The eco-sustainable renovation of knowledge buildings through a cross-border living lab

RESEARCH AND EXPERIMENTATION

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Abstract. Sustainable building management requires creative interpretation of direct user needs, a skilful balance between technological innovation and applied research into the concept of "Possible Quality". Med-EcoSuRe research project proposes a pragmatic approach to innovation, whereby experimentation involving the active engagement of end users is conducted with particular focus on human-environment centred design. The objective of this approach is to disseminate effective energy efficiency strategies in university buildings through a cross-border Living Lab. Physical and virtual tools were implemented to foster dialogue and collaboration between academics, decision-makers and stakeholders, and to support university energy managers in planning and implementing innovative energy measures. This paper, starting from a rapid illustration of the results of the research project, illustrates the value enhancing actions post-closure of the project, in progress and/or planned.

Keywords: University building; Cross-border living-lab; Energy retrofit; Human-environment centred design; Perceived comfort.

Introduction

This paper explores the eco-sustainable retrofit of university buildings through an innovative approach based on a cross-border Living Lab. It reports the main results of the Med-EcoSuRe project with the aim of presenting concrete energy and environmental retrofit strategies applied to knowledge buildings, with a focus on participatory methodologies involving users, academics and policy makers.

The methodology adopted in the article is based on direct experimentation in real world contexts, supported by digital tools and collaborative platforms such as MedBeXLive, which facilitate knowledge exchange and the harmonisation of energy retrofitting practices. The Living Lab approach integrates end-user perspectives into the decision-making process, combining technological and perceptual analyses to optimise the effectiveness of interventions (Karrer, 2022).

The findings presented in the article highlight the value of the Living Lab model for university building retrofitting. In particular, the study illustrates the performance of innovative technological solutions, including the use of digital twins (Clausen *et al*., 2021), energy performance monitoring through IoT, and the testing of retrofitting strategies. The case study of the Solar Carport, for instance, demonstrates how the implementation of photovoltaic systems can generate significant energy and economic savings, with a payback period of less than four years. At the same time, an analysis of user-perceived comfort in university environments provides strategic insights for designing more sustainable, high performing spaces. By adopting an integrated and replicable approach, this study contributes to the broader debate on the energy transition of public buildings, proposing a model based on co-creation and rea world experimentation.

Below, the researchers from the Units involved in the project illustrate the strategies adopted, the methodologies tested, and the results obtained in the context of the eco-sustainable retrofitting of university buildings, highlighting how these have been concretised in post-project improvements that are either underway and/or planned.

Creating an innovation network

Med-EcoSuRe (Mediterranean University as catalyst for Eco-Sustainable Renovation) is a project funded by the European Union through the ENI CBC Mediterranean Sea Basin Programme 2014-2020[1]. The project considered universities the most fertile ground and space to grow open innovation, to experiment with new processes and solutions providing proofs of concept and giving the possibility to educate towards more sustainable building renovation.

A university-based Cross-Border Living Lab (LL) was established to support these efforts. The Lab was designed to address and overcome the fragmentation often observed in renovation processes, particularly within Mediterranean university buildings.

This inclusive approach enabled the university community (energy managers, decision makers, academics, end users) to contribute to co-create the renovation process (Karrer, 2022) and to achieve the common goals of more sustainable university buildings in terms of Energy Efficiency, environmental impact, well-being and aesthetics, as well as increased environmental awareness of users.

The Mediterranean Renewable Energy Centre (MEDREC), a cooperation centre based in Tunisia, initiated and facilitated the establishment of a cooperation network between public and private partners from Tunisia, Italy, Spain and Palestine, promoting the transfer of knowledge on the renovation of university buildings in the Mediterranean region. The partnership of the project includes four universities, an Agency for Energy and Environment and an Association for the Internationalisation and Innovation of Solar Companies.

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01 | The space BeXLab, University of Florance

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Med-EcoSuRe supported the use of an ICT platform – Med-beXlive[2] – which is an *agora* that allows rapprochement and dialogue between all actors concerned by the university building's energy efficiency. This platform facilitates cooperation and co-creation in the Living Lab community, the sharing of methodologies and results, and promote the adoption of sustainable renovation practices through workshops and seminars.
The platform is operational, providing a common ground for future cooperation, and replication of the results by:

– creating exchanges between all the registered actors, and facilitating the emergence of new projects (industrial, research, etc.);
– creating cross-border working teams around specific projects.

To ensure the sustainability of Med-EcoSuRe, a charter for the Mediterranean Cross-border LL was signed by the project partners enabling to exploit and capitalise on the LL results beyond the project lifetime. An action plan for the next five years is included defining the activities to be carried out jointly. This signed charter gives a formal status to the LL, which allows better exploitation of its results.

From the Med-EcoSuRe project to the Mediterranean Cross-Border Living Lab (MCbLL): the method

The core concept of the Med-EcoSuRe project was to envision universities as living Labs to experiment and pilot innovative and eco-sustainable renovation strategies and approaches for Mediterranean public buildings.
As collaborative ecosystems for open innovation and experimentation, based on collaboration between stakeholders (academia, companies and institutions), and enhancing the importance of the user experience in real-life settings, the Living Lab approach has been selected as the best methodology to address the complexity of building renovations in the Mediterranean region.
In the context of the project, the University of Florence was responsible for developing a dedicated methodology to exploit Living Lab for the renovation of university buildings, resulting in a two-level structure, precisely a cross-border level and a local level.
In the first case, a cross-border LL entity to connect local Living Labs in Mediterranean universities, called Med beXLive, has been defined for the exchange of best practices, sharing of knowledge, and harmonisation of tools to conduct joint research. Initialised by the network of project partners, experts in the field of building energy renovations, the cross-border Living Lab addresses region-specific climatic and cultural challenges to develop scalable and replicable renovation models, linking innovation with education to promote long-term sustainability goals for the Mediterranean area. Its strategic objectives and operational functioning have been fixed in dedicated guidelines, culminating in the creation of an online digital platform (Fig. 2) to share its activities.
At local level, as places of education, research, and technological advancement (Torricelli, 2017), university buildings can become the physical place of Living Lab (Fig. 1) where researchers, facility managers, stakeholders (innovative companies or public

02 | BeXLab platform: Sensor system and data

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03 | The new campus in Nablus: a. PV campus; b. PV carport system; c. PV plants: control and monitoring operations

03 |

organisations), and end-users can work together to explore innovative approaches, methods and technologies for building renovation, to test and evaluate in real-world pilot projects. The engagement of students as end-users is particularly strategic, fostering their understanding and awareness of sustainability challenges and solutions, in a long-term perspective.
Given the innovative nature of university Living Labs for building renovation, a toolkit has been delivered as project output to provide a step-by-step guide for setting up and experimenting with innovative renovation processes in pilot actions.
The local Living Lab activated in the University of Florence specifically focused on the experimentation of Digital Twin technologies (Clausen *et al.*, 2021), exploring BIM (building information modelling) (Shahzad *et al.*, 2022) and real-time data from IoT sensors for the development of the pilot renovation action (Rinaldi *et al.*, 2020) in the university building. The experience of the advanced collaborative environment consented to spread awareness and knowledge among the academic and local community on the opportunities and challenges of the twin digital and green transition, resulting in the quality of the pilot project developed.

The case study of Solar Carport – Fine Arts Faculty – New Campus

ANNU through Med-EcoSuRe project carried out implementation of solar PV carport system in the new campus in Nablus (Fig. 3) to reduce annual energy consumption. The idea of the solar garage came up as part of the university's constant endeavour to increase the coverage of solar cell systems for the university's total consumption by exploiting the spaces (Violano *et al.*, 2021), and the university's desire to spread new ideas for the implementation of solar energy projects.

Tab. 01 | Real monthly energy output of 280 KWp PV systems

Tab. 01 |

Month	Energy Output (MWh)
January	25.21
February	26.88
March	29.40
April	34.44
May	40.32
June	47.88
July	61.32
August	68.88
September	70.56
October	63.84
November	45.36
December	40.32
TOTAL	554.41

The analysis is based on real time data collected through a monitoring portal[3].

The results show that the photovoltaic plant performance depends on both insolation and environmental conditions.

According to radiation data in the area, the real output yield from 280 KWp PV systems on the rooftop of university buildings was given in Tab. 1.

The efficiency of photovoltaic (PV) systems measures the system's ability to convert sunlight into usable energy for load consumption. For the analysed periods, the system efficiency, calculated as the ratio of the output energy of the PV system (MWh) to the global radiation energy received by the PV array area (MWh), was 20% in 2022 and increased to 21% by August 2023.

The Performance Ratio (PR), which indicates the proportion of actual energy generated by the PV system compared to its energy production under standard test conditions (STC), was calculated as 86% for 2022 and improved to 91% by August 2023.

The Final Yield (Y_f), a measure of the number of hours the system operates per year or day, is determined by dividing the actual energy generated (MWh) by the maximum capacity of the PV array (MW). Over the operational period, Y_f was estimated at 2.951,82 hours, with an average solar hour availability of 5,42 hours per day.

The Capacity Factor (Cf), which varies quite a bit for solar photovoltaic systems depending on the location, reflects the ratio of actual energy generated to the theoretical maximum possible energy (calculated using the PV array maximum capacity in kW and 8.760 hours per year), was found to average 22,6% during the analysis period. This value aligns with the expected range of 10-25% for solar photovoltaic systems, where the variability is influenced by geographical and climatic conditions.

Regarding the performance result analysis, the environmental and economic appraisal reports that the CO_2 emission and electricity bills will be reduced annually according to how much energy is produced by the PV solar system since system operation, as specified below:

- the electricity bill will drop by €83.161in 2023;
- CO_2 emission will drop by 388 tons CO_2.

From an economic perspective, the investment in the PV system demonstrates a strong financial return. With a total investment cost of € 254.678,00 and annual savings of € 83.161,00, the simple payback period is calculated to be 3,06 years. This relatively short payback period highlights the cost-effectiveness of the PV system, reinforcing its value as a sustainable energy solution with tangible economic and environmental advantages.

Software simulation tool for energy retrofit

At present, actions for the rehabilitation of cities, districts and buildings are being promoted for tertiary as well as for residential buildings. However, the complexity of assessing the energy savings achieved, with enough certainty, is well known after energy efficiency improvement measures (or even worse, a combination of them with cross effects) are implemented. The tendency is to solve this issue by using an either detailed or simplified building energy performance simulation tool. Nevertheless, the estimation of the energy consumption made by these tools differs from the measured values, either due to the case definition or the assumptions considered. In the framework of project Med-Eco-SuRe we have a proposal for solving both above-mentioned problems, precisely to use a simulation tool which has been corrected with climatic data and consumption measured data.

The main development work is the correction of the simulation tool using consumption data meters installed in the building, so this development is tested in three buildings and the paper (Sánchez *et al.*, 2018) shows the results of one of them. The benefits presented by this tool are the result of the previously conducted research, which focused on the automated generation of baselines through which the estimated energy situation made by the tool and the real measurement can be corrected. These baselines are stated in terms of the main energy parameters, which define a building. They are thus converted into a diagnostic protocol with which energy indicators and the expected reference values can be compared. This methodology shows the outcome of the optimal rehabilitation project in economic and energy terms.

The tested method offers direct users the opportunity to make judgements on both the building's performance (hardware system) and the way spaces are used (software system), in order to maximise comfort and minimise the use of resources. The software allows the introduction of energy saving measures, taken from a previously studied catalogue. It is possible to analyze the measures that will be used to improve energy efficiency, which implies significant modifications or substitutions in equipment, components, or systems, either referring to the elements of the enclosure or those of the facilities.

The improvement measures are developed in such a way as to provide, for each of the selected interventions, various levels of improvement (previously optimised).

04 | One of the projects developed during the International workshop "Energy Efficiency Action Plan in the Higher Education Building Sector" (Coord. A. Violano. Designers: N. Franzoso, V. Ignarra, L. Fejjari, D. Raucci, S. Argui)

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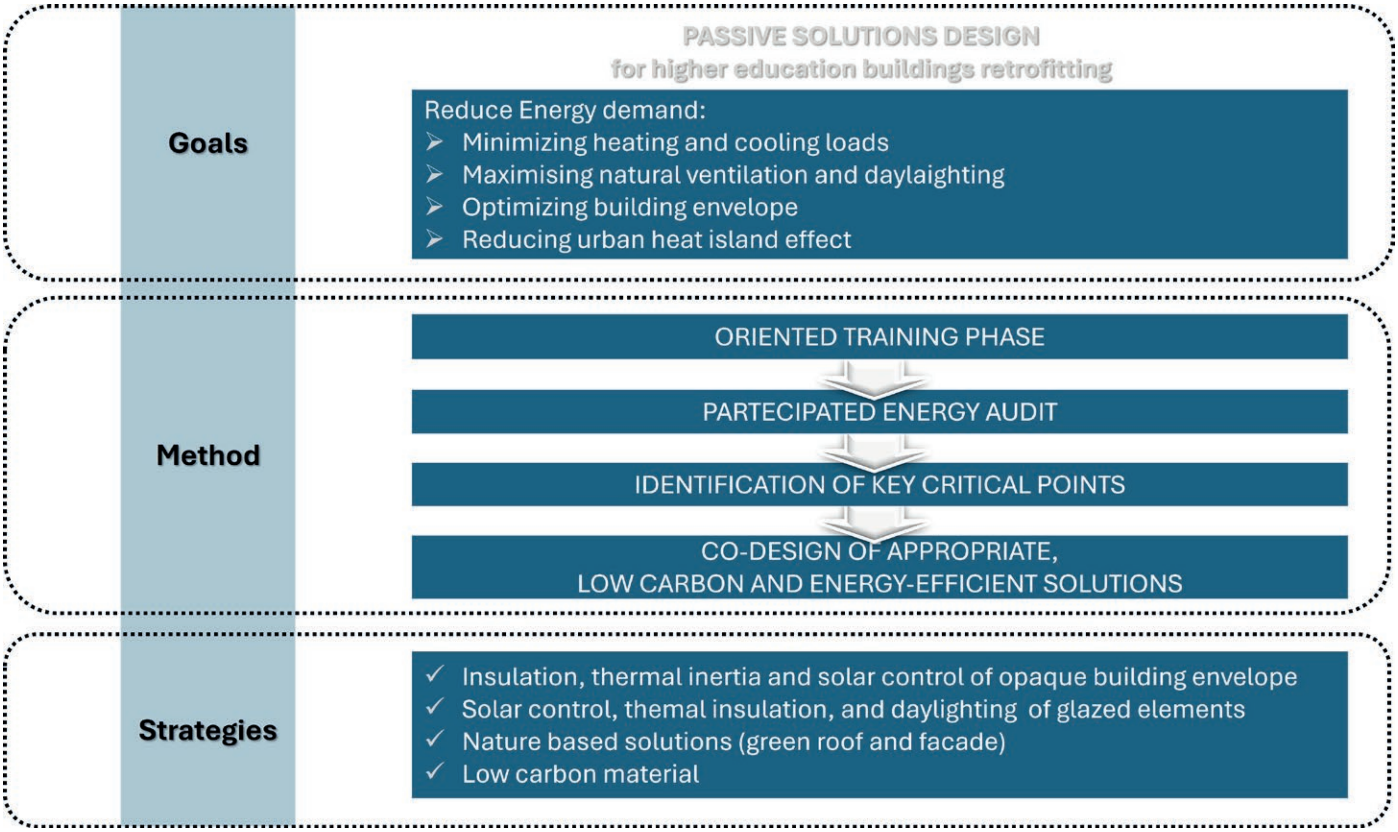


Analysing the activities carried out as part of the research project and the results achieved, it emerges that the developed tool presents a relevant advantage with respect to the existing tools, since it corrects the results of the building simulation tool through actual consumption measurements. The uncertainty of using software tools to analyse the energy performance of buildings is thusreduced.

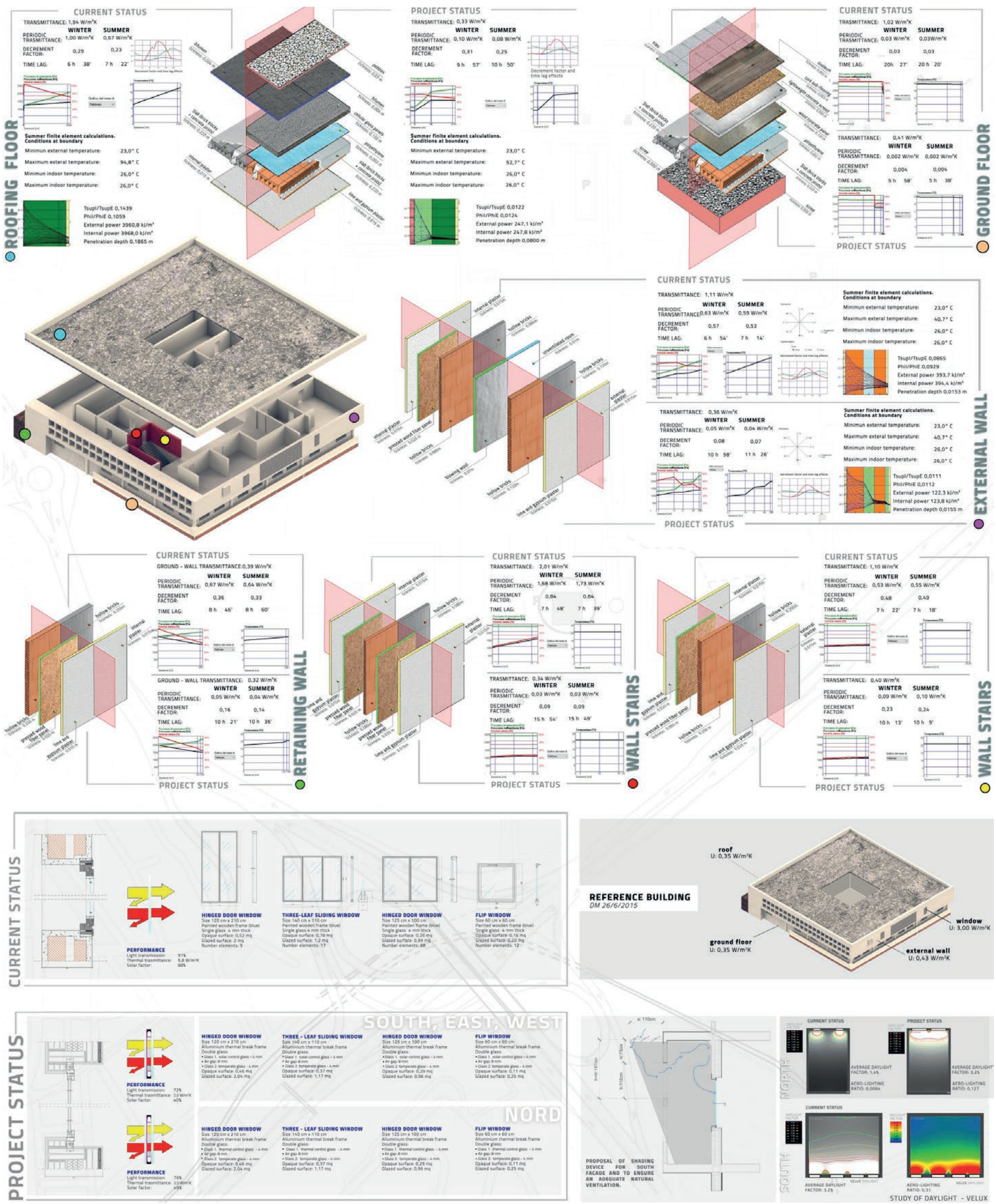
Unlike the energy performance of building simulation tools and their intricate calibration methods, a new way of correcting the results depending on the climate, actual measured consumption and characteristics of the building has been developed. More than three buildings are measured in the project, and they are used to test the software.

Finally, the software tool has an easy interface and moderate computational expenditure.

The value of International Workshops for Training and Research

The energy efficiency of public buildings has been identified as a strategic priority for achieving the 2050 decarbonisation targets in line with European directives. The retrofitting of university buildings serves as an example, both in terms of its positive environmental impact and its educational function, which engages students in innovative teaching and design experiences. In the Med-EcoSuRe research Project, UNICAMPANIA-DADI organised the international workshop "Energy Efficiency Action Plan in the Higher Education Building Sector", involving fifty-three students and ten tutors from partner Universities (Italy, Tunisia, Palestine), to provide theoretical and practical training on energy efficiency and to trigger interactive mechanisms for the co-design of high quality energy and environmental technological solutions specific to the Mediterranean climate (Fig. 4).

Starting with the stated goals of reducing energy needs, a priority action in the implementation of the nZEB methodological framework (Crespo Sanchez *et al.*, 2023), the layout of the workshop (Fig. 5), provided an initial training phase to share a common methodology necessary to make informed decisions on context-appropriate and sustainable renovation actions (Osterreicher, 2018). In the following phases, a Participatory Energy Audit (Violano *et al.*, 2021) aimed at assessing overall conditions and energy and environmental performance of the build-


ROOFING FLOOR
GROUND FLOOR
EXTERNAL WALL
RETAINING WALL
WALL STAIRS
WALL STAIRS
CURRENT STATUS
PROJECT STATUS
REFERENCE BUILDING
DM 26/6/2015
roof
U: 0,35 W/m²K
window
U: 3,00 W/m²K
ground floor
U: 0,35 W/m²K
external wall
U: 0,43 W/m²K
HINGED DOOR WINDOW
THREE-LEAF SLIDING WINDOW
FLIP WINDOW
PERFORMANCE
SOUTH, EAST, WEST
NORD
PROPOSAL OF SHADING DEVICE FOR SOUTH FACADE AND TO ENSURE AN ADEGUATE NATURAL VENTILATION.
NORTH
SOUTH
STUDY OF DAYLIGHT - VELUX

06 | Keyplan of the "Energy Friendly Retrofit"

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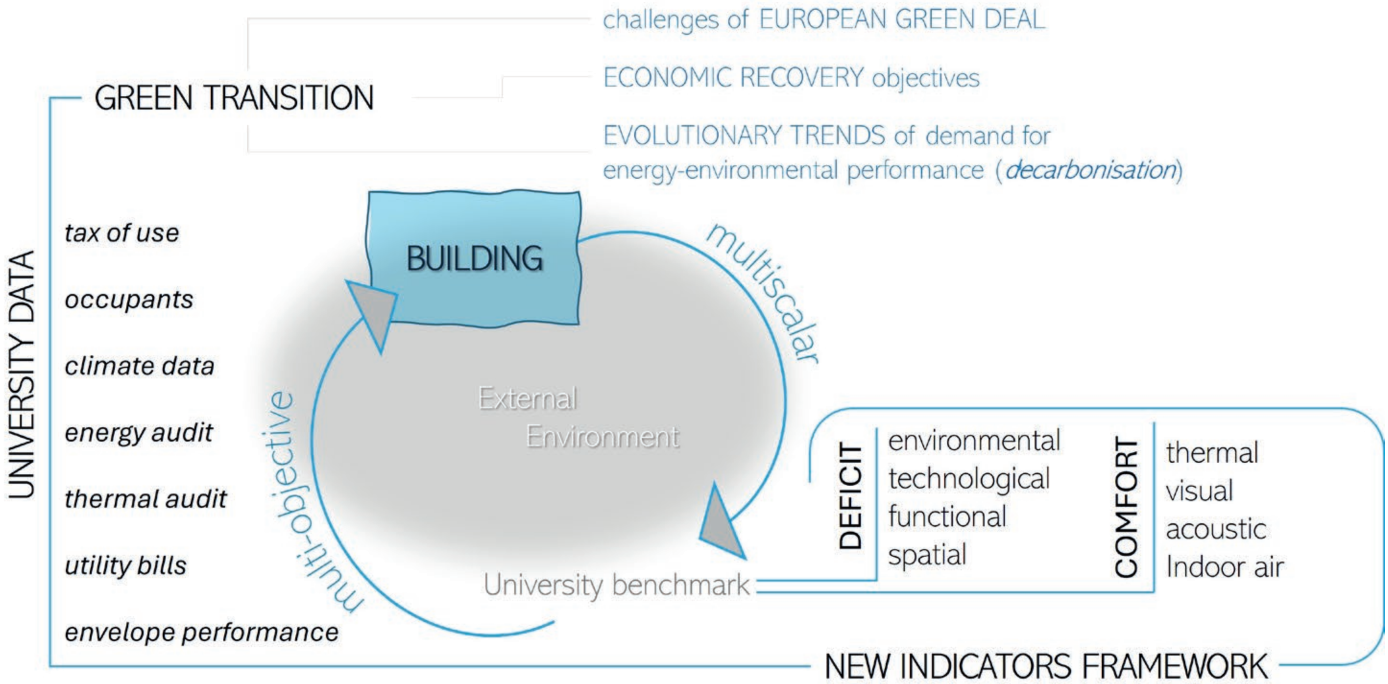


ing, led to the identification of the main critical points. Passive design strategies, appropriate to the specific contexts and user needs, were derived from the analysis through an active and dynamic comparison between students of different nationalities. Technological solutions are aimed not only at improving energy performance in the operational phase, but also at reducing environmental impacts in the life cycle, preferably using local low carbon materials and Nature Based Solutions (green roofs and façades) that can also benefit the surrounding context (e.g. reduction of the urban heat island), in line with decarbonisation goals for the building sector.

These events, which saw students and lecturers in the dual role of stakeholder and designer, introduced advanced design methodologies and technological tools, tested on pilot university buildings in the Mediterranean, but replicable in similar environments, integrating academic research with professional practice in different climatic and cultural contexts.

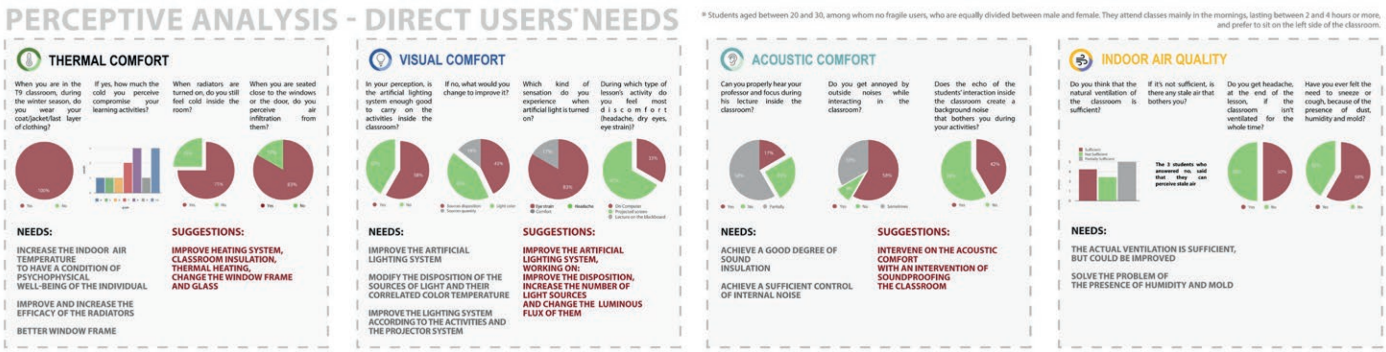
Renovation projects require a holistic approach that goes beyond the mere reduction of energy demand, and considers climatic conditions, indoor environmental comfort, embodied carbon and life cycle environmental impacts, without neglecting functional and spatial quality, involving stakeholders to effectively identify and address goals (Kamari *et al.*, 2017).

The direct involvement of students and academic staff in the rehabilitation of university buildings not only contributes to defining of effective technological solutions but also fosters cultural and behavioural change post-intervention, thereby strengthening the long-term success of decarbonisation strategies (Ahmed *et al.*, 2021).

Living Lab: a collaborative space for "sustainable energy Retrofit" and stakeholder engagement in university buildings

The MCbLL is not only a physical space for monitoring energy performance and evaluating the quality of the indoor environment in university buildings, but a virtual space for the involvement of local stakeholders (Evans *et al.*, 2015) in the evaluation of innovative solutions, improving the perception of opportunities offered by energy efficiency (Calcagno *et al.*, 2023; Trombadore *et al.*, 2023).

In addition to innovative pilot projects, Med-EcoSuRe ensures consistent and long-term stakeholder engagement, emphasising the participatory process and user-perceived comfort. «The most effective way of characterising living labs is probably to analyse actual experiences, and how they evolved over time» (Ballon and Schuurman, 2015). The Living Lab implemented by the UNICAMPANIA-DADI team tested the "Energy Friendly Retrofit" approach (Fig. 6) by combining user involvement (Ahmed *et al.*, 2021), experimentation in real-world contexts (Nansen, 2024; Quevedo *et al.*, 2024) and co-creation (Longoria

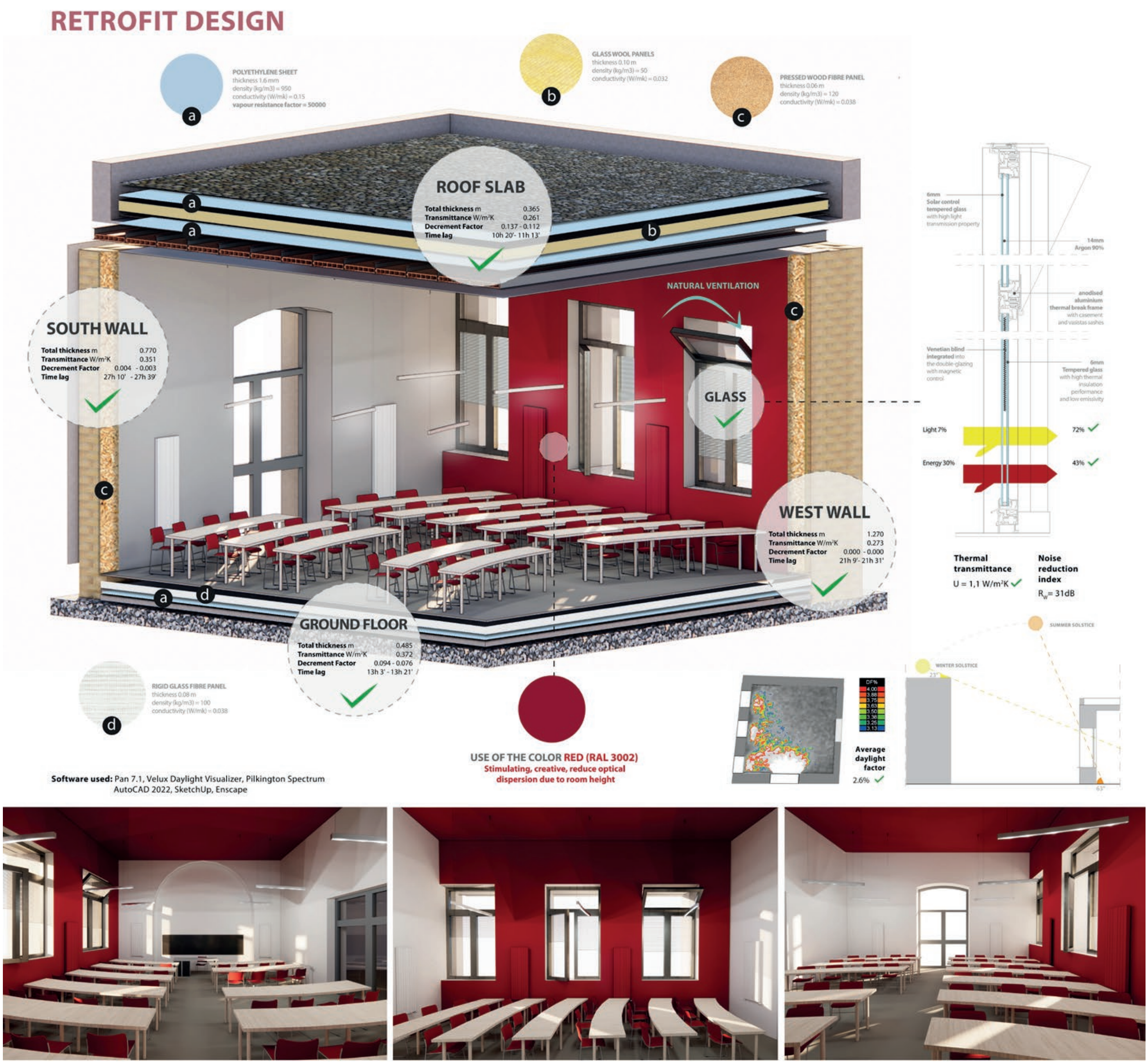


| 07

et al., 2021), which are useful for developing performance indicators and renovation strategies that promote well-being and environmental quality.
The LL, finalised to test the energy and environmental retrofit strategies for university buildings (according to MCbLL), has evaluated the measured and calculated quality of the energy consumption and performance of a university classroom (Phase A), in comparison with the quality perceived by students in relation to the comfort conditions experienced in this physical space (Phase B).
The case study is a university classroom located in climate zone C, with a useful surface area of 76 m² and a heated volume of 418 m³. In Phase A, the technical characteristics of the envelope exhibited notable deficiencies. The south wall, constructed with 71 cm thick tuff blocks, demonstrated a transmittance of 0,78 W/m²K and a time lag of 24 hours, effectively attenuating heat flow. However, the west wall, despite having a lower transmittance of 0,47 W/m²K due to its greater thickness (121 cm), has a lower time lag (18 hours), indicating less effective performance in terms of thermal stability. The roofing slab, constructed from girders, hollow blocks and bituminous sheathing, was identified as a particularly critical component, exhibiting a transmittance of 1.44 W/m²K and a time lag of only 7 hours. This proved to be the primary source of thermal dispersion within the structure. Additionally, the floor slab, with a transmittance of 1.75 W/m²K, was determined to contribute considerably to the overall energy loss.
Phase B was conducted in parallel with the technological analysis. A questionnaire was administered to a sample of 100 students, regular users of the classroom, to evaluate perceived comfort (Fig. 7). From a thermal point of view, the data showed that 100% of the respondents wear an overcoat in the classroom during winter, indicating the inadequacy of the envelope and heating system, and 83% perceive air infiltration from the windows and doors. In addition, 75% of the students judge the classroom to be uncomfortable even in summer, due to the absence of a cooling system. In terms of visual comfort, 58% consider the artificial lighting to be adequate, but 43% suggest changing its layout. 67% of respondents experience discomfort when using the video projector. With regard to acoustics, only 25% report difficulty in hearing the lecturer clearly, but 58% perceive external noises from the street as adversely affecting concentration. Finally, 58% of students report the presence of humidity, despite good natural ventilation in the classroom, which is limited by the impossibility to open windows due to external noise. The combined results of these analyses highlighted the need for a holistic approach to energy and environmental retrofit (Kamari *et al*., 2019; Sánchez *et al*., 2019). The different technological solutions proposed to adapt the university classroom to the requirements of the mandatory standard (Hu, 2018) were integrated and combined with reorganising design solutions for functional spaces, including the use of colour and greenery (Crespo *et al*., 2023).
The experimentation demonstrated the effectiveness of a model that integrates technological and perceptual analyses of users to design more effective and appropriate solutions. This participatory approach not only improves the quality of the built environment but also stimulates user awareness of the benefits of monitoring comfort conditions that are not solely instrumental. The results of the experimentation provide a replicable reference point for interventions on public buildings in the Mediterranean context, with significant implications for the energy and climate transition.

Conclusions: future perspectives and proposal for a coordinated international Living Lab

Building on the achievements of the Med-EcoSuRe project, the MCbLL intends to expand its network by incorporating new stakeholders, enhancing its ICT platform for knowledge-sharing, and broadening its scope to include diverse public buildings. Key innovations, such as digital twins and participative co-creation methodologies, 08 |



will remain central to its approach, facilitating real-life experimentation and adaptive solutions tailored to varying climatic and socio-economic contexts.

To achieve its ambitious goals, the Mediterranean Cross-border Living Lab (MCbLL) must overcome challenges such as fostering long-term stakeholder engagement across diverse contexts, securing the financial and technical resources needed for advanced tools and technologies, harmonising governance across a cross-border network, and ensuring sustained funding and effective commercialisation of innovations.

Nevertheless, the future potential of MCbLL is encouraging. The initiative aims to establish an international Joint Research Centre, which will facilitate long-term collaborations and guarantee the sustainability of results through training programmes, advisory services and development strategies. By capitalising on the potential of Euro-Mediterranean initiatives and focusing on capacity-building, the MCbLL has the potential to become a reference network for integrated and cross-border strategies.

NOTES

[1] Available at: https://www.enicbcmed.eu/projects/med-ecosure (accessed on 17 February 2025).

[2] Available at: https://medbexlive.org/ (accessed on 17 February 2025).

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