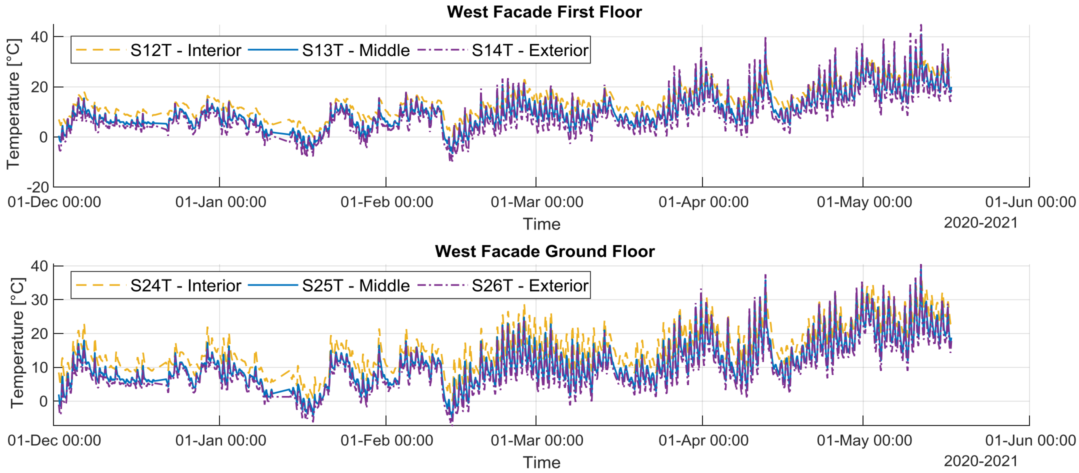


Figure 19. Temperature data provided by the sensors for the Western Façade First Floor (above) and Ground Floor (below).

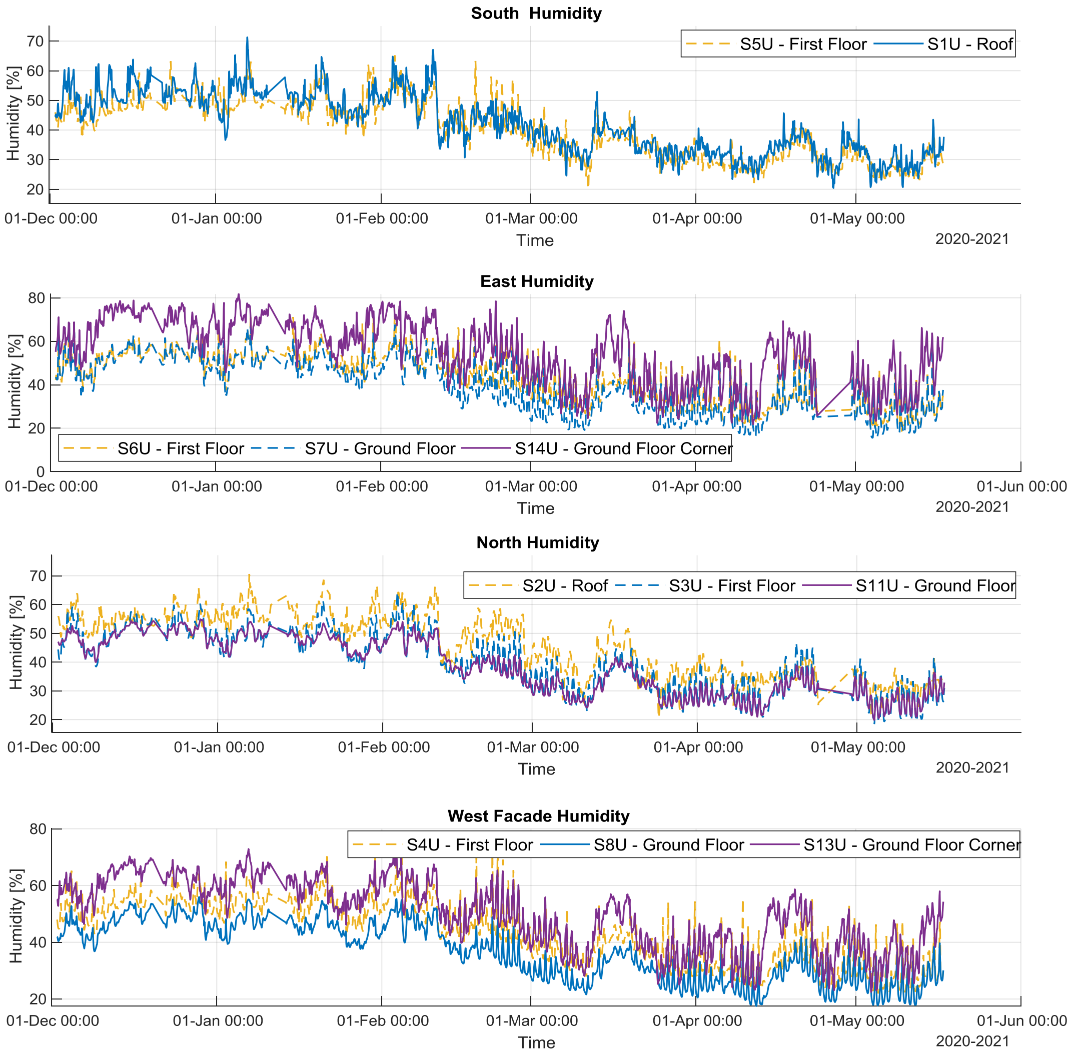


Figure 20. Humidity data provided by the sensors from various locations of each Façade.

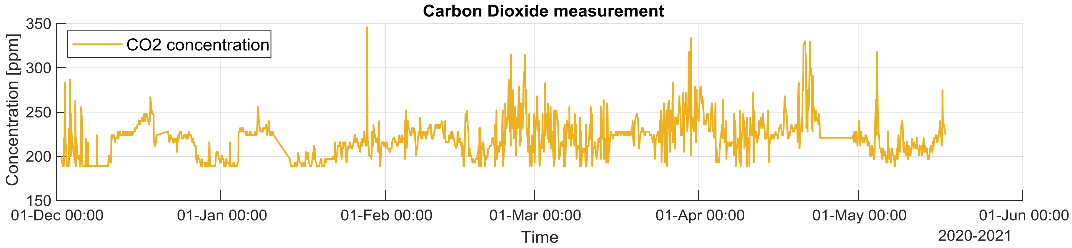


Figure 21. Carbon Dioxide (CO_2) concentration within the experimental module.

The LSF module is also equipped with a CO_2 sensor, whose provided data are reflected in Figure 21. Higher values of CO_2, between 300 and 350 parts per million (ppm) are recorded during human interference in the building, stated for maintenance or observation. However, even the top values of CO_2 concentration remain in the normal CO_2 concentration of air quality.

As the LSF experimental module is completely off-grid and during the monitorisation period the wind turbine was not yet installed, there were two intervals (January 10, 2021 – 08:02 AM to January 14, 2021 – 01:42 PM and April 23, 2021 – 07:18 AM to April 30, 2021 – 02:11 PM) in which the energy production of the roof PV was insufficient (due to heavy cloud cover) and the sensors could not provide data (as the graphics show).

3.2. Analysis of the energy production

The next section presents an energy analysis report of the LSF module. The energy shown in the following diagrams is provided only by the roof PV. The wind turbine and louver PV have not been integrated into the physical system during the monitoring period. For comparison, a winter month - December (Figure 22) and a final spring month - May (Figure 23) have been chosen. The blue line represents the state of charge of the storage system, the orange bars represent the energy production of the roof PV, while the red bars represent the energy consumptions by the LSF module. Against expectations, the higher energy production is in December, given by the necessary energy to charge the

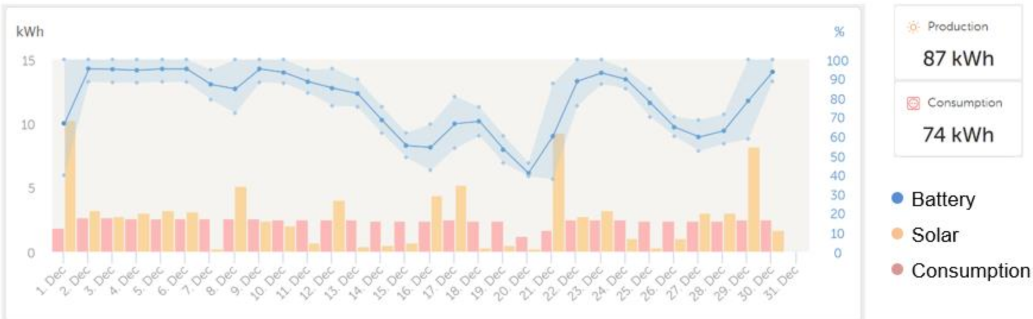


Figure 22. Energy analysis report of the LSF module during December 2020.

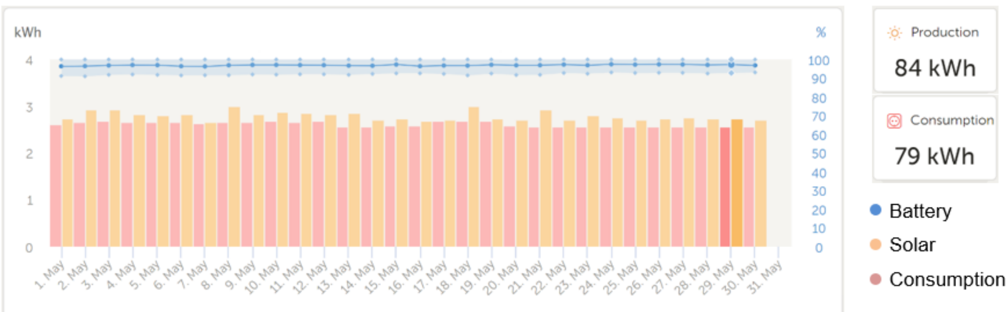


Figure 23. Energy analysis report of the LSF module during May 2021.

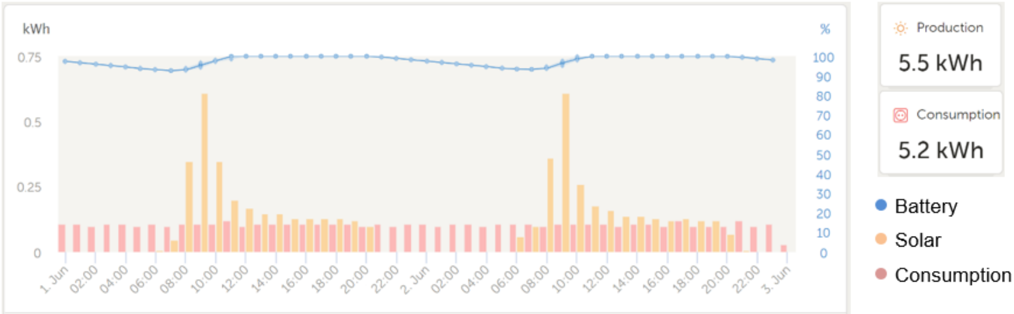


Figure 24. Energy analysis report of the LSF module – two days overview.

batteries. It can be observed that there are periods of up to 10 kWh energy production/day, which compensate for cloudy and snowy days when the energy is assured from the batteries. In normal operation, the LSF module energy consumption is constant and is approximately 2.6 kWh/day (Figure 24), however, to not discharge the batteries more than 40% to extend the batteries life, the consumption has been reduced and only the essential equipment is powered. Figure 24 presents the hourly energy analysis during two summer days. Over the nights, the batteries are discharged up to 92-93%, which covers eight-nine hours without solar radiation. The essential equipment consists of the SCADA system and the measuring system. In the end, if we want to assume the total energy that can be generated by the three renewable energy sources (roof photovoltaic panels, louver photovoltaic panels, and wind turbine), we can say that the energy provided is around 5 kWh during peak production.

3.3. Conditions and limitations of the study

The outcomes of this study are based on the analysis of only six months of thermal behavior and it was not possible to statistically analyze and compare the behavior of this building during large periods of time. The results presented are particular to Banat zone due to the particular type of climate. However, the benefits of holistically designed buildings and of the recycled-PET thermal wadding insulation can be extrapolated to other areas.

Another limitation of this study is the fact that the building is an experimental laboratory that was not constantly inhabited during the monitorisation period. Since this building is mainly used for short periods of time (maintenance or observation), potential actions of building occupants who could alter in any way the indoor environmental quality were not addressed.

Furthermore, at the time of monitorisation, the external photovoltaic shading lamellae were not installed, a fact which led to the lack of sun shading of the glass curtain and a lower rate of indoor comfortable hours in the days with clear sky and outside temperatures above 20°C. Another equipment that was not yet installed at the time of the monitorisation period was the wind turbine, which could have been helpful with the energy production during the two periods of heavy cloud cover of the sky when the energy production of the roof PV was insufficient.

5. Conclusions

Given the EU commitment in the Paris Agreement to limit the increase in global average temperature to less than 1.5 °C above pre-industrial levels and the significant contribution of GHG emissions of the building sector, it is imperative to minimize both the embodied GHG emissions and the operating GHG emissions from the construction and renovation of buildings. The weight of embodied GHG emissions varies with the design, the origin of energy and mix of materials used, and with the construction of the buildings, while the operating GHG emissions are determined by the building performance and the amount of renewable energy in building energy consumption in correlation with fossil-based energy sources.

To achieve buildings with reduced impact on the environment (wheater from construction or operational phase) and moderate construction costs, one needs the embody a holistic approach, integrating cross-disciplinary analysis and multi-object optimization. The holistic design approach of the LSF experimental module presented in the paper involved the adoption of various criteria regarding sustainable building, such as resource efficiency, material efficiency, ecology preservation, environmentally conscious design, life cycle design, reusable/recyclable materials, modular and standardized design, environment-friendly demolition method, waste recycling and reuse, safety design, consideration of life cycle cost, materials cost and, health and well-being. Besides assigning renewable energy sources, conservation sources of energy, and inclusion of passive design strategies, to meet energy efficiency targets, the holistic design of the modular laboratory has required an integrated design with consideration for technology and operation. The monitored energy system included in the design of the LSF experimental module brings an important contribution in having a genuine overview of the building's performance during the operational phase. Despite the fact that the building hadn't any mechanically cooling, heating or dehumidification system to augment the indoor comfort conditions the recordings showed for the monitored period that during mid-season, the rooms had adequate comfort conditions. Not controlling the solar radiation (as the shading PV lamellae were not installed yet at that moment) increased the risk of overheating hours, as the results showed for the last two weeks of monitorisation. The future use of an external solar shading device will be more efficient in reaching thermal comfort conditions within comfort limits, reducing the risk of excessive solar gains and overheating.

Furthermore, additional studies are demanded to complement and validate the effectiveness of the research presented and to disseminate the assets on a holistic design approach and improving the energy efficiency in buildings.

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