Nearly zero energy building renovation: From energy efficiency to environmental efficiency, a pilot case study

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Greenhouse gas emissions have been recognized as one of the major cause of the global warming phe- nomena. The built environment accounts for more than 40% of the overall energy consumption and 36% of the overall CO2 emissions in Europe. Recent studies show that housing is one of the most responsi- ble sector for world ecological impacts. The European Parliament developed the concept of Nearly Zero Energy Buildings (NZEB), characterized by a very low energy demand and a high renewable energy on- site production. In fact, energy efficiency is the first step towards the ambitious aim to reduce of 80% by 2050 the EU carbon emissions. The zero-energy building target is an achievable goal, which relies on a careful design that encompasses a synergy between passive and low-energy strategies. However, consid- ering the whole life cycle of buildings, NZEBs reduce the operational energy close to zero, increasing the relevancy of the embodied energy, which occurs during the construction phase. Balancing the values of the operational and embodied energy is necessary to minimize buildings footprint on the environment. In this paper the renovation and re-use of the Atika building, a demonstrative energy-efficient building, is presented as case study of an environmental efficient methodology for energy retrofitting. The case relies on the methodology developed by Active House, a holistic vision for sustainable buildings labeling.

Keywords:
Zero energy building renovation
Technological design
Building energy simulation
Active house label

1. Introduction

In the last decades, the construction sector witnessed an increasing awareness concering the needs of energy efficiency and CO_2 reductions as reaction to the global warming. It is universally recognized that the CO_2 growth in the atmosphere is the main cause of climate changes. It has been estimated that the diurnal temperatures are rising of about 0.1 °C every decade and the average global temperature in 2100 will grow up to 5 °C [1]. The buildings are the major contributors to this tendency, accounting for more than 36% of EU's greenhouse gas emissions. However, one quarter of 2050 building stock still must be built [2], thus the construction sector has a big potential in reducing carbon emissions and energy consumption [3,4]. Studies show that it is possible to reduce the greenhouse gas emissions of about 40% by means the technologies already available in the market [5]. Therefore, buildings are considered one of the strategic sector to achieve 2020 EU efficiency target [6–9]. The European Parliament issued the Directive 2002/91/EC on the energy performance of buildings (EPBD), with the successive Recast released in 2010 [10], aiming to reduce buildings' GHG emissions of 80% by 2050, through a gradual definition of minimum energy performance requirements that will lead to Nearly Zero Energy Building (NZEB) target. NZEBs are defined as buildings with outstanding performances and a very low energy needs, which should be covered by renewable sources [11]. Different research programs have been focused on the definition of a clear pathway through the achievement of the ambitious NZEB goal [12–14], which is defined by three consecutive steps: the reduction of energy demand [15], the use of low energy heating and cooling systems [16–18], and the optimal energy export into the external grid [19–21].

Although energy efficiency is an essential step towards sustainability, it should not be the only key indicator for evaluating the buildings performance. An interesting study on sustainability's concept highlighted the limiting nature of current standards [22], which focusing on numbers, labels and parameters easily measureable. However, beyond the quantitative factors such as physical and technical elements, there are qualitative parameters that define buildings sustainability: as social, cultural and environmental [23]. These parameters are often missing in the actual standards and building codes, due to the difficulty to measure it and compare. In this scenario, the Active House Standard (AHS) was conceived to integrate all these aspects into a unique holistic and

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multidimensional approach to building design [24]. It is a design guide, which inform the architects during the design stages giving an overall measurable impact of different strategies, considering together energy, environmental and thermal comfort aspects [25]. The results are displayed on a radar, a useful graphic tool that help to visualize the whole performance giving to the designers the possibility to monitor the behavior regarding the different evaluated category. The radar is a perfect decision-making tool, as it is able to display quickly the effects of a specific design choice on the whole building performance. Usually, in the current practice the quality of the specific project, is evaluated through one or two parameters at time, focusing on a bi-dimensional evaluation of building performances. For example, operational and embodied impacts [26–28], operational energy and thermal comfort provided [29–31] or cost beneficial analysis [32].

In fact, the benefits of some design strategies are difficult to evaluate, due to the different effects induced on different performance categories: e.g. implementing thermal mass of the envelope might reduce the cooling loads during the building operation [33,34] but increases considerably the embodied energy associated to the construction phase [35,36]. Balancing design strategy's effects on both embodied and operational phase is necessary to minimize the overall buildings' impacts on the environment.

Energy efficiency cannot be the only parameter used to define the robustness of a certain design solution, even though it is a first important step to accomplish sustainability. The future buildings will be very energy efficient, with a consequent low operational energy demand. Reducing heating and cooling needs to almost zero increases the influence of the energy spent during the construction, which becomes the critical phase in terms of energy used on the whole building's life cycle [37–39]. For this reason, sustainability concepts are including impacts from cradle to grave, integrating an LCA-driven approach [40,41].

In this way, it would be more appropriate to refer to environmental efficiency instead of energy efficiency only, which usually indicates the only energy used during the operational phase. In the same way, life cycle energy can't be evaluated alone without considering the strong effects that the design choices have on the indoor comfort provided: a multi-dimensional approach becomes essential [42–45]. Active House embraces the complexity and multidisciplinary effects of design, offering a multidimensional decision-making tool able to inform designers on the effects of design options on the whole building performance.

This paper aims, through a case study of a low energy building, to demonstrate how the use of Active House Standard methodology can be used as a promising guide for a comprehensive evaluation of the building's quality. The radar graph represents an encouraging decision-making tool for evaluating the potential of different design strategies and it can be easily adopted from the early design stage to increase the awareness of the designer during the building design process.

2. The building renovation approach

This paper shows the VELUXlab building as an environmental efficient renovation case study towards zero energy target. The renovation process was focused, on one side, to maximize the energy efficiency, reducing heating and cooling needs, and on the other side, to tackle the building's life cycle performance, including environmental impacts of materials and components used in the construction. To maximize the environmental efficiency, it is important to weight the design alternatives on both operational and embodied phase, considering the whole building's life cycle. For example, the proportion between the energy saved due to the highly envelope's resistivity and the energy spent in the insulation's manufactory is not linear and, at a certain point, the second one can prevail [47]. The approach applied during the case study design refers to the broader LCA concept, which usually considers as indicators the global worming potential (GWP), the cumulative primary energy demand factor (CED) and non-renewable primary energy factor (CEDnr) [46]. Usually LCA approach evaluates the whole building impacts, without any distinction on the final value between the two components. There is no a common agreement or a standard methodology to balance the operational and the embodied impacts in buildings design in a clear comparative way, although researchers are focusing on this issue [47,48]. In the presented case study, the renovation has been designed, step by step, using the Active House standard as multidimensional decision tool. The usefulness of this approach relies on the immediate visualization of building's performances on several indicators at the same time, thanks to the radar plot tool.

2.1. The active house specification

The Active House standard is a building certification protocol with the aims to create healthier and more comfortable lives for their occupants without negative impact on the climate. The Active House vision defines highly ambitious long-term goals for the future building stock. The purpose of the vision is to unite interested parties based on a balanced and holistic approach to building design and performance. The label can be issued to buildings that has been evaluated in accordance with the Active House specifications and meet the minimum requirements, considering the three main quantitative indicators: indoor comfort, energy efficiency and environment. An Active House is a combination of these three factors that concur to create a healthy and sustainable living space. The three main categories are then sub-dived into three sub-categories, to each of these it associated some ranking criteria useful to calculate the Active House class of a design project. There are four classes (1 to 4), where 1 is the best achievable and 4 is still acceptable; if a building falls outside these classes, it means that is not classifiable as Active House.

Table 1 describes the ranking criteria and how they have been use dot guide the VELUXlab renovation, the highlighted category are the ones analyzed in the paper.

The Active House standard is focused on the balanced between all the categories and accounts for the contextual implications that might bring a project to perform perfectly in some categories and less in others.

In this case study, the evaluation has been done using the Active House radar, a graphical tool useful to show the performance achieved on each of the above-mentioned indicators.

3. The case study. Renovation approach and description

The case study is the renovation of Atika building (Fig. 1, left side), conceived as a demonstrative residential example of an energy efficient home for South-European climate. After the renovation, the building had improved performances and changed name into VELUXlab (Fig. 1, right side). The original building, designed by ACTX/IDOM studio, consists of a modular housing structure easily assembled and transported, developed under the Model Home 2020 project [58].

The building was composed by a modular pre-fabricated construction, chosen for the benefits over the whole construction process: prefabrication reduces the assembly time of almost one third if compared to conventional buildings, it is precise and precisely controlled on manufactory site, it is easily implementable and it enhances the construction's quality.

The Atika building design approach followed the bioclimatic approach described by Givoni [59]. The rooms were organized around an internal patio and shaded to prevent overheating, while the roof

Table 1
Active House ranking criteria for each category and use in the case study. The ranking criteria are given as they were at the time of the VELUXlab renovation; during the years, in fact, the standard evolved and has been refined based on the applied research of the Active House Alliance partners. *summer and winter are defined by the external running mean temperature [51,52], when it is lower than 12 °C, then the season is winter; when it is above it is considered summer. **In the environmental loads, there are also other parameter of the LCA methodology [55,56], however they are not reported are they were not used but just calculated during the life cycle assessment.

	Sub-category	Parameter	Class: criterion	Use in the case study
Comfort	Daylight	DAYLIGHT FACTOR DF: minimum room average value	1:$>$5% 2:$>$3% 3:$>$2% 4:$>$1%	*Used to design the roof windows*
		DIRECT SUN AVAILABILITY [49,50]	1:$>$10% 2:$>$7.5% 3:$>$5% 4:$>$2.5%	*Used to design the roof windows and the patio, based on the carpet graph and heating savings*
	Thermal environment [51,52]	MINIMUM WINTER OPERATIVE TEMPERATURE *Requirement met for 95% of operative hours	1:$>$21 °C 2:$>$20 °C 3:$>$19 °C 4:$>$18 °C	*Used to design the insulation levels, based on the carpet graph*
		MAXIMUM SUMMER OPERATIVE TEMPERATURE *Requirement met for 95% of operative hours	If mechanical cooling [52] 1:$<$25.5 °C 2:$<$26 °C 3:$<$27 °C 4:$<$28 °C if natural cooling [50] 1:$<$(0.33 Trm)+20.8 °C 2:$<$(0.33 Trm)+21.8 °C 3:$<$(0.33 Trm)+22.8 °C 4:$<$(0.33 Trm)+23.8 °C	*Used to design the windows and shading system, based on the carpet graph*
	Indoor air quality [53,54]	STANDARD FRESH AIR SUPPLY hourly concentration of CO_2 inside the rooms, requirement met for 95%	1:$<$500 ppm 2:$<$750 ppm 3:$<$1000 ppm 4:$<$1200 ppm	*Used to design the ventilation system*
Energy	Energy demand	ANNUAL ENERGY DEMAND calculated according national building code	1:$<$40 kWh/m^{2}y 2:$<$60 kWh/m^{2}y 3:$<$80 kWh/m^{2}y 4:$<$120 kWh/m^{2}y	*Used to optimized the heating and cooling systems*
	Energy supply	ORIGIN OF ENERGY SUPPLY Percentage of energy form renewable source	1: 100% 2:$>$75% 3:$>$50% 4:$>$25%	*Used to implement and design the PV panels and the solar thermal*
	Primary energy	ANNUAL PRIMARY ENERGY PERFORMANCE Balance between primary energy used and supplied	1:$<$0 kWh/m^{2}y 2:$<$15 kWh/m^{2}y 3:$<$30 kWh/m^{2}y 4:$>$30 kWh/m^{2}y	–
Environment	Freshwater consumption	MINIMIZATION OF FRESHWATER USE Improvement respect national average	1:$>$80% 2:$>$50% 3:$>$40% 4:$>$25%	*Used to install the best-practice equipment for the domestic hot water supply*
	Sustainable construction	RECYCLABLE CONTENT percentage of the recycled materials weight on total	1:$>$50% 2:$>$30% 3:$>$10% 4:$>$5%	*Used to choose the materials: re-use of Atika, use of recycled materials as the powdered polystyrene*
		RESPONSIBLE SOURCING percentage of materials with environmental certificate	1:100% wood + 80% others 2:800% wood + 50% others 3:65% wood + 40% others 4:50% wood + 25% others	*Used to choose the new materials*
	Environmental loads **[55–57]	PRIMARY ENERGY CONSUMPTION DURING LIFE CYCLE	1:$<-$150 kWh/m^{2}y 2:$<$15 kWh/m^{2}y 3:$<$150 kWh/m^{2}y 4:$<$200 kWh/m^{2}y	*Used to choose the new materials, especially for the powdered polystyrene. Used to design the PV system*
		GLOBAL WARMING POTENTIAL	1:$<-$30 kgCO$_2$/m^{2}y 2:$<$10 kgCO$_2$/m^{2}y 3:$<$40 kgCO$_2$/m^{2}y 4:$<$50 kgCO$_2$/m^{2}y	*Used to choose the new materials, especially for the powdered polystyrene Used to design the PV system*

Fig. 1. A picture of the building as Atika (left) and after the renovation, as VELUXlab (right). The structural core is the same but equipment and the building's shell is improved according to the concept of environmental efficiency.

Fig. 2. Atika's prefabricated blocks. The structural modules are kept as the original design of Atika. The core blocks arrived on the construction site pre-assembled and new layers for improving the building's energy efficiency have been added on site. In this picture, the left side of the building is shown, the metallic structure and the internal insulation are visible.

enhanced natural ventilation and solar panels efficiency, due to its tilted shape. The structure was made by steel frames, while it was stabilized vertically with steel columns and shear diagonal braces. The floor was a mixed structure of galvanized metal sheet and reinforced concrete. The roof was insulated with 160 mm of expanded polyurethane panels and covered with high-pressure laminated plates. The building renovation took place in 2012 and the Atika residential building was complete transformed into an office building and experimental facility, the renovation was followed by both from industrial partners and researchers.

The building renovation enhanced the relationship between the building and its context, applying the same bioclimatic approach to the new environment. The general architectural concept has been maintained, while the technology and the building envelope have been renovated, considering the actual climate condition and the different building use. The Climate Consultant energy design tool [60] (Fig. 3) has been used to analyze the effect of the passive strategies and to validate the suitability of the previous shape for the Milan (Italy) climate condition.

The architectural design and the orientation allow reaching an increase indoor thermal comfort: the south facing patio (Fig. 4) maximizes the winter solar gains and serves as natural shading during summertime [1]. The wall facing south and the east/west facades are completely opaque, in order to keep a compactness of the building to the critical expositions during high solar radiation season. The segmented profile of the internal ceiling, instead, enhances natural ventilation inside based on the air buoyancy.

4. Comfort and energy efficiency evaluation

The effectiveness of the building renovation process has been evaluated by dynamic thermal simulations in order to calculate the expected useful and primary energy consumption in transient state, overlooking the under-estimation usually embedded in the steady-state approach. The building behavior has been derived by dynamic simulation: Trnsys v.17 [61] environment has been used in order to represent the closest as possible the reality. The building geometry and the seasonal energy consumption (useful and primary energy) are summarized in Fig. 6.

From the building services point of view the VELUXlab building has been equipped with an efficient air-to-air heat recovery system (90% of efficiency), an air-to-water heat pump (electrical power absorption of 7 kWp), 12 m^2 of photovoltaic panels with a power of 2 kWp and 6 m^2 of solar panels for domestic hot water production (Fig. 5). The optimal orientation, the high thermal insulation of the building envelope, the optimization of solar heat gains and the other heating passive measures contribute to reduce the annual useful heating energy consumption to 9.8 kWh/m^3y. Considering the properties of building and the plant system characteristics, the primary energy consumption has been estimated equal to 3.82 kWh/m^3y. The cooling energy need, instead, is reduced from 32 kWh/m^3y (useful energy) to 9.14 kWh/m^3y of primary energy by using the above mentioned energy efficient technologies. Thanks to its performance, the building has been classified as a nearly zero energy building [62]. The presented simulation results have been calibrated by means of in situ measurements: the building has been, in fact, equipped with different temperature/humidity sensors in order to collect information concerning the real internal set point during the building operation. Specifically, the monitoring system consists of a network of 10 temperature and humidity reading point, located in different positions as reported in the Fig. 7.

Each points identified by numbers represents a compact data logger [63] (dimensions of $50 \times 24 \times 15$ mm) with a long life internal power supply allowing an easy set-up, readings and data download. The data logger has been installed easily in different point considering the absence of cable and awkward connection. The specific characteristics of the sensor are collected in Table 2.

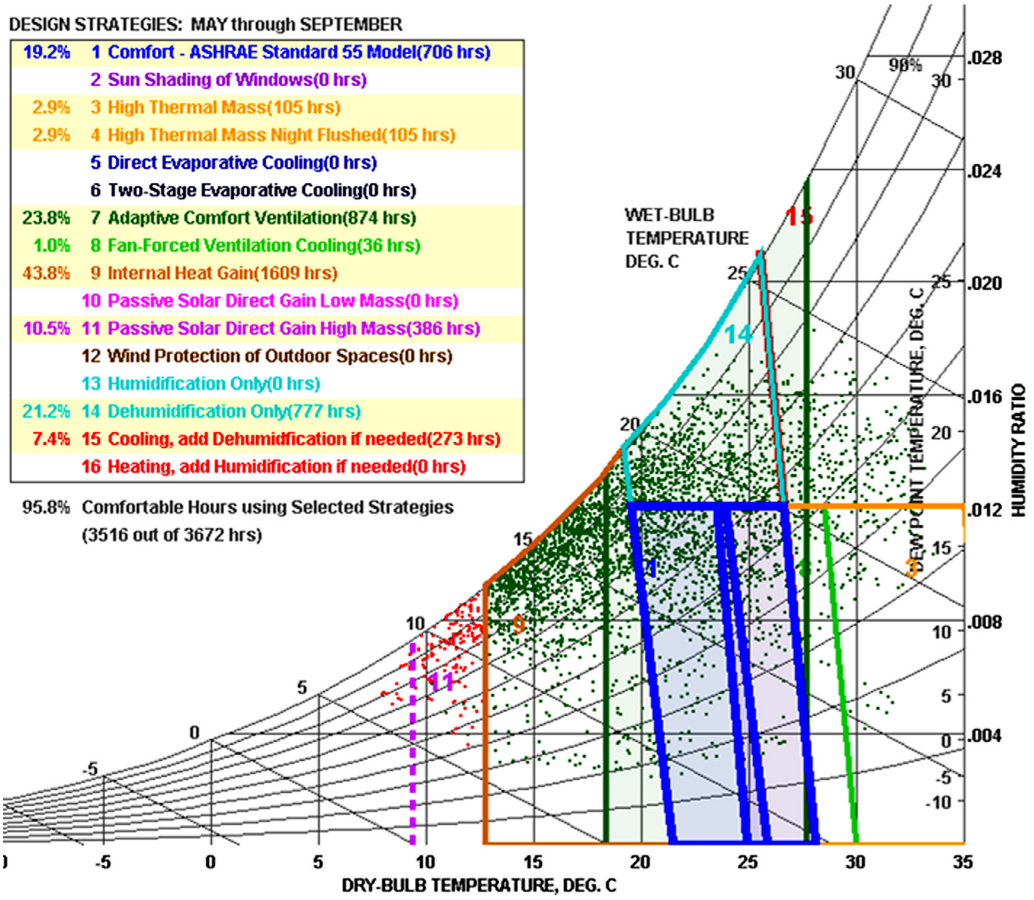


Fig. 3. Bioclimatic chart, temperatures for the warm season (May–September) are shown, the passive strategies that can be useful for natural cooling are highlighted in yellow from the list. The calculation is made following the adaptive method EN 15251:2007 [51] and it is useful to display the potential of the most common passive conditioning technique for a specific climate. In the case of Milan, a normal building without any passive strategy applied can have up to 19% of hours in the comfort range, this percentage increase when a strategy is considered. Milan is characterized by cold winter and humid-hot summer, therefore the most effective way to reduce a building's conditioning needs are: maximizing the internal heat gains (43.8% of comfortable hours without heating system), enhancing natural ventilation during summer (23.8% of comfortable hours without cooling system) and dehumidifying the external air (21.2% of comfortable hours without conditioning). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Characteristics of the temperature and humidity data logger with temperature and humidity sensor.

Dimensions	50 × 22 × 10 (mm)
Weight	11 gr
Probe material	AISI316L stainless steel
Temperature range	−20 °C ÷ +65 °C
Temperature resolution	0.25 °C
Uncertainty temperature	±0.4 °C from +5°C to +40 °C
Humidity range	5% ÷ 95% RH (non condensante)
Humidity resolution	0.1%
Uncertainty humidity	±3% from 20% to 80% RH ±4% from 5% to 95% RH
Battery	3.0 V CR2032 litium
Autonomy	10 years – 3 million of input

As reported in the Fig. 9, the modeled temperature generally followed the measured values with maximum discrepancy of 0.8 °C. The temperature levels is the results of the calibration model that take into account the real use of the building with the users interaction.

The monitoring results has been used also to analyze, in the real conditions, the performance of the renovated vertical envelope. The Fig. 10 represents the surface temperature of the east-facing wall during summer conditions: the building envelope's technology allows to reach an optimal indoor summer comfort level due to different resistive layers (polyurethane and powdered EPS) combined with a ventilate external cavity. The temperature distribution shows 75% of the hours below the threshold of 26 °C during the whole month of July, providing superior overall thermal comfort.

The calibrated building model has been also used to verify the indoor comfort provided over the year, in relation to the AH specifications. The yearly analysis on users' comfort expectation is represented in Fig. 11. The calculation refers to the classification proposed by Active House that classify the performance on the basis of the percentage of hours that falls into each class. The thresholds are defined by the static and dynamic approach, respectively for winter and summer seasons [51,52]; and to achieve a certain class, 95% of the hourly temperatures should fit into these thresholds.

The results related to the design choices shows: 42% of all the hours during the year belong to Class 1 (very comfortable) with only less than 5% to Class 4 (not comfortable). However, VELUXlab building is not a residential building but an office and it is occupied only during working hours (from 08.00 am t0 06.00 pm); therefore, the real discomfort hours are less, demonstrating the efficacy of the design solutions adopted in providing comfort to occupants.

The pleasant indoor environment is given by a combination of thermal and daylighting performances that have been accurately designed to maximize the occupants experience inside the build-

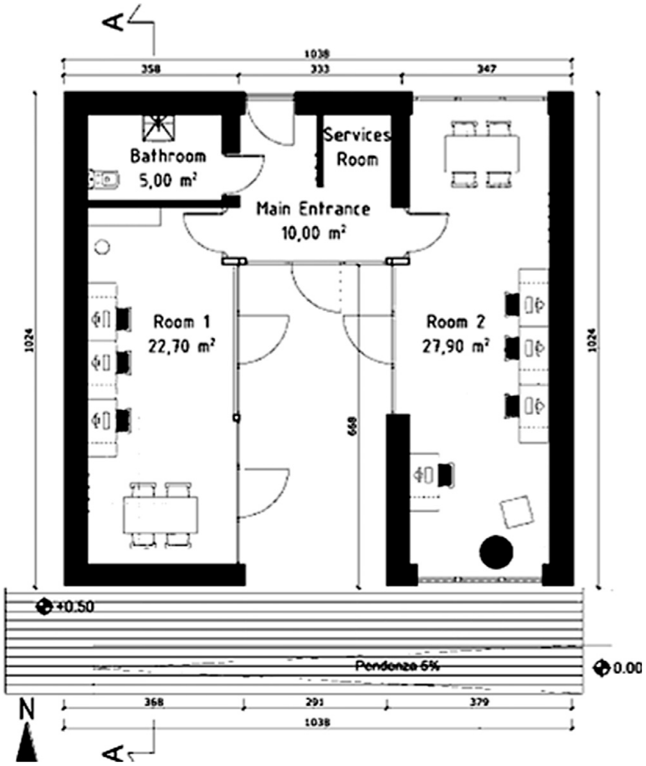


Fig. 4. Architectural plan of the VeluxLab building.

ing. To that end, we performed an analysis on the roof and the effects of adding roof-windows, which could increase and maximize both the daylight factor (DF) and the solar gains during winter. To prevent overheating, automatic shading devices protect the windows from the direct solar radiation during summer. Fig. 12 shows the comparison between the different scenario: with and without skylights. The choice of using the daylight factor as parameter to evaluate the visual comfort was guided by the standard chosen: Active House ranking system is based on DF for the "visual comfort" category evaluation. The daylight factor is the percentage of indoor to outdoor illuminance under overcast sky conditions that hits the working plane surface. The analysis was done using VELUX Daylight Visualizer 2. This software has been validated against CIE 171:2006 and have an accuracy error lower than 1.29% [64–66]. It relies on the Ray-tracing calculation method and it uses the standard overcast sky condition and it is generally recognized as a reference software for the calculation of the sky component in the daylight factor evaluation [66]. From Fig. 12, it is clear how the roof-windows increase the daylight factor of 3% and they are essential to achieve the highest score on the Active House ranking, as it requests a DF of 5% to guarantee visual comfort.

According to the Active House system, the results reach the Level 1 ($DF > 5\%$ on average) considering the amount of daylight on a horizontal work plane (Fig. 10 left and Fig. 11).

The roof-windows have been designed also to minimize the thermal bridges and the heat dispersion through the envelope. The detailed analysis allowed to preserve the continuity of the thermal insulation layer through the envelope and frame joints. The analysis was made using the finite element method with an external temperature of −10 °C (Fig. 14). Two critical points have been detected from the isothermal representation: theta 1 and theta 2. The critical temperatures for air condensation in those two points are equal to 12.5 °C and 16.0 °C respectively and the calculated actual temperature, in the studied technological detail, are above the thresholds, thus the air condensation is prevent.

5. Environmental efficiency evaluation

The VELUXlab building has a very low energy demand, achieved thanks to an iterative process that considered the previous Atika design and the new retrofit requirements. A great attention was also given to the embodied impacts of the interventions planned, with regard to the LCA methodology. Recyclable and recycled materials have been extensively used in the renovation, according to the "sustainable construction" Active House category. The concept focused on re-use at best Atika's components and to implement new ones that offer the possibility to be recycled at the end of their life. For example, the continuous cycles of installation and dis-assemblage of Atika's macro components ruined the external cladding and compromised its structural verticality. A new façade was designed to restore the building's visual integrity and simultaneously improve the envelope's thermal resistivity. The new cladding was directly added on the old one, optimizing the construction process and creating a 3 cm ventilated air gap to enhance the summer performances (Fig. 15 and Table 3). This strat-

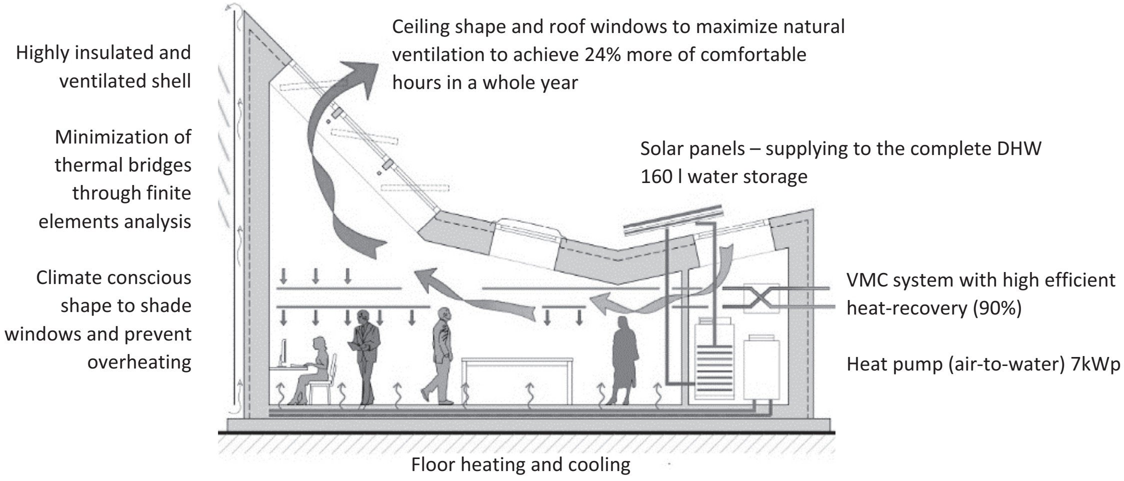


Fig. 5. Section with the passive strategies used. Natural ventilation has been enhanced by the tilted surface of the roof, which is optimized for both shading the internal patio and maximizing the efficiency of PV and solar panels. The heat pump and solar panels serve the floor heating/cooling system and mechanical ventilation with heat recovery has been integrated to supply fresh air when natural ventilation is not possible due to external extreme conditions. The passive strategies potential has been also validated by dynamic thermal building simulations, carried out by Trnsys 17 simulation environment (geometrical model is shown in Fig. 6).

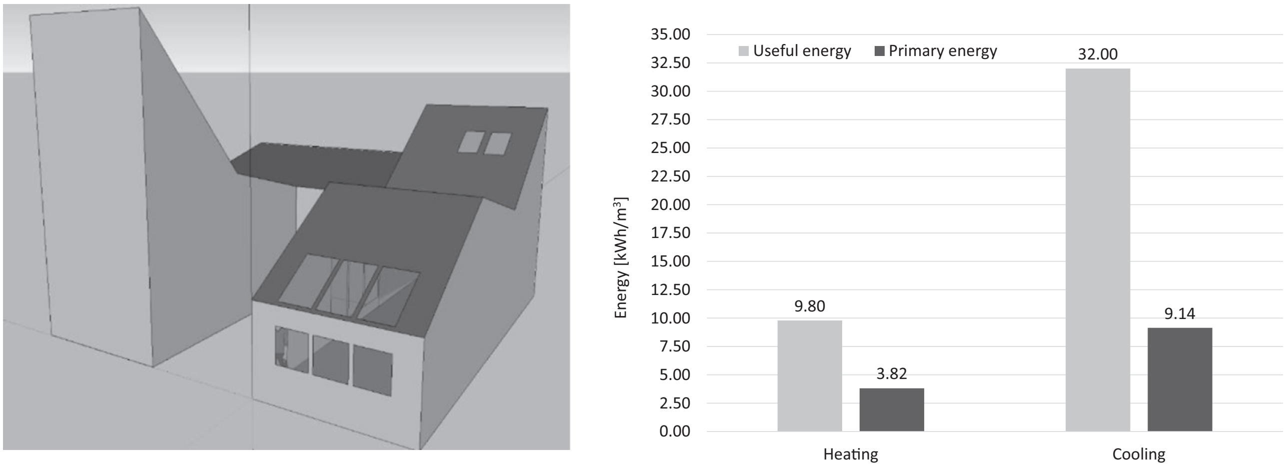


Fig. 6. 3d building model used for dynamic simulation (left) and energy consumption levels in kWh/m^{3}y (right). The dynamic simulation software Trnsys has been used to validate and optimize the design; this tool allows to have hourly results for the major building parameters (e.g. temperature, heat flux, heat gains). Detailed results of the simulations are reported in [61].

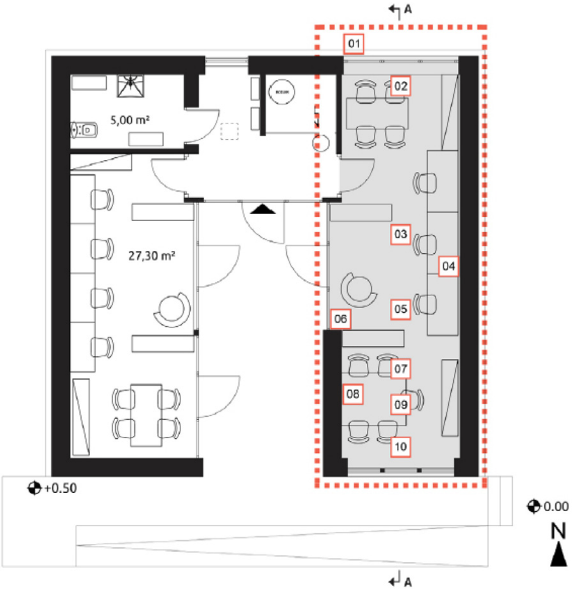


Fig. 7. View of the building with the sensors network.

egy helped to reduce the cooling needs during hot seasons, dampening the heat stress on the walls, especially on the big south oriented opaque façade, which benefits from the ventilation layer due to the buoyancy created by the air stratification (as shown from the results of the monitoring analysis).

The new cladding is made of pre-assembled insulated panels, composed by a core of rigid polyurethane with an integrated perforated metallic profile, which serves as structure for the external cladding and allows the natural movement of the air in the ventilation gap (Fig. 16). They were mounted on a galvanized steel substructure and, externally, they bear plastered thin recycled glass panels.

The new panels were mounted on a metallic sub-structure, placed directly on the old cladding. However, a thin air gap between the two facades was resulting from the compromised integrity of Atika's building cladding. This gap was interrupting the air tightness and the thermal resistivity continuity, influencing the thermal behavior of the renovated building. An additional insulation layer was designed to cover the gap, to maximize the envelope's performance. Different materials alternatives were provided for the additional insulation layer, in order to optimize simultaneously the "thermal comfort", the "annual energy performance"

Fig. 8. Left: Sensors set-up phase. Right: temperature-humidity sensor.

Table 3
Vertical walls – technical description of the materials layer form inside to outside. Total thermal transmittance and time lag are highlighted. VELUXlab envelope has been optimized for enhancing its performance accordingly to the requirements needed. *The final average thickness corresponds to 0.05 m.

Layer	Materials	Thickness [m]	Conductivity [W/(mK)]	Density [kg/m^3]
1	Oriented strand board	0.012	0.156	700
2	Plasterboard on metallic structure (50 mm)	0.013	0.210	90
3	Glass fiber membrane	0.04	0.048	15
4	Still air chamber	0.01	0.067	1
5	Rock fiber insulation panels	0.08	0.042	40
6	Wood wool panels	0.075	0.091	350
7	Powdered polystyrene	Variable*	0.034	32
8	Polyurethane preassembled panels	0.06	0.024	38
9	Ventilation chamber	0.03	–	–
10	Plastered Recycled fiberglass panels	0.025	0.09	500
OE	Old element from Atika – structure/insulation	–	–	–
Thermal transmittance (W/m^{2}K)				0.14
Attenuation factor (–)				0.0032
Time lag (h)				10 h 57′

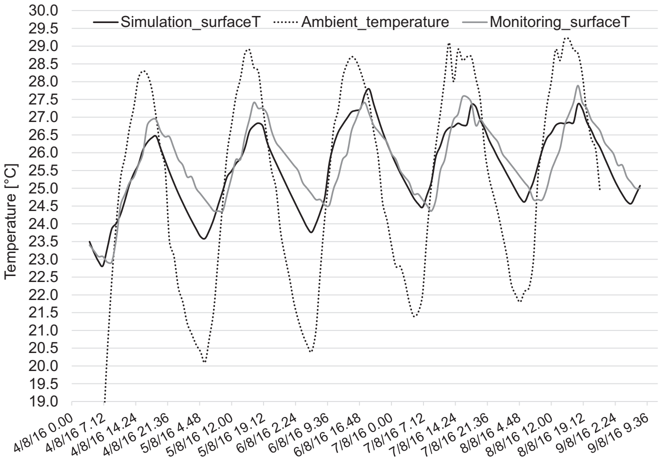


Fig. 9. Comparison between monitoring and simulation results. The monitoring results has been collected by the data logger number 4.

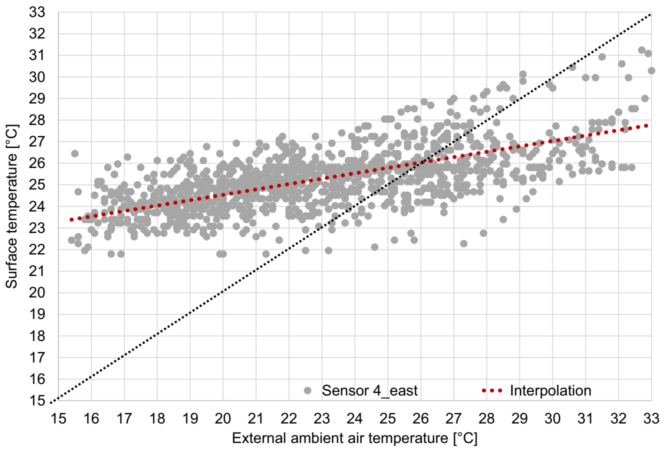


Fig. 10. Comparison between wall surface and external ambient air temperature. The surface temperature refers to the east wall orientation.

and the “environment loads” categories. The Active House tool was used to guide the design decision toward the material choice that had the maximum operational savings and the minimum embodied impacts, in this way the energy performance was improved without drawbacks on the environmental impacts. The effects on the annual performance, were, however, very similar, as the additional thermal resistance induced by the insulations was negligible.

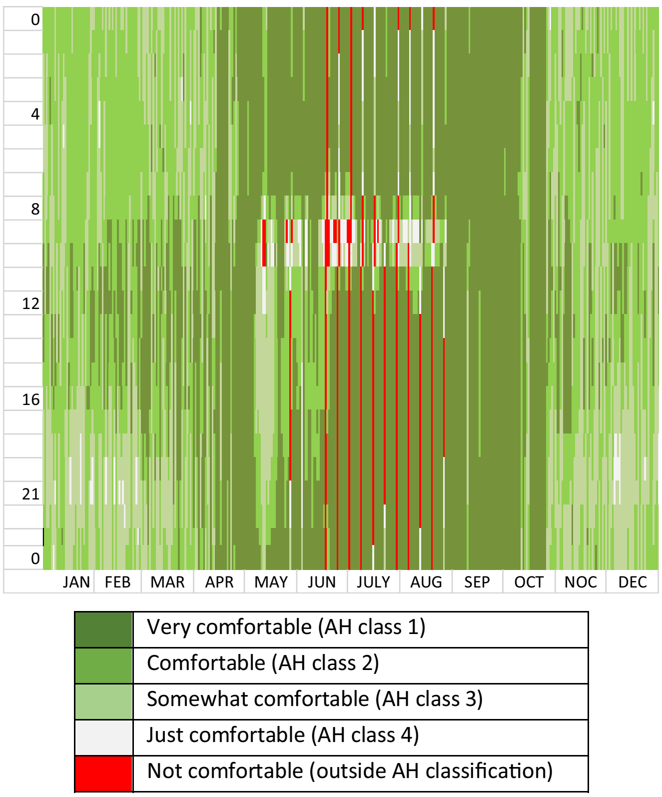


Fig. 11. Carpet graph indicating the comfort Active House class achieved by each hour of the year. Vertical axe: Hours of the day (top-down), Horizontal axe: Months of the year. Only 5% of the hours during the year are classified as “not comfortable”.

However, the embodied impacts associated to different materials can be predominant, therefore, this was used to guide the intervention.

The life cycle optimization approach led to consider four typologies of insulation materials: polystyrene, rock wool, wood wool and a new low embodied energy material, represented by powdered polystyrene from the construction site disposal. The latter was inspired by the concept of environmental efficiency: due to the building’s components transport there was a big availability of EPS waste (expanded polystyrene) as disposal material, which was identified as a big resource. The evaluation was made according to the kBOB database [67]. In order to perform the analysis, different assumptions were done:

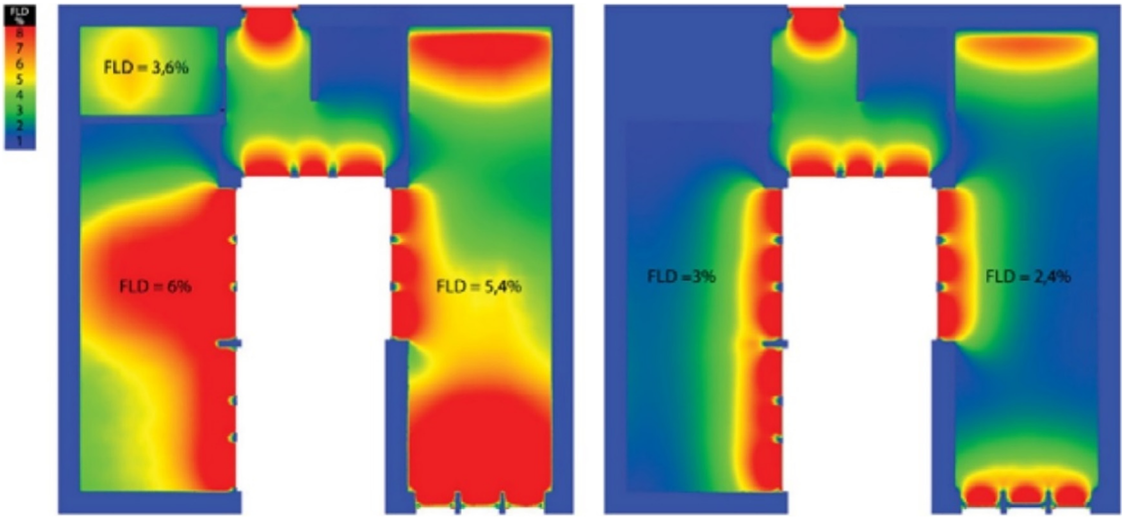


Fig. 12. Daylight factor for two building solutions: left side with roof windows and right side without roof windows. The FLD scale correspond to Daylight Factor (DF).

Fig. 13. The optimal design of the transparent surfaces allows reaching a high level of internal natural light.

- operative energy demand does not differ significantly in the alternatives and therefore only embodied impacts can be evaluated;
- the quantity of materials needed is the same for each alternative;
- the indicator used are CED (Comulative Energy Demand), CEDnr (non-renewable Comulative Energy Demand) and GWP (Global Warming Potential);
- impacts related to the manufactory of the materials are considered for all the alternatives;
- impacts of transportation are calculated only for the options with new materials;
- the distance of transport is assumed 30 km;
- for the option with re-use of construction waste the impacts associated to the disposal phase are subtract.

Fig. 15 shows the results of the embodied impacts related to the four options. The use of different material contributes in different way to the Active House certification: the highest benefits are visible when powdered EPS is employed. Compared with XPS: the GWP indicator is reduced up to 60% and the energy indicators of about 50%.

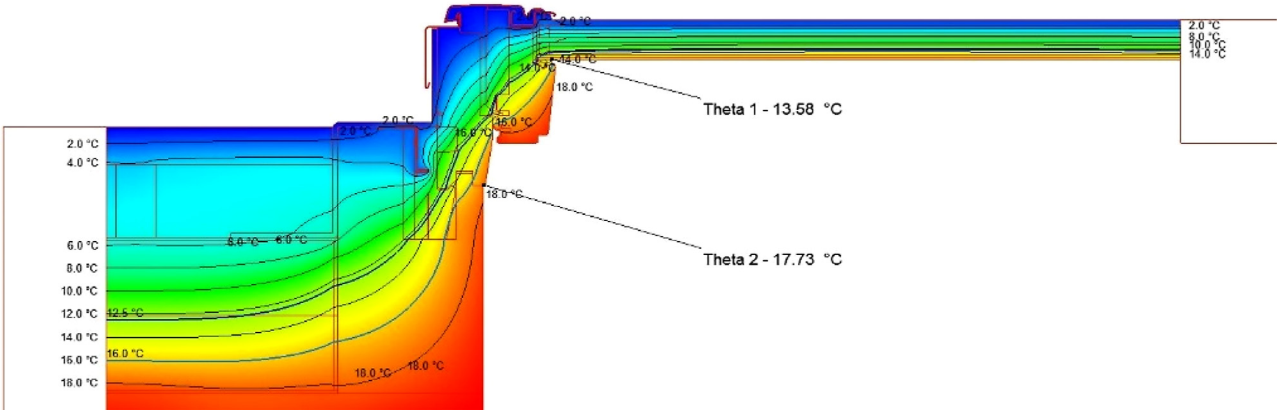


Fig. 14. Finite element analysis of the connection between roof and windows. The colors represent the isothermal area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

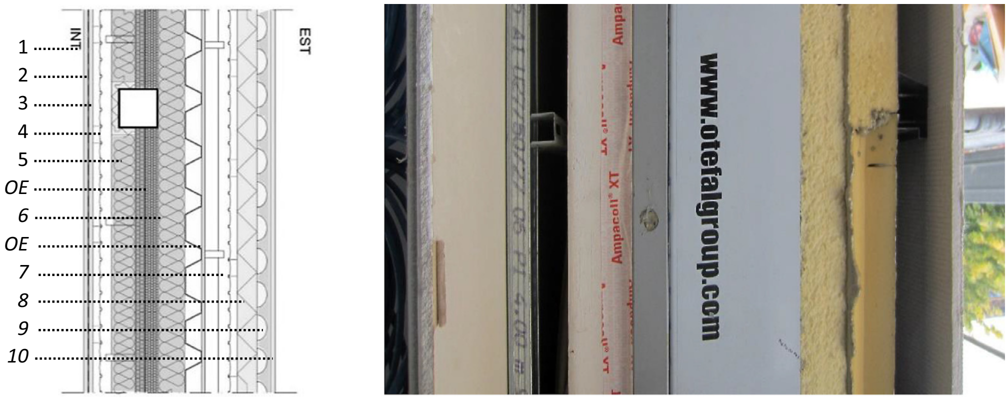
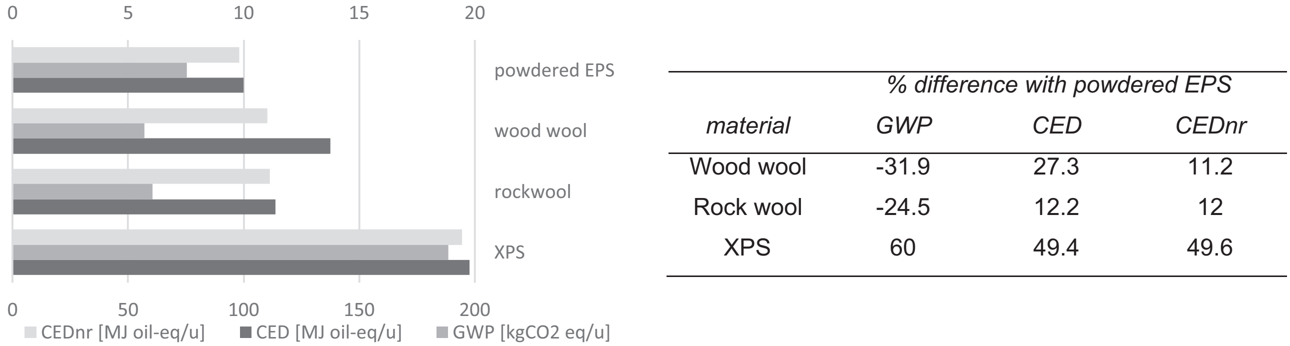


Fig. 15. Vertical walls, lefts side is the inner layer and on the right the external cladding: technological details and picture. The technical description of the materials used can be found in Table 2. It is possible to notice the multi-layering of the walls and the quantity of insulation implemented in the shell.

Fig. 16. Image from the construction site. The building is covered with polyurethane panels, which have an in-built horizontal metallic profile for an easy implementation of the cladding with ventilated cavity.



	% difference with powdered EPS		
material	*GWP*	*CED*	*CEDnr*
Wood wool	-31.9	27.3	11.2
Rock wool	-24.5	12.2	12
XPS	60	49.4	49.6

Fig. 17. Left side: Graph of the embodied impacts for the material's alternatives considered. The measures have been reported in function of the unit of product. The driving criteria of the insulation material choice was the embodied impacts analysis, since that the operative savings were similar for all the alternatives. Right: table with the percentage difference of the powdered EPS with the other materials: positive values correspond to a reduction, negative values to an increment. The highest benefits are visible when powdered EPS is compared with XPS, reducing GWP up to 60% and the energy indicators of 50%.

	% difference with powdered EPS		
Material	GWP	CED	CEDnr
Wood wool	−31.9	27.3	11.2
Rock wool	−24.5	12.2	12
XPS	60	49.4	49.6

Considering the embodied energy spent for each solutions, the powdered EPS was added to the construction, enhancing the building's thermal behavior with environmental awareness (Fig. 18).

The roof was optimized for windows and photovoltaics panels (PV) integration. VELUXlab building has been equipped with a PV system, in order to cover the electrical need of the laboratory. The process to dimension the installation followed the principle of life

Fig. 18. On the left, gap between the old and the new façade. On the right, the gap filled with powdered insulation.

Table 4
Embodied impacts of 1 MJ of electricity produced with a general grid mix and the PV inclined on the roof. GWP indicator is optimized by the electrical energy grid, however CED and CEDnr are minimized by a PV system.

Energy source	GWP [kgCO$_2$ eq/MJ]	CED [MJ oil-eq/MJ]	CEDnr [MJ oil-eq/MJ]
PV	0.0195	1.38	0.264
grid	0.00766	2.48	1.8

cycle optimization, considering the optimal balance between “origin of energy supply” and “environmental loads' indicators: it was important to balance the additional embodied energy introduced by the integration of PV panels with the operational impacts embedded in the solution. In other words, how much operational impacts do we have per kWh produced when we supply it with PV and with the normal electricity grid? In the Table 4 the embodied impacts of the electricity produced by PV panels has been compared with the electricity mix coming from the national grid.

The PV panels is the better solution considering the energy indicator CED and CEDnr, however the carbon emissions related to 1 MJ produced with PV is much higher than the one taken directly from the grid. To balance the higher GWP, however, the “origin of energy supply indicator” was considered: PV helped to increase the category up to class 1 and therefore it was preferred.

The position has been optimized and sized at 2 kWp, for an annual production up to 2400 kWh (Fig. 19). The balance between energy needs, environmental impacts and AH labeling helped to define a sustainable strategy, which is completely customize on the building.

Fig. 20 shows the final performances of VELUXlab building, evaluated according the standard Active House. The attention to details and renovation strategies allowed achieving the maximum score in the primary energy indicators and excellent results on the environmental label.

6. Discussion and conclusions

The presented paper shows a case study of high-energy efficiency building renovation and the integrated design process methodology used to improve the building environmental performances. The building retrofitting has been carried out according to the Active House vision, which encompassed the energy, environment and comfort aspects. Life cycle analysis guided the retrofit and the design choices, allowing to enhance the building performances on both the operative and the embodied perspective. The presented method balances these two factors in order to find a solution that optimize the building design on a life cycle approach, assuring the reduction of energy use in the whole building's life. VELUXlab has been a first prototype of the application of this method, which is not straightforward but it is a step by step learning process. The AH radar plot has been useful to guide towards a more environmental efficient design, minimizing the retrofit impacts on the environment. The focus on the embodied calculation has been made with the LCA method, while the operative impacts have been calculated through a multidimensional analysis: thermal dynamic simulations, finite elements analysis and lighting

Fig. 19. Aerial view of the VELUXlab, with photovoltaic and solar panels systems installed on the pitched roof.

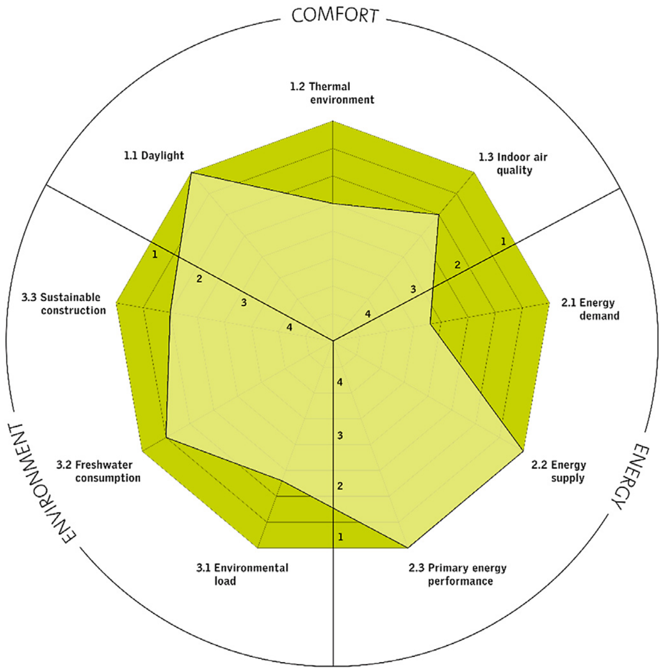


Fig. 20. Active House radar for VELUXlab. Performances are rated on a 4-points scale, where 1 is the highest and 4 the lowest score achievable for being "certified" as Active House. The wider is the light-green area, the better is the design solution considered. VELUXlab is the first Italian building certified AH as built. The calculation is referred to the AH system for evaluating new projects, while VELUXlab is a retrofit, however, the results achieved optimize its behavior, indicating the ambitious project developed.

level evaluation have been assessed, according to the AH specification.

The integrated approach allowed to reach a high efficient building with low energy consumption. VELUXlab requires only 3.82 kWh/m^3 for heating and 9.14 kWh/m^{3}y for cooling. It is certified as Active House class 1 in the "primary annual energy performance" category thanks to the strong integration of renewable energy sources (PV and solar thermal). As shown by the results the "thermal comfort" is guaranteed in class 3.5 for more than 95% of the occupied hours, while the visual comfort is assured by the roof windows, which double the daylight factor (from 3% up to 6%) and assure the class 1 in the "visual comfort" category. The attention given to the environmental impacts during the design allows VELUXlab building to achieve a mean class in the overall environmental category 2, demonstrating that it is possible to optimize both embodied and operational energy impacts.

The overall results show that VELUXlab building can be considered an outstanding example of low-energy retrofit toward nearly zero energy buildings as well as a model of a smart and sustainable re-use of an existing structure, aiming at the environmental efficiency optimization from building's cradle to grave. Moreover, VELUXlab building shows that it is possible to optimize the materials choice and equipment installation based on the relationship between the energy spent in the construction and the energy saved during the operation. However, it must be said that the case-study is a retrofit and the possibility to re-use the old structure (of Atika building) had positive influence on the final LCA. Despite the limitation given by the specific case study, the analysis highlights the potential of Active House as a tool for an environmental-efficient and multidimensional design process. Further investigations are needed to better frame the methodology used in the case of VELUXlab building and to integrated it into a more structured design process methodology that could inform designers toward very efficient, comfortable and sustainable buildings.

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