Energy retrofit with prefabricated timber-based façade modules: pre- and post-comparison between two identical buildings

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Abstract

The introduction of prefabrication into the building façade retrofit market is still difficult due to many financial, economic, and social constraints, as well as technical and performance requirements that differ from those of new construction. The technical feasibility, construction details, and actual comfort and energy-saving benefits provided by the installation of prefabricated façade modules are still being investigated, as is one goal of the specific case study presented here. The Renew-Wall project aims to create a new modular, timber-based, non-intrusive system for retrofitting buildings, developing a series of significant and fully customisable innovations compared to currently available solutions. This paper describes the main properties of the designed prefabricated façade system, with a focus on its energy and thermo-hygrometric performances. Simulation and laboratory tests are compared with an experimental analysis conducted on two identical mock-up buildings (test cells) during a two-year monitoring campaign in which only one of the two test cells was retrofitted. The results show simulated average annual energy savings of 67%, perfectly in line with what was measured on-site. The prefabricated façade system also demonstrates efficient vapour release and a reduced risk of mould and fungus attack.

Keywords

building façade retrofitting, timber-based façade, hygrothermal performance, building renovation, prefabricated construction

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1 INTRODUCTION

In the context of deep energy retrofit of buildings, which is defined as a renovation that captures the full economic energy-efficiency potential of improvement works to existing buildings, leading to a very high-energy performance (Shnapp, Sitjà & Laustsen, 2013), improving the performance of the building façade, even with prefabricated systems, is one of the most successful strategies for reducing overall energy consumption (Martinez & Choil). The number of European-funded projects involving prefabricated façade systems and deep renovation solutions is thus significantly increasing, and the literature (D'oca, Op 't Veld, & Tisov, 2017) demonstrates that significant efforts are being made to advance these solutions both technically and financially.

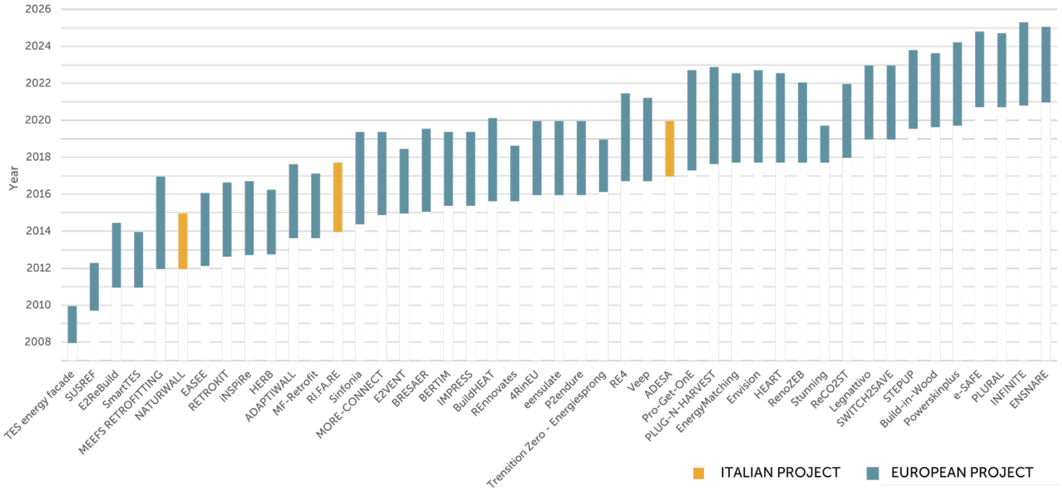


FIG. 1 List of funded European and Italian projects on prefabricated façade modules. The bars represent the duration of the projects.

Currently, prefabrication is widely used in new construction, involving prefabricated concrete staircases, windows, partition walls, and other components (Richard, 2005). Today, building façades can also be completely pre-assembled off-site, with a variety of materials, either timber-based (Callegari, Spinelli, Bianco, Serra & Fantucci, 2015; Capener, Burke, Le Roux & Ott, 2014), metal-based (Dannapfel et al., 2019; Torres et al., 2021) or with reinforced concrete (Pittau, Malighetti, Iannaccone & Masera,2017; Salvalai, Sesana & Iannaccone, 2017). Their benefits are widely discussed in literature, including cost, time, human resources, environmental sustainability (Teng, Li, Pan & Ng, 2018), materials, management and planning, and architectural design: compared to in-situ construction, they ensure less dependence on weather conditions, high quality, and fast assembly (Shahpari, Saradj, Pishvaee & Piri, 2020). Prefabricated façades can also incorporate elements of the HVAC system (Dermentzis, Ochs, Siegele & Feist, 2018) or intelligent control systems (Arnesano et al., 2019), resulting in a multifunctional component (Capeluto, 2019): an additional layer of thermal and acoustic insulation, a structural reinforcement to increase the seismic resistance of the building (Zanni et al., 2021), a component that can improve the hygrometric and air-tightness performance of the wall (Pihelo & Kalamees, 2021), or an element that gives the building a new and improved exterior appearance. The façade module can also include windows, glazing, and shading elements to control solar gain, illuminance, glare, and summer overheating.

Even though these benefits are valid for both new and existing building interventions, introducing prefabrication into the building retrofit market remains problematic. A number of financial, economic, and social barriers (D'Oca et al., 2018), as well as technical and performance requirements, still exist despite interesting innovations in incentives and business models to accelerate the implementation of the integrated product (Azcarate-Aguerre, Heijer & Klein, 2018). Prefabricating is indeed difficult when dealing with constantly changing starting conditions, and designing façade components that can be easily adapted to each experimental use case is still a challenge (Kasperzyk, Kim & Brilakis, 2017), whether in terms of the appropriate materials to be used, the integration of HVAC systems and shading elements or, more generally, the overall relationship to the existing context. This is especially true in Italy, where the built environment displays a wide range of varieties and shapes as a result of its extensive architectural history (Alfano & de Santoli, 2017) and where research on prefabricated façade systems is still limited, not least for this very reason (Fig.1).

The real concern for stakeholders in this field, however, is still to understand the actual energy consumption savings achieved by installing these systems. Many researchers have already contributed to this topic. Silva et al. (Silva, Almeida, Bragança & Mesquita, 2013), using a dynamic simulation model, vary a façade panel's insulation thickness to improve its thermal performance. The panel is then installed and tested on a test cell façade, while the analysis on a real building is conducted using the calibrated simulation model. De Masi et al. (De Masi, Ruggiero & Vanoli, 2021) also work on test cells, conducting thermal analysis of a prefabricated façade at different times of the heating season and with different types of actual outdoor conditions (wind, rain, solar radiation). Paiho et al. (Paiho, Seppä & Jimenez, 2015) describe the advantages of these systems in terms of reducing heating energy consumption in cold climates, not limiting the discussion to the contribution of the insulation layer but including the technological elements that can be included in a prefabricated façade module. Li et al. (Li et al., 2018) work on the construction details, paying particular attention to limiting a façade panel's heat loss, also considering thermal bridges. The panel is then tested in a building whose internal microclimate is monitored for an entire year. The study of thermal bridges is also crucial for Evola et al. (Evola, Costanzo, Urso, Tardo & Margani, 2022), who illustrate significant reductions in mould growth and surface condensation risks due to the higher internal surface temperatures achieved by installing a prefabricated panel on the façade of a pilot building. Bagarić et al. (Bagarić, Banjad Pečur & Milovanović, 2020) monitor the temperature and relative humidity distribution inside a building after the application of a prefabricated ventilated sandwich panel, albeit without a direct comparison with the pre-retrofit condition. Such a comparison can be found in Höfler et al. (Höfler, Knotzer & Venus, 2015), where the retrofit process of a building is described in detail, exploring the pre- and post-construction issues.

However, in all examples presented here and in all those known to the authors, the pre-post retrofit comparison is always made on the same building, before and after the efficiency intervention, and therefore at different times and under different climatic conditions. This methodology risks making the analysis misleading because different boundary conditions can strongly influence the comparison, even when using calibrated simulation models. To close this gap and methodologically enhance the assessment of energy and indoor microclimate improvements made by prefabricated façade systems, this paper compares two identical buildings: one retrofitted with a prefabricated façade and one without any improvement. The retrofit of the first mock-up is carried out with a new, non-invasive timber-based façade module developed specifically for retrofitting existing buildings as part of the "Renew-Wall" project. The system offers customisable modules based on the variety of shapes of existing Italian buildings. It is designed to optimise prefabrication processes to achieve a cost-effective product even compared to conventional energy improvement strategies (ETICS, window replacement, and new CMV systems (Controlled Mechanical Ventilation)). The Renew-Wall system was validated with a two-year environmental monitoring campaign. In the first year, the two mock-ups, without any high-performance thermal design solution, were put under the same starting conditions, to verify their similar behaviour. In the second year, with the prefabricated façade installed on one of the two buildings, the actual energy consumption savings and thermal performance improvement provided by the system were measured and compared with the non-retrofitted case. This paper describes the main properties of the designed prefabricated façade system, focusing on its energy and thermo-hygrometric performance. The definition of these performances was also aimed at obtaining the ETA (European Technical Assessment), a technical assessment of the product's suitability for use, issued by ETA-Danmark, a company accredited as a Danish TAB (Technical Assessment Body).

The paper is organised as follows: Section 2 describes the prefabricated façade module in all its features, underlining the choices behind its design. Section 3 focuses on its thermo-hygrometric performance, illustrating the simulations and laboratory tests conducted on the panel and discussing the results. Section 4 describes and reviews the experimental monitoring campaign of the two identical buildings, with a detailed comparison between the monitored data on real buildings and the simulations conducted on the panel in the previous section. Section 5 lists the innovative aspects of the research work and its future developments.

2 CHARACTERISATION OF PREFABRICATED FAÇADE MODULES

The Renew-Wall prefabricated façade system comprises four different modules, which vary according to the façade portion of the building to be retrofitted (Fig. 2).

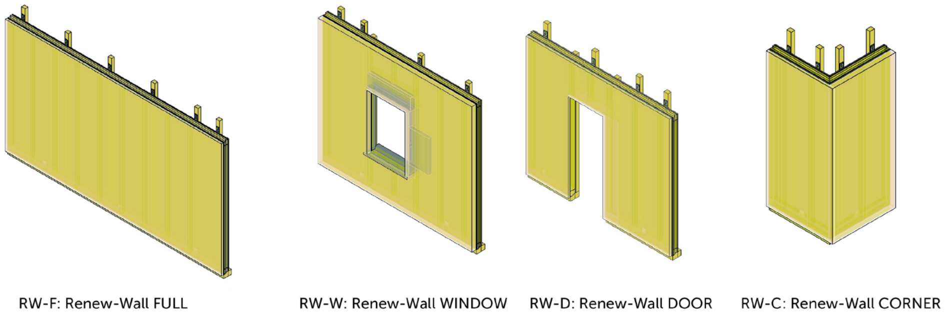


FIG. 2 The four different modules of the Renew-Wall system. Image courtesy of LAMARC Laboratory, University of Trento.

The load-bearing structure consists of a wooden frame with an upper and lower plate and vertical studs arranged at regular intervals, varying in number depending on the length of the panel, and with an insulating layer in between. The frame is reinforced by an OSB (Oriented Strand Board) panel on the inner side and a DWD panel – a vapour-permeable wood-fibre board that can be used as rigid underlays or façade panels – on the outer side to promote vapour transpiration. The next layer on the inner side is a low-density insulating levelling layer of varying thickness depending on the geometric unevenness of the wall to be covered, and the next layer on the external side is an additional insulating layer to achieve the required U-value transmittance. Different types of finishing are available, from plaster with different colour gradations to ventilated façade systems, which are highly customisable in material and texture (Fig. 3).

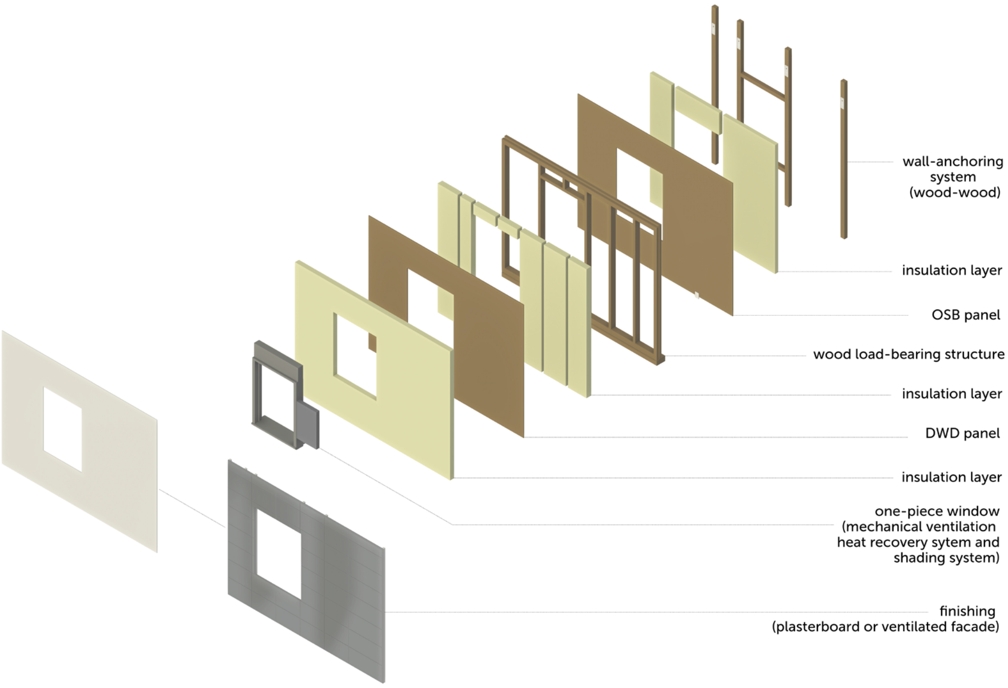


FIG. 3 Exploded isometric view of Renew-Wall Window module components. Image courtesy of LAMARC Laboratory, University of Trento.

Table 1 shows the thermal properties of the Renew-Wall FULL panel (RW-F).

TABLE 1 Thermal properties of the Renew-Wall Full module

Renew-wall RW-F module layers [inside to outside]	Thickness [m]	Thermal conductivity [W/mK]	Specific heat [J/KgK]	Density [Kg/m³]
Mineral wool	0.08	0.038	1030	30
OSB	0.015	0.13	1500	615
Wood structure + mineral wool	0.12	0.05	110	500
DWD	0.016	0.09	2100	615
ETICS (mineral wool)	0.1	0.038	1050	100

Two alternatives (Fig. 4) were designed for the structural connection to the existing wall.

- Wood-wood solution, for load-bearing masonry buildings, realised by anchoring with a plate (240 x 80 x 6 mm) to wood studs that are fixed to the building before the panel is installed.
- Halfen-type solution, for concrete-framed buildings, made with two plates, one C-shape (170 x 86.2 x 6 mm) and one Omega-shape (60 x 170 x6 mm). On the metal plate connected to the Renew-Wall module, there are a series of holes in which to insert the connecting screws, and a horizontal slotted hole, to allow for adjustments, in which to insert the “HZS-type” fixing screw.

An additional stabilisation system with metal plates is provided to facilitate the placement of the panel during installation and to limit out-of-plane movements. The designed anchoring systems and the high flexibility in module sizing allow the application of panels of different heights and widths.

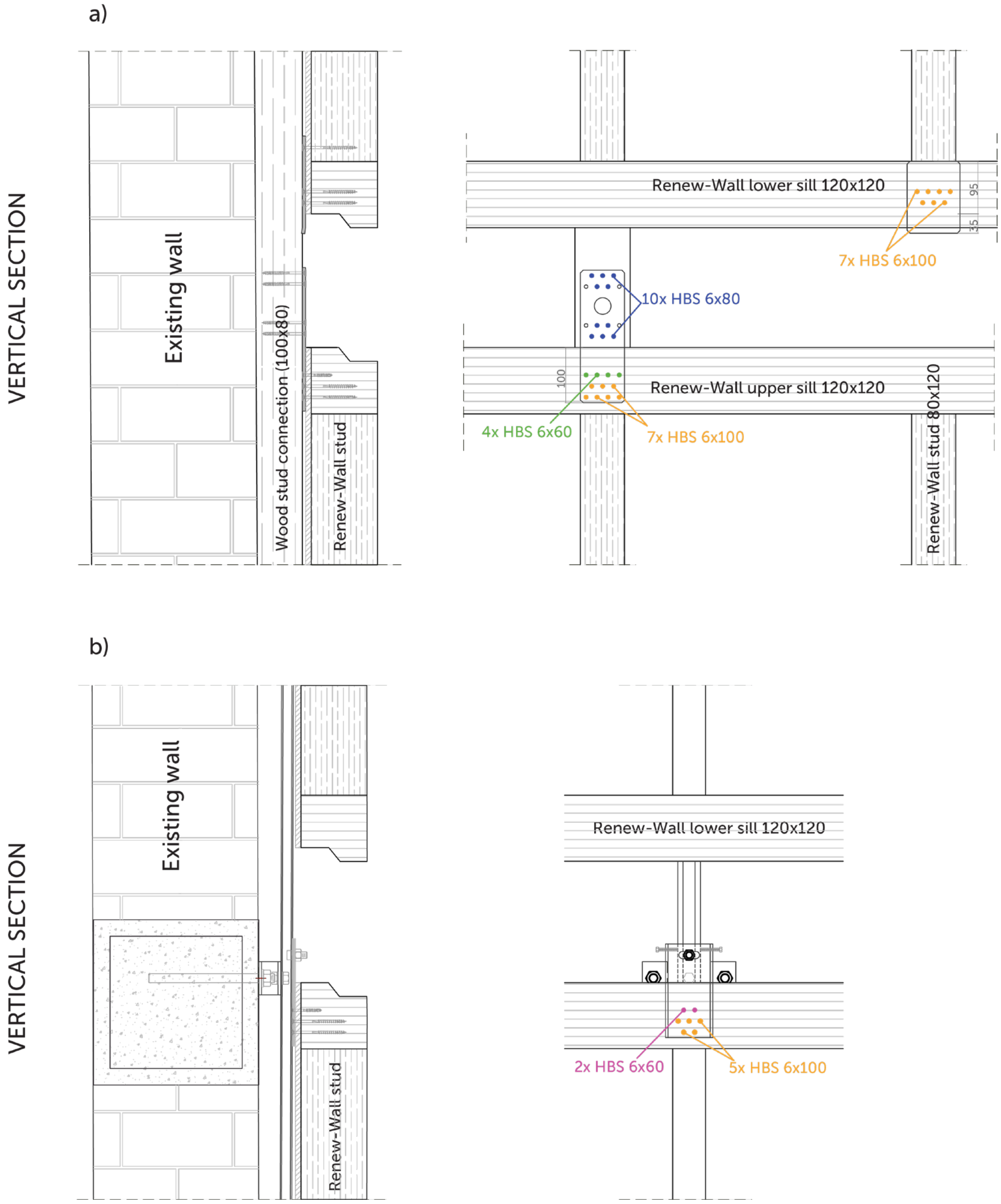
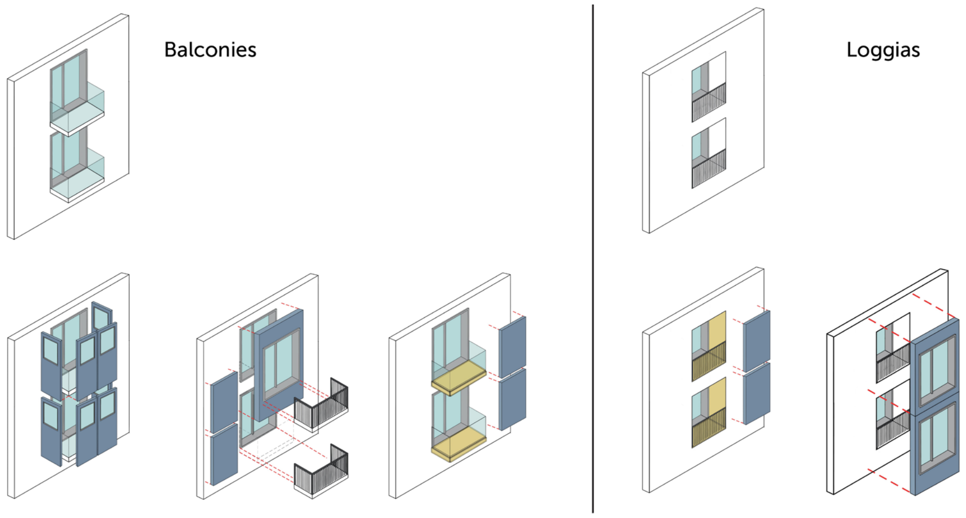


FIG. 4 Renew-Wall structural connection to the existing wall: a) wood-wood solution; b) Halfen-type solution.

With the Renew-Wall panel, the aim was to condense three energy-efficiency solutions for existing buildings into a single intervention: insulation, new CMV systems, and window shading. The following detail elements were designed:

- Window casing
- Embedded Heat Recovery Mechanical Ventilation (HRMV) system
- Shading system
- Wired electrical connections
- Wall gasket system
- Wall joint covers
- Drip Profiles
- Wall baseboards

Although a case-by-case analysis is needed to determine whether the thickness of the newly retrofitted exterior wall can reduce the amount of sunlight entering the building, the one-piece window embedded in the wall panel is perfectly in compliance with Italian and European regulations on thermal behaviour for different climate zones. The HRMV machine – an already marketed product – has a reduced thickness (H x W x T: 830 x 510 x 80 mm) and seamlessly integrates with the external insulation, with minimal impact on the building layout, ensuring the highest levels of indoor comfort. This makes it possible to maintain the size of the existing windows while providing adequate thermal insulation, integrate the HRMV machine while minimising masonry work, and eventually restore existing shading systems. The window casing allows the integration of different solutions for the shading system to filter sunlight according to preferences and needs. Each solution considered can be included in the overall panel thickness, assuming a minimum outer insulation layer of 100 mm or even reducing it if HRMV does not need to be installed. Electrical connections for blinds, HRMV systems, outdoor electric lighting, and alarm systems can also be easily integrated into the panel. To ensure water and wind tightness, Renew-Wall panels include a double gasket system. Along the perimeter of the panel, on the outer side, is a joint metal cover with both an aesthetic and protective function. There is also a drip profile at the bottom of the panel for rainwater drainage. The Renew-Wall system finishing includes an insulated baseboard at the very base of the building, applied directly to the building before the panels are installed. Its thickness is compatible with the Renew-Wall panel and adapts to a potential unevenness of the existing wall. A preliminary study was also conducted on retrofit methods for balconies and loggias. Figure 5 shows the results of the analysis with prefabricated façade modules indicated by dark grey colour. However, for these parts of a building, traditional techniques are still preferred for simplicity and speed of application.



Conversion of the balcony into a loggia through façade modules

Application of façade modules and replacement of the existing balcony with a new prefabricated one

Traditional balcony insulation + facade modules

Traditional loggia insulation + façade modules

Closed loggia with façade modules

FIG. 5 Potential solutions for retrofitting balconies and loggias with prefabricated façade modules (b).

The installation of prefabricated façade systems also requires another set of procedures and checks to ensure that the work is done correctly. One of the first steps is to accurately survey the building's measurements using tools such as laser scanners or photogrammetry. With this information, a BIM (Building Information Modelling) model of the building can be created, allowing the exact components needed for installation to be designed and manufactured in the factory, which can be virtually pre-assembled on a digital twin for more efficient and accurate installation on site.

The Renew-Wall modules, as shown in Figure 4, are developed to be hung and positioned from top to bottom using a crane and skilled workers, avoiding the need for scaffolding and reducing material waste. The installation is done outside the building, so there is no need for indoor work other than removing existing windows, all the finishing around them and eventually creating a hole for the CMV system. Installation tolerances are largely solved through the digital twin of the building that is made before installation and assembly with an accurate laser scanner survey. However, additional compensation is provided at the depth level (z-axis) thanks to the low-density insulation panel behind the structural layer that absorbs irregularities in the existing wall and at the façade level (x- and y-axes) thanks to the detailed design and flexibility of the previously described structural connections that allow partial roto-translation of the panel itself before fixing.

3 THERMO-HYGROMETRIC PERFORMANCE

3.1 HYGROMETRIC BEHAVIOUR

To achieve efficient vapour release, the values of the air layer thickness equivalent to water vapour diffusion ("sd") were decreased from the inside to the outside of the wall. For this reason, an OSB (Oriented Strand Board) panel is applied as a vapour retarder in the inner part of the wall, while the outer part comprises a DWD panel – an MDF (Medium Density Fiber) vapour-permeable wood-fibre board –, which makes the wall breathable due to its vapour permeability characteristics (water vapour resistance factor "μ" = 11). To corroborate these design choices, some laboratory tests were conducted by the Institute of BioEconomy, IBE-CNR from San Michele All'Adige (TN, Italy), on the façade panels, analysing their water and air tightness, which were found to comply with the requirements of the UNI EN 12865, UNI EN 1026:2016, and UNI EN 12114:2001. Moreover, details of the wall and joints were analysed using WUFI 2D software (Fig. 6). Water tightness between the panels is solved by two different levels of gaskets. Since the connection between the wooden structural part of the two panels is currently under patent application, the detail is darkened in Figure 6, and the horizontal section is not present in Figure 4.

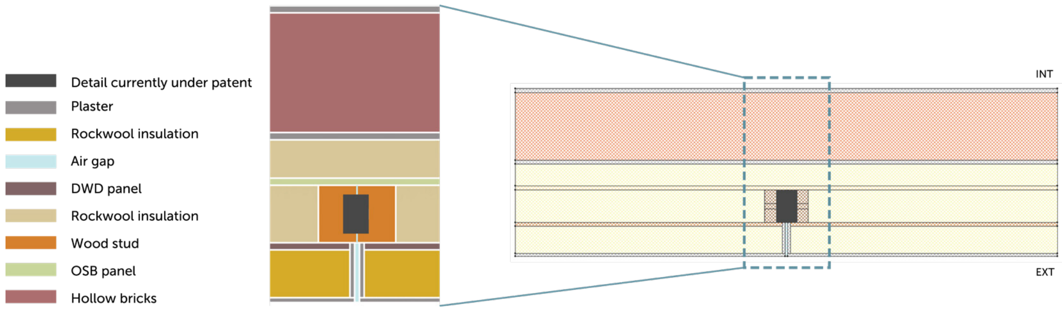


FIG. 6 Detail of the panel-to-panel connection (a) and its modelling in WUFI (b).

Material properties, starting water content and relative humidity conditions for each material, a calculation grid adapted to the geometry of the simulated component, and weather conditions were set by cross-referencing data from data sheets and the software database. The weather file compiled from actual monitored data (see Section 4) was used as the outdoor reference; indoor conditions were set according to UNI EN ISO 15026, internal humidity class 3. The following were assumed: a north orientation of the wall, which is more damaging given the absence of solar radiation; a building height of less than 10 m; a pitched roof with rain load as prescribed by ASHRAE Standard 160. The running period of the simulations is 3 years.

The results show that the water content decreases over time, attesting to the ability of the façade panel to dry out during the simulation period (Fig.7).

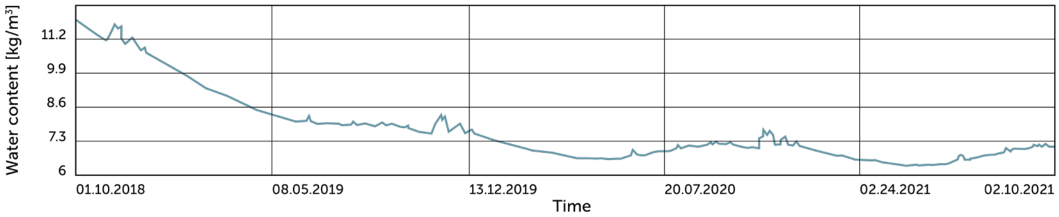


FIG. 7 Water content of the simulated detail (Fig.6) over 3 years of simulation.

The limits prescribed by WTA recommendations (International Association for Science and Technology of Building Maintenance and Monuments Preservation, 2014) regarding moisture content in wood materials are met. Figure 8, for example, shows that by cross-referencing moisture and air temperature values through the WTA conversion table, simulated wood humidity values in the load-bearing panel can be plotted on an XY space (plotted in black). These values always fall within non-risk areas, represented in the graph by a colour scale ranging from green (low risk = wood humidity 0%) to red (high risk = wood humidity 30%).

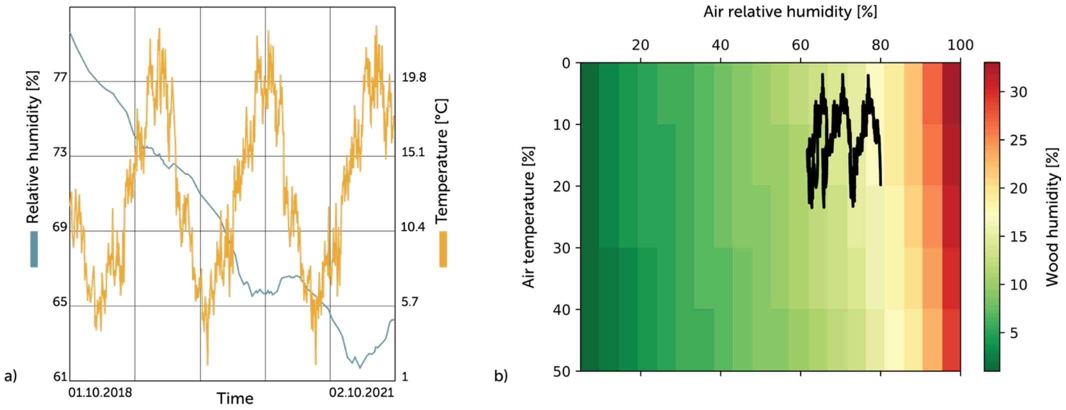
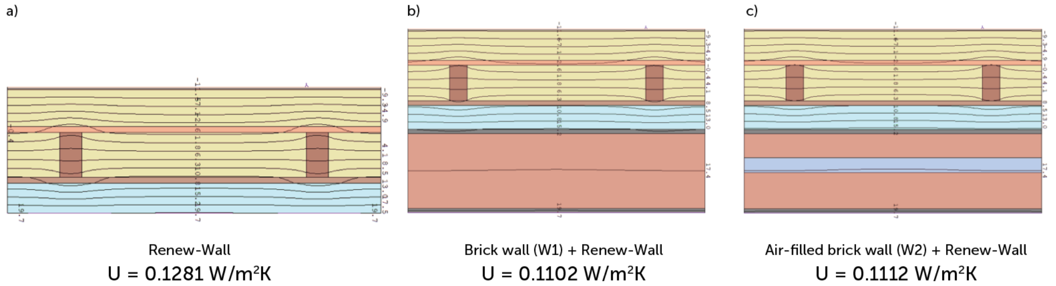


FIG. 8 Simulated (WUFI) air temperature and relative humidity inside the structural wood stud of the Renew-Wall panel (a); correlation between these values and wood humidity according to WTA recommendations (b).

The simulated humidity values for wood components are such that any risk of mould and fungus attack is avoided. The highest values are found in the first year of the simulation, where the initial moisture has to be balanced with the ambient moisture, which, on average, is always lower. These results can be considered valid only when related to the simulation input data, especially the characterisation of the materials and the environmental conditions set. Only small air-filled volumes were modelled, assuming perfect adhesion of the low-density levelling insulation layer to the existing wall. Otherwise, the potential presence of additional air gaps could alter the obtained results. In Section 4, simulated values can be compared with those measured on-site.

3.2 THERMAL PERFORMANCE

The wall stratigraphy described in Table 1 helps meet very low thermal transmittance values as there are a total of three layers of thermal insulation: one between the panel and the existing building, one inside the wooden frame, and one in the outer finishing layer. High standards of energy certification can be accomplished, even for buildings with poor thermal starting performance. Environmentally sustainable and biocompatible materials suitable for obtaining major sustainability certifications were selected. The thermal behaviour assessment was conducted using a finite element simulation software, THERM LBNL (Fig.9). The design thermal transmittance "U" Renew-Wall panel, considered without the existing wall behind, is 0.1281 W/m^{2}K, a value comparable with a high-performance building component.



Renew-Wall
U = 0.1281 W/m²K

Brick wall (W1) + Renew-Wall
U = 0.1102 W/m²K

Air-filled brick wall (W2) + Renew-Wall
U = 0.1112 W/m²K

FIG. 9 Finite element simulation of the Renew-Wall panel (a), the panel mounted on the W1 wall (b), and the panel mounted on the W2 wall (c).

Considering the application of the panel on two different existing brick walls (Tab. 2), typical for buildings in Italy from the 1960s-1970s to be retrofitted, the values are confirmed to be excellent (Fig. 9b and Fig. 9c).

4 EXPERIMENTAL ANALYSIS IN TEST CELLS UNDER ACTUAL OUTDOOR CONDITIONS

To test the actual thermo-hygrometric performance of the Renew-wall system under real outdoor conditions and for some experimental tests on the assembly of the façade modules, two small test cells were designed and built in Malosco (TN), Italy, in an area free of shading obstacles (Fig.10).

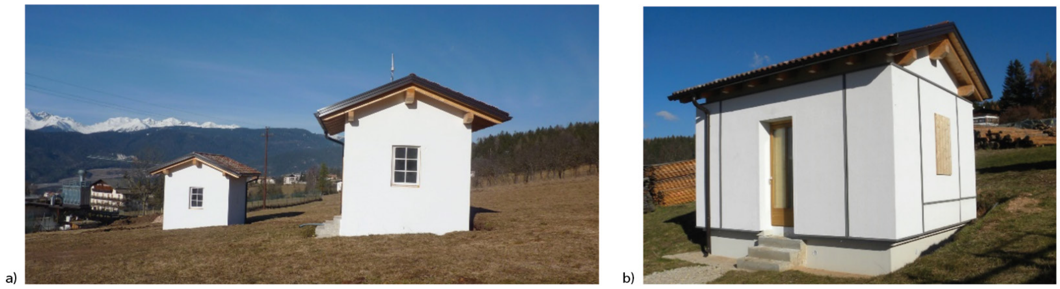


FIG. 10 Test cell A, in the background, and test cell B before retrofit (a); test cell A after retrofit (b).

Test cells are facilities which fill the gap between laboratories and full-scale buildings, allowing to keep all the necessary indoor condition under control, while letting outdoor conditions vary as in the real environment (Cattarin, Causone, Kindinis & Pagliano, 2016). The primary use is for testing building envelope systems, but given the nature and the equipment of the test facility, the interaction between building envelope systems and HVAC terminal units can also be investigated (Goia, Schlemminger & Gustavsen, 2017).

The positioning and the distance between the test cells were optimised in advance using software applications (Ladybug tools) to minimise mutual shading throughout the year. Also, considering the topography of the construction site, a distance of approximately 9 m between one cell and the other avoids any mutual interference. The installation was realised in an open green space, free of any other building. The dimensions of the cell floor plan are approximately 12 m^2 with a volume of 35 m^3 and a height at the roof ridge of 3.6 m (Fig. 11).

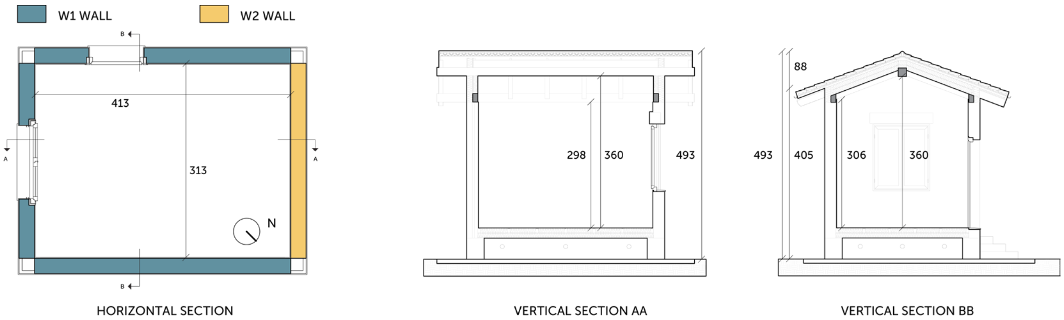


FIG. 11 Horizontal and vertical sections of test cells A and B before retrofit (values in centimeter).

The two mock-up buildings are the same in terms of shape, size, construction materials, exposure, and HVAC system to ensure perfect comparability. Their construction details reflect the typical buildings from the 1960s-1970s that are the main target of retrofit interventions in Italy. Two walls, the one facing northeast and the one facing northwest, were monitored more in-depth. Their thermal properties are shown in Table 2.

TABLE 2 Thermal properties of test cell walls before retrofitting

		Thickness	**Thermal conductivity**	**Thermal resistance**	**Specific heat**	**Density**
Wall type	**Wall layers (inside to outside)**	**[m]**	**[W/mK]**	**[m^{2}K/W]**	**[J/KgK]**	**[Kg/m^3]**
Wall W1	**Plaster**	0.015	0.55	-	850	1530
	Hollow bricks	0.25	0.181	-	840	908
	Plaster	0.015	0.55	-	850	1530
Wall W2	**Plaster**	0.015	0.55	-	850	1530
	Hollow bricks	0.08	0.212	-	840	942
	Air gap	0.05	-	0.168	-	-
	Hollow bricks	0.12	0.206	-	840	958
	Plaster	0.015	0.55	-	850	1530

To limit upward and downward heat losses and thus focus the performance analysis on the walls, the ground floor and roof are strongly insulated (U = 0.15 W/m^2K). There is only one window, on the southeast wall, which is necessary both to allow ventilation and to test the installation of the RW-W panel solution. The shading system consists of a simple removable external wooden panel. A further opening, on the southwest side, provides access to the building. The heating system consists of an electric fan coil – maximum power 2500W – with adjustable temperature set-points.

The two buildings were monitored for two years. During the first, the identical behaviour of the two cells was demonstrated; in the second year, after the installation of the Renew-wall panel on only one of the buildings, the energy savings and the different thermal performance of the retrofitted test cell were verified. This allowed the comparison of two identical buildings, except for the addition of the Renew-Wall panel on one of the two, under the same indoor and outdoor climatic conditions. Examples like this are extremely rare in the literature because the pre-post retrofit intervention comparison is usually made on the same building in different years and, therefore, with different climatic conditions.

The monitoring system, more extensively described in (Callegaro & Albatici, 2021), includes sensors to monitor the thermal performance of the envelope (Fig 12a):

- Flow meters and temperature sensors, both surface and layer-by-layer, for the northeast and northwest walls;
- Surface temperature sensors for the roof and the ground floor – the indoor environmental conditions;
- T-UR-CO2 sensor – and the external weather data;
- T-UR, wind speed and direction, horizontal radiation.

Table 3 describes the specifications, accuracy, and precision of the sensors. An energy meter measures the consumption of the heating system.

TABLE 3 Technical specifications of installed sensors

		Sensor	Range	Precision	Accuracy
Surface temperature - Wall		PT100	-50 … +180°c	0,1 °C	±0,3°C
Surface temperature - Roof		NTC 10 kΩ @ 25 °C	-40 … +105 °C	0,1 °C	0+70°C: ±0,3°C; outside 0+70°C: ±0,4°C
Surface temperature - Floor		0.015	0.55	850	1530
IEQ sensor	**Temperature**	Thermistor NTC 10 kΩ	0 … 40°C	0,1 °C	±0,5°C
	Relative humidity	Capacitive	0 … 95 %	1%	± 3 %UR
	CO2	Non-dispersive infrared (NDIR)	0 … 2000 ppm		400-1000 ppm: ± 75 ppm or 3% of the reading; 1000-2000 ppm: ± 40 ppm or 5%
Weather station	**Temperature**	NTC 10 kΩ @ 25 °C	-40 … +105 °C	0,1 °C	0+70°C: ±0,3°C; outside 0+70°C: ±0,4°C
	Relative humidity	Capacitive	0 … 100 %UR	0,1 %	± 1,8 %UR (0 … 85 %UR) / ± 2,5 %UR (85 … 100 %UR) / ± (2 + 1,5% reading) %@ T=others
	Wind velocity		0-50 m/s	0.1 m/s	
	Wind direction		0-359°	1°	
	Solar radiation	Pyranometer	0-1800 W/m^2	1 W/m^2	

The Renew-wall panel was also equipped with temperature and humidity sensors positioned both on the structural studs (Fig. 12b) and in the central part in each layer, mainly to verify the absence of risk of condensation or fungus attacks, which were previously simulated.

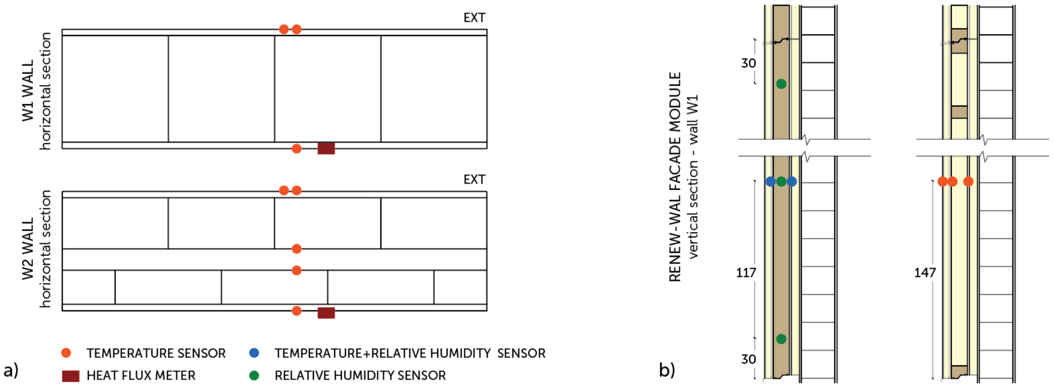


FIG. 12 Sensor's location on the walls (a) and Renew-Wall panel (b)

Figure 13a shows the indoor temperature trend during a summer week without a running HVAC system. Figure 13b shows the heat flux for the northwest wall during a winter week, and Figure 13c the energy consumption in the two cells for the month of February of the first monitoring year, which is considered representative.

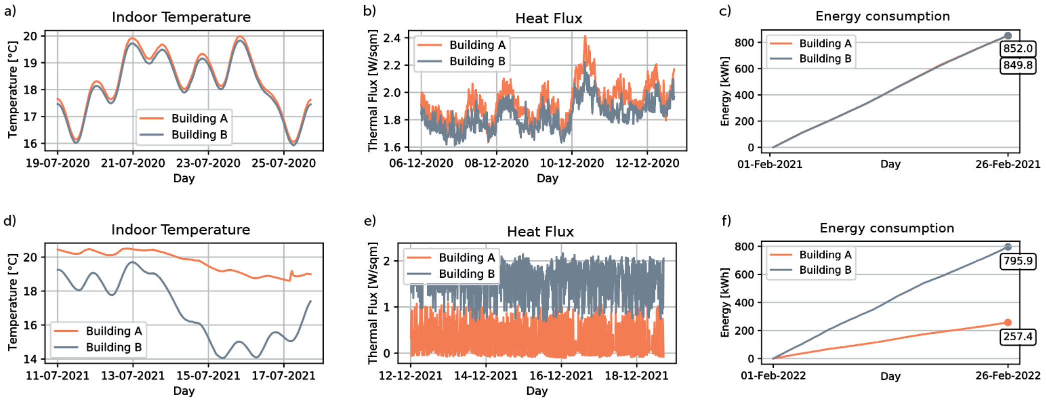


FIG. 13 Comparison between indoor temperature, heat flux for the northwest wall, and energy consumption before (a-b-c) and after (d-e-f) retrofit. The retrofitted building is building A.

These trends are compared with post-retrofit ones (Fig. 13d-e-f) in the same period the following year. The Renew-Wall façade panel is applied to building A. Figure 13a shows the perfect alignment of the thermal behaviour of the two non-retrofitted cells. Figure 13e shows the reduction in terms of measured heat flux for one of the monitored walls, while 13f reveals the enhancement brought by the installation of the Renew-Wall panel in terms of energy consumption. Focusing on this aspect, Table 4 shows that the average monthly saving is about 65%. The analysis also covered all other monitoring months and all other monitored variables not shown here.

TABLE 4 Difference in energy consumption between the two test cells after retrofit of cell A (second year of monitoring)

	Test cell B	Test cell A	
Months	**Energy consumption [kWh]**	**Energy consumption [kWh]**	**Energy savings [%]**
October	501.7	168.7	66.37
November	843.3	231.0	72.61
December	865.5	323.3	62.65
January	735.0	335.4	54.37
February	795.9	257.4	67.66

To check whether the pre- and post-retrofit energy consumption could already be predicted by simulation, two energy models were realised, one in semi-steady state and one in dynamic state conditions, using TERMUS and EnergyPlus software. In the latter case, the model was calibrated using monitored data. An *epw* weather file was created with data collected from the weather station installed on the roof of one of the two test cells while the building was modelled, taking into consideration the data sheets for the building materials and for the electric fan coil unit. The heating system schedule was set up based on the monitored heating fan coil performance data. Since no one lived in the test cells, internal loads were not modelled. The values obtained from the on-site blower-door test were included to simulate infiltration. Model calibration was performed after a series of sensitivity analyses on the variables with the largest discrepancies by comparing the indoor ambient temperature data and the energy consumption of the heating system, respecting the limits of Normalised Mean Bias Error (NMBE) and Root Mean Square Error (RMSE) coefficient of variation defined by the standard (ASHRAE Guideline 14, 2014). The results show an energy saving of 35% in the case of the semi-stationary simulation, which is known to be less accurate, and an average annual saving of 67% through dynamic simulation, perfectly in line with what was measured on-site. These results may not be representative of other buildings as well since the test cells are not inhabited, and the thermal loads are not comparable to actual buildings, but they still represent a valuable benchmark for future work.

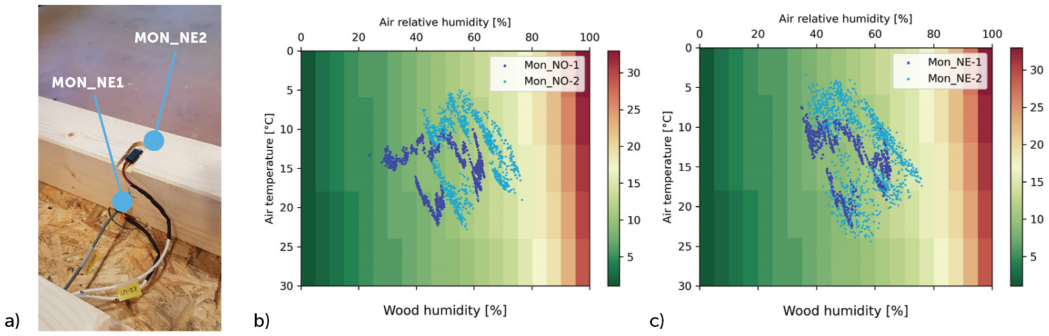


FIG. 14 Temperature and relative humidity sensors on the wood structural stud of the northeast Renew-Wall panel (a); Measured values of air temperature and relative humidity correlated with wood humidity (according to WTA recommendation) for the wood stud of the northeast (b) and northwest (c) Renew-Wall panel.

The monitoring of the hygrometric performance of the façade panel also confirmed what was simulated during the design phase. The graphs in Figures 14a and 14b, realised following what was done for Figure 8, show the air temperature and relative humidity data monitored in two structural wood studs (northwest wall: MON_NO; north-east wall: MON_NE) over a period of one year. The sensors were placed during the construction of the panel before the on-site installation

(Fig. 14a). The measured values, plotted in blue and light blue in Figures 14b and 14c, are even less worrying than the simulations (Fig. 8b), which represents the worst-case scenario.

Through heat-flux meters mounted on the two northeast and northwest walls, the actual thermal transmittance was measured to compare it with the simulated one. The analysis lasted 7 days, from Dec. 27, 2020 for the non-retrofitted cell and from Oct. 24, 2021 for the cell with Renew-Wall panel. Table 5 summarises the comparisons for both designed and actual thermal transmittance.

TABLE 5 Designed and measured thermal transmittance of the two walls of test cell A before and after retrofit

Designed thermal transmittance [W/m^{2}K]	**PRE-RETROFIT**		**POST-RETROFIT**		**Percentage reduction**	
	Wall W1	**Wall W2**	**Wall W1**	**Wall W2**	**Wall W1**	**Wall W2**
	0.62	0.735	0.111	0.114	82.1 [%]	84.5 [%]
Measured thermal transmittance [W/m^{2}K]	**PRE-RETROFIT 7 days of analysis from December 27, 2020**		**POST-RETROFIT 7 days of analysis from October 24, 2021**		**Percentage reduction**	
	Wall W1	**Wall W2**	**Wall W1**	**Wall W2**	**Wall W1**	**Wall W2**
	0.6317	0.9361	0.1551	0.3606	75.5 [%]	61.5 [%]

There is a negligible discrepancy for the W1 wall, while in the air-filled brick wall (W2), the air gap has probably led to convective air movements that have affected the measurement: the on-site thermal transmittance is higher than the designed for both the building without and the building with the Renew-wall panel. The percentage reduction is highlighted in the rightmost column of Table 5.

These differences, in terms of heat flux, between before and after renovation, are also clearly highlighted by thermographic images taken during the winter season of the second year of monitoring (Fig. 15). The images were captured with the NEC Avio Handy Thermo TVS-200EX, with an outdoor temperature between 2 and 3°C and an indoor temperature of about 21.5°C. The emissivity of the envelope surface was set at 0.95. In Building B, heat losses are evident at masonry mortar joints and at major thermal bridges. In the retrofitted building, the only small surface temperature variations occurring are visible at the joints of façade modules.

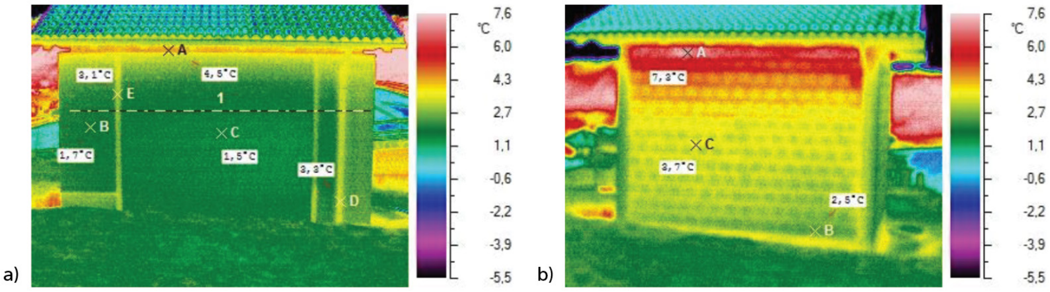


FIG. 15 A comparison between thermographic images: retrofitted test cell A (a) and test cell B (b).

5 CONCLUSION

The research carried out and described in the previous sections involved the design and testing of a prefabricated timber-based façade panel for building retrofitting purposes, developed within the Renew-Wall project. The project addressed different aspects of the design of a prefabricated module, from its prototyping to its site installation and characterisation in terms of thermal, acoustic, structural and fire resistance, air-water tightness performance and life cycle assessment. This paper, specifically, describes the energy and indoor microclimatic simulation and monitoring analysis of the Renew-Wall system, both in laboratory tests and in two experimental test cells. The comparison between two identical buildings, of which only one was later retrofitted with Renew-Wall panels, allowed the researchers to understand the strengths and weaknesses of the system, with particular regard to thermal, hygrometric, and energy performance. In literature, the assessment of the benefits of energy efficiency retrofit solutions is usually carried out by monitoring a single building before the retrofit intervention, e.g., for one year, and then, the following year, by monitoring the same building, renovated. In this way, however, the boundary conditions are different: for example, outdoor weather conditions can vary from one year to the next, or the occupancy and internal gains schedules, which certainly change between two monitoring campaigns, affect the building's thermal performance differently. Instead, in this specific case study, two identical buildings were compared, verifying for one year their performance was the same and then retrofitting only one of the two, thus making the comparison as objective as possible. The test cells were extensively monitored, and two years of data were collected on indoor and outdoor microclimatic conditions and heating consumption. The results show that the Renew-Wall panel has an excellent thermo-hygrometric performance, reducing the monitored building's energy consumption by 67%. The absence of mould and fungus attacks was also verified. Although it was likely easy to predict that the retrofit would lead to a decrease in energy consumption, the acquired data can be considered extremely reliable because it is based on an objective comparison, as explained before. The information gathered represents a first step in the validation process of the Renew-Wall façade panel, as it comes from non-inhabited buildings used as a test. Future developments will involve the installation of the system in actual buildings to evaluate its response to real internal thermal loads – people, lights, equipment – and its summer energy performance, even in the presence of a cooling system. The computational and simulation models, calibrated on the monitoring data, will be used to assess the installation of the Renew-Wall panel in other locations and under other environmental conditions as well. Thanks to these models and the data collected, it will be possible to compare such innovative retrofit systems with standard renovation approaches. The ultimate goal is to improve the system created so far to highlight the benefits and accelerate the adoption of these solutions in the energy retrofit market.

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