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SPECIAL ISSUE

MULTIFUNCTIONAL FAÇADES FOR RENOVATION THROUGH INDUSTRIALIZATION

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ENSNARE modular façade system combining RIVENTI's and ONYX's technologies. Image courtesy of Nuria Jorge.

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SmartWall

Towards residential nZEB with off-site prefabricated hybrid façade systems using a variety of materials

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Abstract

Following the need of urban areas to maintain the existing building stock and simultaneously upgrade the overall energy performance, the renovation down-to-nZEB state has already become a necessity. In this regard, a vast range of prefabricated solutions have been developed lately. The main objective of such solutions would be not only to constitute an effective system to tackle building energy consumption but also to be versatile in terms of implementation and economic viability. In this regard, an adaptable off-site prefabricated envelope solution with an embodied HVAC system called "SmartWall" has been developed. The SmartWall can minimise thermal losses through the well-insulated envelope while, at the same time, its integrated HVAC system efficiently maintains indoor thermal comfort conditions. This study examines the virtual implementation of the SmartWall as a "Plug-n-Play" renovation solution to reach the nZEB state of a typical apartment in a multi-family residence in Athens. The analysis considers two SmartWall alternatives using conventional and eco-friendly materials. The results indicate a reduction of 88% in primary energy consumption without affecting thermal comfort conditions and highlighting that the nZEB state can be ensured if the SmartWall application is enhanced with photovoltaic modules.

Keywords

nZEB renovation, prefabricated wall, all-in-one façade kit, integrated HVAC component, TRNSYS simulation

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1 INTRODUCTION

In the realm of building renovation, the demand for efficient and cost-effective solutions has led to the emergence of innovative retrofitting methods. One such method gaining significant traction is the utilisation of prefabricated façade systems (Rovers et al., 2018). These systems offer a transformative approach to renovating existing buildings by providing a range of benefits, including improved energy efficiency, reduced construction time and cost, enhanced aesthetics, and minimised disturbance to occupants. Prefabricated façade systems encompass a wide array of modular components and panels that are manufactured off-site and then assembled on the building's façade in order to thermally enhance the envelope and upgrade the HVAC systems towards nearly Zero Energy Building (nZEB) state (Sandberg, Orskaug, & Andersson, 2016). The advantages and applications of prefabricated façade systems shed light on how they are revolutionising the landscape of building renovation and revitalisation projects (Evola, Costanzo, Urso, Tardo, & Margani, 2022). By leveraging the potential of these systems, building owners and developers can achieve remarkable outcomes in terms of both performance and aesthetics while streamlining the renovation process.

Efficient, integrated HVAC systems and renewable energy sources (RES) are necessary for achieving the nZEB state through deep renovation schemes (Attia et al., 2017; Fiorentini, Cooper, & Ma, 2015). Passive and heat recovery systems, smart windows, adaptive control systems, and nano-enabled coatings must also be fully utilised towards the energy balance and optimisation of multifunctional wall panels. The integration of HVAC systems into multifunctional façades is a crucial technology that has been studied and developed by several EU-funded projects. These projects aim to determine the feasibility and technical suitability of integrating various components such as heat pumps, convectors, ventilation units, heat recovery systems, RES, thermoelectric components, and smart control systems (D'Oca et al., 2018).

A range of such innovative building solutions have been explored and developed within the frame of EU-funded projects to enhance energy efficiency and performance.

- MORE-CONNECT involves a prefabricated roof module that incorporates heating units and integrated renewable energy sources.
- E2VENT project focuses on an adaptive ventilated façade with smart heat recovery and thermal energy storage. It utilises phase change materials.
- 4rinEU explores an externally added prefabricated timber façade with integrated ventilation and solar thermal panel.
- iNSPire project integrates a micro heat pump with heat recovery into a prefabricated timber frame wall panel.
- P2ENDURE involves a Plug-and-Play combination of multifunctional wall panels with smart windows and a prefabricated HVAC system.

Other projects include a prefabricated wall panel with an embedded duct system for heat recovery in domestic hot water distribution, a thermoelectric system that integrates radiant cooling and PV technologies in the building envelope, attached or integrated photovoltaics and solar thermal systems for electricity and hot water production, and thermal active insulation that reduces heat losses and complements the heating system. In more detail, the project MORE-CONNECT has developed roof modules that integrate renewable energy sources and combined heating units. The initial models were put to use in Heerlen, the Netherlands. As part of this initiative, prototypes of Dutch dwellings built in the 1960s were retrofitted with prefabricated modular roofs. These roofs include integrated combined heating units (convectors) with decentralised demand and CO_2-controlled mechanical ventilation units with heat recovery. The roofs also have 40 m^2 PV panels corresponding to 6.4 kWp. To minimise the disturbance for occupants during maintenance or parts replacement, a fully prefabricated installation box containing an air-to-air heat pump, boiler, mechanical exhaust fan, and PV converters was placed on the roof.

Moreover, E2VENT provided energy-efficient ventilated façades that can adapt and exchange heat for significant energy savings through an innovative adaptive ventilated façade system (FIG 1). This system includes a Smart Modular Heat Recovery Unit (SMHRU) for air renewal that recovers heat from extracted air using a double heat exchanger, ensuring indoor air quality while limiting energy losses. Additionally, the system includes a Latent Heat Thermal Energy Storage (LHTES) based on phase change materials that provides a heat storage system for heating and cooling peak saving. The system has a smart management feature that controls it on a real-time basis, targeting optimal performance, including sensors, communication with existing systems, and prediction of weather patterns. Finally, the system has an efficient anchoring system that limits thermal bridges.

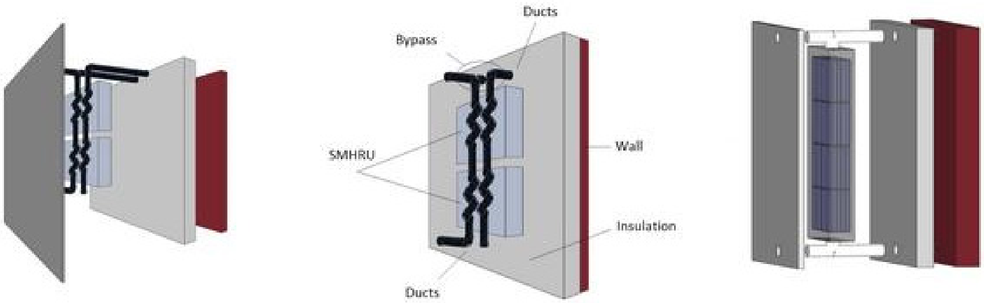


FIG. 1 E2vent system (left), Smart Modular Heat Recovery Unit (SMHRU, middle) and Latent Heat Thermal Energy Storage (LHTES, right)

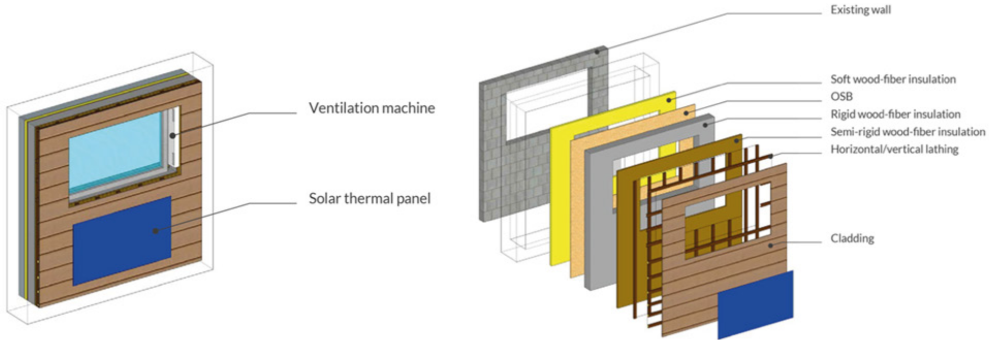
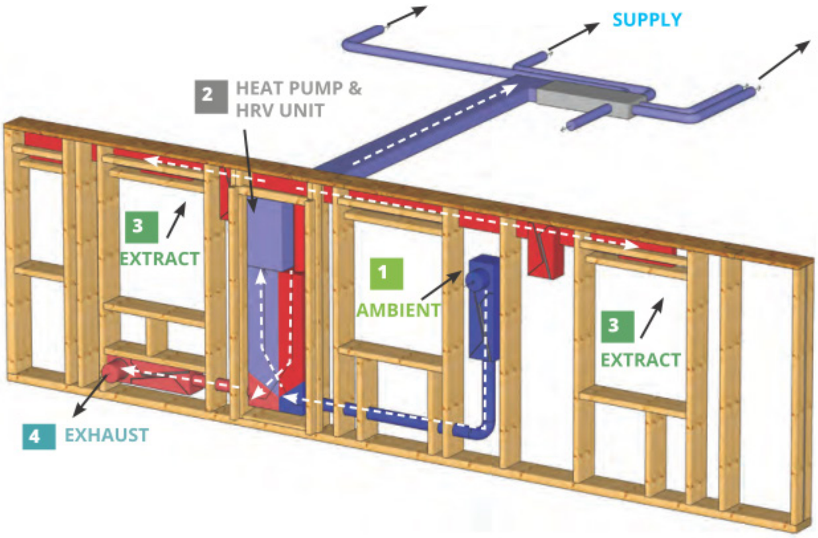


FIG. 2 Prefabricated timber-based façade module – 4rinEU project

The 4rinEU project developed a timber-based prefabricated multifunctional façade, which does not replace the existing façade but is added externally to improve performance and expand the number of functions of the existing envelope. The technology involves a prefabricated timber façade module that integrates various components such as new windows, a decentralised ventilation device, and a solar thermal panel. The integration of such components allows for the direct installation of devices during envelope renovation, increasing the building's energy performance and improving user comfort (see FIG 2).

A timber façade-integrated prefabricated system has been developed as part of the iNSPire project. This system includes a kit consisting of a wooden frame envelope module that incorporates ducts and an air-to-heat pump. During the prefabrication stage, pipes, ducts, and wires for domestic water, heating, ventilation, electricity, and solar energy generation are integrated into the timber frame façade elements. A micro heat pump is added to the exhaust of the Mechanical Ventilation with Heat Recovery (MVHR) unit (see FIG 3)., and the condenser is added to the supply air, utilising the remaining heat for active heating. Acoustic silencers are also included in advance, and air outlets and inlets can be integrated through the prefabricated window reveals. Unlike previous projects that applied prefabricated timber envelope retrofit solutions, this concept attempted to incorporate heat recovery ventilation systems despite the potential installation's impact on occupied flats (Ochs, Siegele, Dermentzis, & Feist, 2015).



1 OUTSIDE AIR IS DRIVEN THROUGH THE DUCTS INTEGRATED INTO THE FAÇADE. A SILENCER AND A FILTER ARE FITTED TO THE MVHR AND MHP UNIT

2 THE OUTSIDE AIR IS PREHEATED IN THE HEAT EXCHANGER AND FURTHER HEATED, IF REQUIRED, THROUGH THE HEAT PUMP. IT IS DISTRIBUTED THROUGHOUT THE FLAT THROUGH THE DUCTS

3 EXTRACTED AIR OR WARM EXTRACTED AIR IS DRIVEN THROUGH THE HEAT EXCHANGER, WHERE IT PREHEATS THE INCOMING COOL AIR

4 THE REMAINING ENERGY OF THE EXHAUST AIR IS USED AS A SOURCE FOR THE MICRO-HP AND IS THEN DRIVEN THROUGH THE SILENCER TO THE OUTSIDE

FIG. 3 Prefabricated MHVR wall system with integrated micro heat pump and ventilation unit with heat recovery

Furthermore, P2ENDURE has developed an advanced Plug-and-Play (PnP) solution that combines multifunctional wall panels, smart windows, and prefabricated HVAC systems. The integration of 180° rotating windows with double positioning Low-E glass reduces thermal radiation in the summer and minimises heat dispersion from the interior during the winter. These windows not only promote natural ventilation but also seamlessly integrate with cutting-edge home automation solutions, offering high energy efficiency, improved indoor climate, and enhanced security features. The PnP HVAC assembly comprises an air-heat pump, domestic hot water (DHW) storage capacity, mechanical ventilation system, expansion barrel, and control systems. It can be equipped with a split-engine option consisting of two cores, one for energy conversion and storage and the other for ventilation and heating/cooling. The application of smart connectors significantly reduces on-site installation time for pipe and duct connections. Additional thermal technologies leverage a compact seasonal storage system based on innovative high-density materials capable of supplying heating, cooling, and domestic hot water (DHW) using up to 100% RES (Piaia, Turillazzi, Longo, Boeri, & Giulio, 2019). The system design integrates various components and utilises enhanced thermo-chemical materials, which have undergone rigorous testing and evaluation through field trials, including prototypes tailored for three distinct climate zones.

Last but not least, in terms of integrating smart solutions, several projects (BERTIM[1], E2vent[2], iNSPiRe[3], RetroKit[4]) have included the design and development of building monitoring systems. These systems enable user interaction, operational control, and communication with sensors and hardware. Real-time intelligent management systems and control strategies have been implemented to optimise building performance and ensure the availability of detailed building supervision information. Recognising the potential of ICT-based innovations, such as smart control systems, the European Commission acknowledges their significant contribution to deep renovation initiatives. These – and many more – EU-funded projects not only focus on smart building controls but also on effectively translating captured building data into user-friendly information and establishing effective communication channels with end-users.

As a continuation of the aforementioned retrofitting solutions, an all-in-one façade component called "SmartWall" has been developed. This prefabricated kit consists of high thermal performance materials and incorporates an HVAC distribution system, aiming to reduce thermal losses through the envelope as well as increase the heating and cooling systems' efficiency (Katsigiannis et al., 2022). In the current work, the application of SmartWall is assessed as a renovation solution in a poorly insulated multi-family pilot building in Athens, Greece. Two versions or two different alternatives of design materials are examined with respect to the energy performance of the renovated building without affecting the indoor thermal comfort conditions. The building in the initial state (existing) and in the two SmartWall renovation scenarios are fully simulated using TRNSYS software. The effectiveness of such a renovation solution, as well as the potential for the building to reach the nZEB state – with a single retrofitting intervention – is explored.

2 SMARTWALL SYSTEM OVERVIEW

The SmartWall is a multifunctional wall assembly that incorporates several technologies, such as fully prefabricated masonry with either metal or timber-based frame and various insulation materials, a slim-type fan coil for heating and cooling, and high-performance windows. This system can be installed on an existing envelope either on the exterior as a façade wall or on the interior when space or aesthetic considerations are at stake. Photovoltaic panels can be mounted on vertical external surfaces for power generation (see FIG 4). Alternatively, photovoltaic (PV) panels can be installed on the roof in case the building geometry features balconies or volumes that create shadows. It is applicable to any climate in Europe, yet it is especially effective in climates with

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[1] http://www.bertim.eu/

[2] http://www.e2vent.eu/ (2015-2018)

[3] www.inspirefp7.eu/

[4] http://www.retrokitproject.eu/

significant cooling demands. The SmartWall is constructed as a modular Plug-and-Play panel that contains flexible piping and electrical wiring connections, enabling it to accommodate existing or new heating/cooling systems and electrical services (switches, plugs, etc.) and reducing on-site installation time.

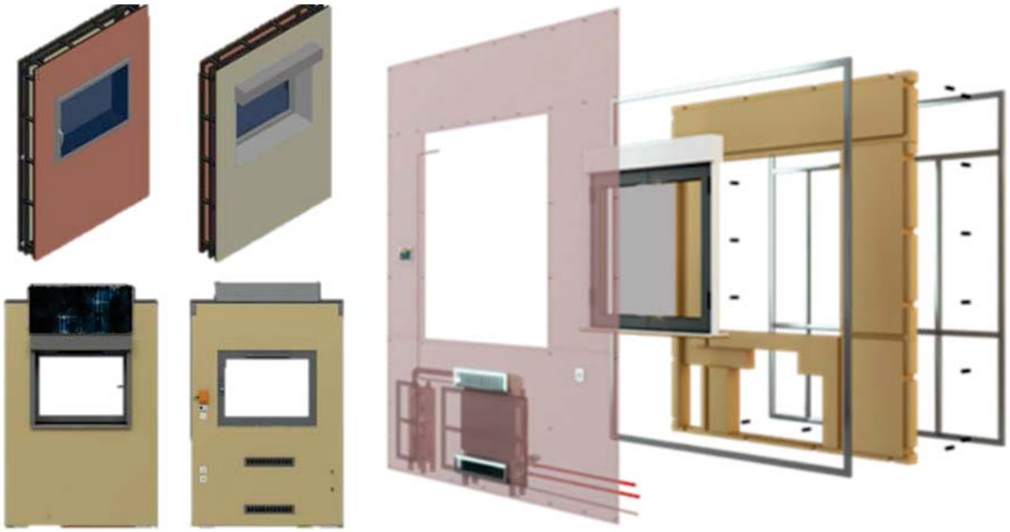


FIG. 4 SmartWall internal and external view - with and without installed PV (left), SmartWall layer overview (right)

The SmartWall, as a versatile modular façade panel, can be adapted to any dimension up to 4 m in height and can be decorated with any finishing material. The dimensions of a SmartWall panel, in case of a real implementation, depend on several parameters such as the building geometry limitations, the integrated commercial components, i.e., the common size of the wall boards (interior/exterior) and/or the slim-type fan coil dimensions. Depending on which side of the external wall the SmartWall panel is installed (interior or exterior), the selection of the appropriate finishing layers may differ.

For more peculiar structural elements such as bulges and balconies, where SmartWall cannot be fitted, the thermal performance is not affected. Existing thermal bridges, in such cases, are neither minimised nor increased. In most cases, utilising a well-insulated façade with high-performance Low-E windows and incorporating an efficient HVAC system allows the upgrade of a renovated building to nZEB status. Additionally, the incorporated smart systems, such as a human-centric HVAC control system and smart window blinds, provide an optimal balance between visual and thermal comfort.

The layout of the SmartWall HVAC systems is illustrated in the overview provided in FIG 5. A low-temperature air-to-water heat pump is used to supply the terminals inside the SmartWall panel for both heating and cooling. Inside each room, the conditioned air is distributed by the integrated slim-type Fan Coil Unit (FCU) utilising water as the heat transfer medium (FIG 5). The FCU is a device that combines a pipe coil where the water flows and a fan that blows air heated or cooled from the coil before it goes into the room. Such FCUs are used to be fed with low to medium water temperature for heating, meaning 45 - 55 °C, whereas the respective temperature range needed for cooling in order to provide their nominal capacity values is 7-12°C. For a general application, the domestic hot water is also supplied by the same heat pump. In addition to the heat pump's operation for hot water production, solar panels can be utilised. And a PV system with panels is used for renewable electricity production. Inside the SmartWall panel, a dedicated control system is installed, which is responsible for operating the SmartWall and eventually regulating indoor conditions by using acquired data from fan coil operation, temperature, relative humidity and air quality sensors, fire protection system, etc.

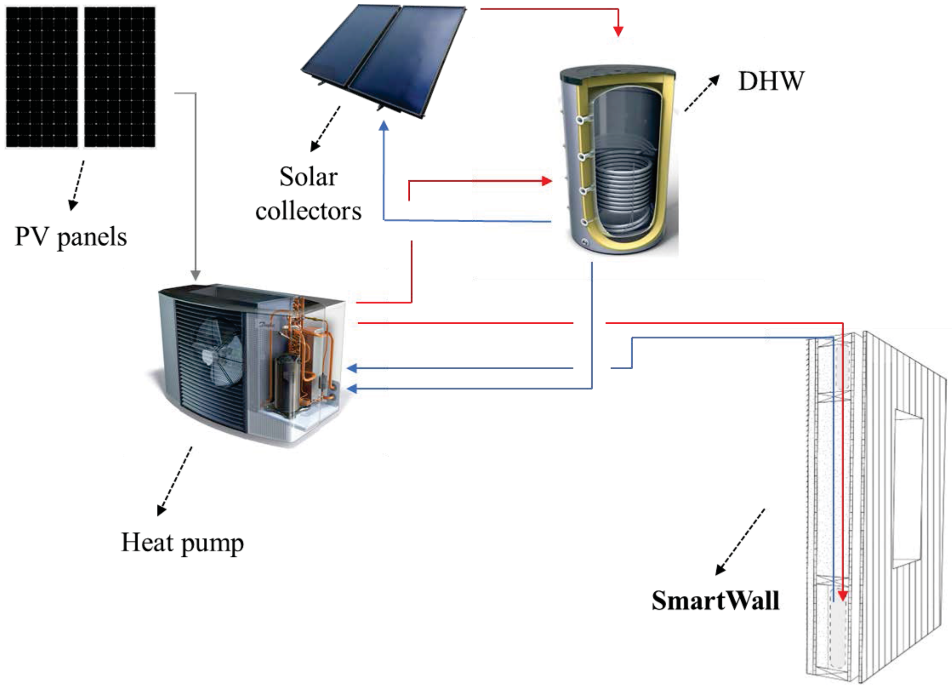


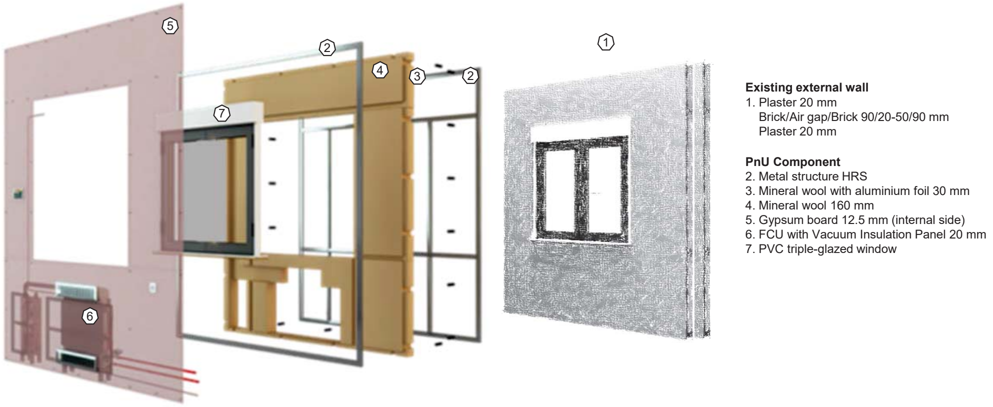
FIG. 5 SmartWall auxiliary system overview – Power (PV), heating (heat pump and solar collectors) and cooling (heat pump) generation

The current study examines two different SmartWall alternatives depending on the design materials used for construction. All materials are commercial materials, and their characteristics are available from the manufacturers. Three basic design components differentiate each type; the frame, the material used for insulation and the finishing boards.

2.1 METAL-BASED SMARTWALL

Regarding the metal version of SmartWall, the wall materials are anchored on two frames made by Hollow Rectangular Section (HRS) structural steel members with section dimensions of 50x30 mm and a thickness of 1.8 mm. Spacers made by the heat breaker structure are placed in the fixing points to ensure movement treatment, except for the bottom side, where the spacers are made from the HRS frame, for structural reasons. The use of this type of SmartWall is identical for high-risk seismic areas. Regarding thermal performance-related materials, a mineral wool layer of 160 mm thickness is used as a main insulator, while a mineral wool layer with aluminium foil of 30 mm thickness covers the side between the existing envelope and the added wall panel.

Additionally, a 20 mm thick VIP panel is incorporated in the rear side of the HVAC systems to create a thermally homogenous surface with similar thermal resistance. Last but not least, a 12.5 mm thick gypsum board constitutes the internal side of SmartWall coated with a multifunctional layer. In the case that the SmartWall is externally applied, a cement board is used instead. The inventory of the materials used for the SmartWall construction as well as their thermal properties, are presented in TABLE 1. The final thermal transmittance (U-value) of the SmartWall panel, including the HVAC systems of the FCU, is 0.25 W/m^{2}K.



Existing external wall
1. Plaster 20 mm
Brick/Air gap/Brick 90/20-50/90 mm
Plaster 20 mm

PnU Component
2. Metal structure HRS
3. Mineral wool with aluminium foil 30 mm
4. Mineral wool 160 mm
5. Gypsum board 12.5 mm (internal side)
6. FCU with Vacuum Insulation Panel 20 mm
7. PVC triple-glazed window

FIG. 6 Metal frame SmartWall panel - layer configuration

TABLE 1 Thermal properties of SmartWall incorporated materials

SmartWall alternative	SmartWall material	Thickness	Thermal conductivity	Density	Specific Heat Capacity
		mm	W/mK	kg/m^3	J/kgK
Metal-based	Steel	-	60.5	7854	434
	Gypsum board	12.5	0.20	680	980
	Mineral wool	160	0.035	28	1030
	Air cavity	-	0.167	1.2	1000
	Vacuum Insulation Panel (VIP)	20	0.0075[5]	195	800
Timber-based	Timber frame and studs		0.13	650	1200
	Weatherboard	20	0.13	570	2100
	Wood-fiber board	60	0.048	270	2100
	Wood-fiber blow-in insulation	100	0.038	30	2100
	Oriented Strand Board (OSB)	22	0.13	595	1700
	Softwood fibre insulation	60	0.036	60	2100
Both alternatives	Window glass	40	0.056[6]	-	-
	Window frame	100	0.14[7]	-	-

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[5] Taking into account the edge effect

[6] the resulting U-value of glass is U_g=1.40W/(m^{2}K)

[7] the resulting U-value of frame is U_f=1.40W/(m^{2}K)

2.2 TIMBER-BASED SMARTWALL

This SmartWall version, in addition to the first above-mentioned type, consists of more eco-friendly materials, meaning materials with lower embodied energy. The frame is made of two lightweight timber-based frames interconnected by horizontal supports of the same material and several anchoring points together with some fixings needed to secure the interconnection with the existing masonry. Wood fibre blow-in and softwood are used for the insulation layers, while OSB (Oriented Strand Board) and weatherboards are combined with a ventilated layer to complete the wall assembly, as presented in FIG 7. The final U-value of the SmartWall panel, including the mechanical parts of the FCU, is 0.188 W/m^{2}K.

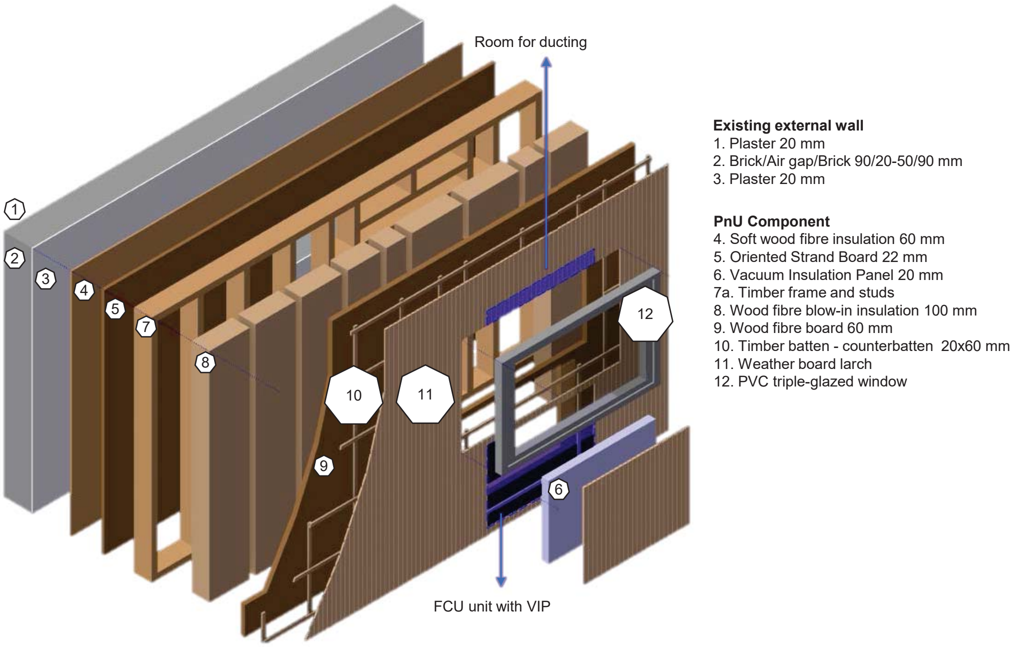

FIG. 7 Timber frame SmartWall panel – layer configuration

3 METHODOLOGY

The SmartWall application is examined as a renovation solution on a typical storey of a detached multi-family building in Greece. The retrofitting scenarios are assessed in terms of energy performance and thermal comfort conditions with the two aforementioned SmartWall types. As a reference case, the existing state of the building has been considered. The energy performance is examined based on the heat losses through the envelope (heating demand), the efficiency of the installed heating and cooling system (energy consumption for HVAC), and the contribution of the renewables (PV production vs energy consumption). The indoor conditions are examined in terms of ensuring thermal comfort regardless of the installed HVAC system.

It should be mentioned at this point that the differentiation of each examined renovation scenario refers to the design and the materials used for the wall assembly. The incorporated systems of the retrofitted state for heating, cooling and DHW are identical for both cases examined.

The calculation of the final U-value has been conducted via COMSOL Multiphysics software – in compliance with ISO 10211:2007 – taking into account all thermal bridges that occurred from integrating the mechanical equipment into the SmartWall. Moreover, adjusted U-values have been considered for the wall parts that include windows, doors or other openings. The thermal behaviour of the external wall with the metal-framed SmartWall is characterised by an overall U-value of 0.25 W/m^{2}K, whereas the corresponding U-value for the timber-based SmartWall is 0.178 W/m^{2}K.

3.1 CASE STUDY DESCRIPTION

The case study where the SmartWall solution is implemented is a typical floor of a multi-family building located in a southern suburb of Attica (Voula), Greece, constructed in 1971. The building is detached (see FIG 8) with a total floor area of 881.57 m^2 distributed into four levels. The renovated area is the first floor that corresponds to 222 m^2 with a continuous 3-side balcony of circa 78 m^2. The examined storey consists of two apartments (A1 and A2) and an unconditioned adjacent staircase area.

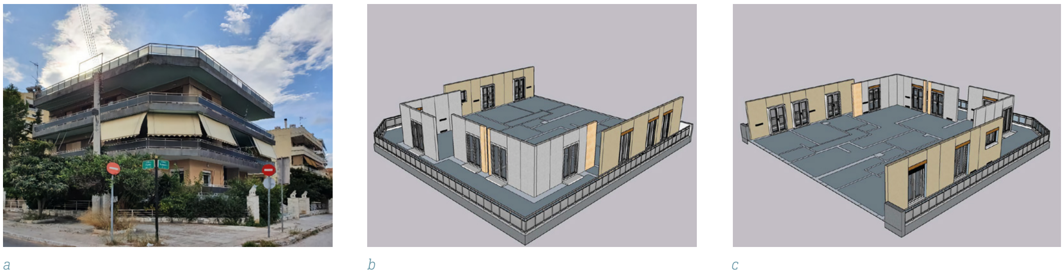
a b c

FIG. 8 Greek pilot building (a) – Isometric views of SmartWall application on 1st floor (b & c)

Main construction details include a structural frame for all floors, brick masonry with cement rendering or plaster finish, with exterior acrylic paint, and without a thermal insulation layer. The external walls constitute a surface of approximately 151 m^2 with a 23.4% window-to-wall ratio. The U-value of the uninsulated existing external wall based on the Greek regulation is 2.44. The corresponding U-value for the horizontal building elements is 3.05 for the roof and 2 W/m^{2}K for the floor/ceiling surfaces. The thermal performance of the external wall for the existing and the two renovated states with the corresponding SmartWall types are presented in TABLE 2. U-values for the examined renovated states are calculated taking into account the existing wall layers and all potential thermal bridges from integrated parts (FCU and openings), normalised based on each SmartWall type area.

TABLE 2 Thermal transmittance of external wall

	Existing state	SmartWall – Metal frame	SmartWall – Timber frame
Total thickness mm	200-230	410-440	502-532
U-value W/m^2K	2.44[9]	0.25[10]	0.18[11]

The existing state of the building includes electric radiators of 2 kW in each conditioned zone and split-type air heat pump units for cooling with SEER of 1.7. Additionally, it is only naturally ventilated mainly during periods when the outdoor temperature is favourable. Infiltration from openings is determined considering 9.8 $m^3/(h \cdot m^2)$ and 12.5 $m^3/(h \cdot m^2)$ for doors and windows, respectively. Greek regulation proposes a typical fresh air change rate for residences equal to 15 m^3/h·per occupant or 0.75 m^3/h·per m^2 of conditioned area.

3.2 TRSNYS IMPLEMENTATION

The building is geometrically defined in Sketchup and imported into TRNBuild (see FIG 9). Weather conditions used for the simulation process are provided from the TRNSYS library (file "GR-Athinai-167140" of the meteonorm database). The renovated area has been divided into 17 thermal zones, as illustrated in FIG 10. From these, nine zones contain conditioning systems for heating and cooling, in which the SmartWall panels with embedded FCUs are installed. The ground floor, the semi-basement, and the 2nd floor of the building are also included in the model. However, it is assumed that horizontal surfaces adjacent to the renovated floor are adiabatic.

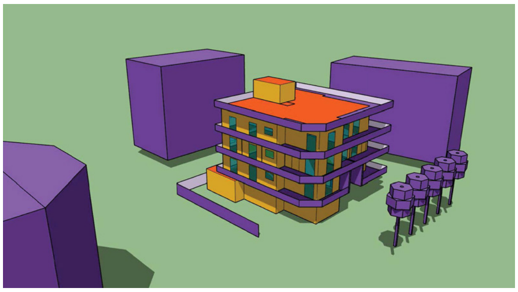

FIG. 9 Building 3D model

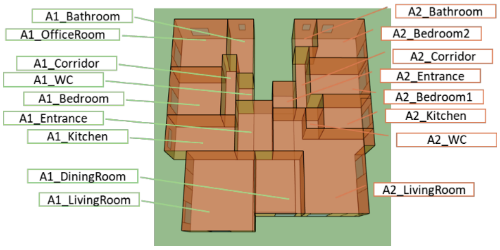

FIG. 10 Assigned thermal zones of the renovated floor

The SmartWall components and their supply systems are defined and simulated via TRNSYS studio. The software's extensive libraries provide a wide range of components, and its dynamic energy analysis accurately models the transient behaviour of HVAC systems. The main components of the model, as well as their functionality presented, are developed in three main segments with respect to the active systems (FIG 11).

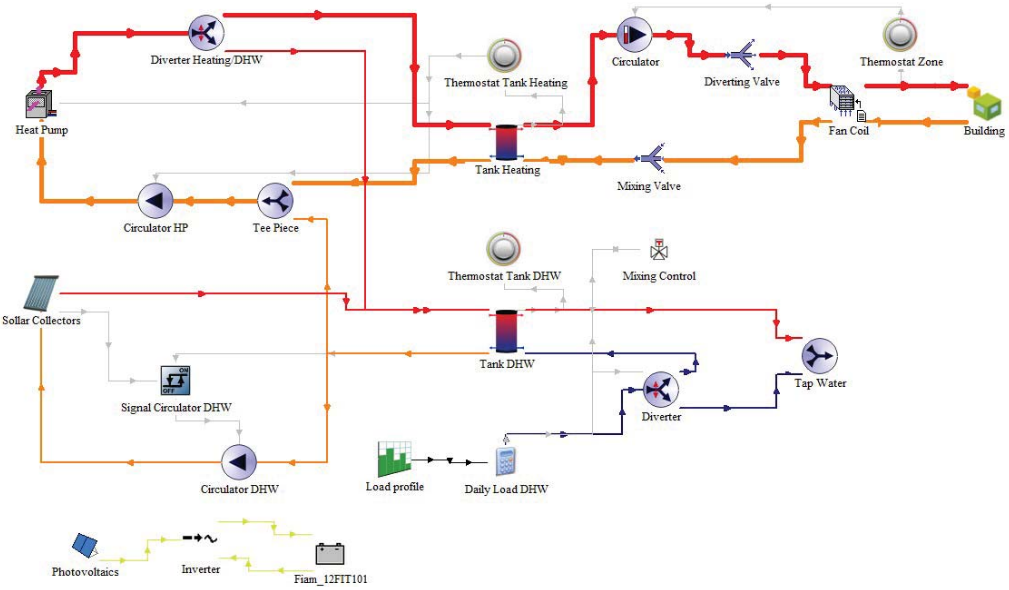

FIG. 11 Overview of simplified TRNSYS model of SmartWall support system

The building unit (type56) encompasses various parameters and regulations related to the building, including its geometry (FIG 9.), operational aspects (occupancy, heating schedules, regimes, etc.), and thermal characteristics of its elements (walls, roof, floor, windows, etc.).

Inside each zone, the distribution is facilitated by a fan coil unit and its corresponding thermostat. Each thermal zone is assigned a variable-speed 2-pipe fan coil with a rated capacity of 2.18 kW for heating. This fan coil unit acts as the terminal device responsible for supplying conditioned air to the zone in accordance with the control signal from the thermostat.

An air-to-water heat pump is used to condition the circulating water that reaches the fan coils. One heat pump is assigned for each apartment. This heat pump, which is an inverter-compressor, low-temperature system with a rated capacity of 9.37 kW for heating and 9.00 kW for cooling, serves as the main source for heating/cooling water for space conditioning and DHW. It maintains the water inside the tanks at different temperature ranges throughout the year, ensuring energy and environmental efficiency. In order to facilitate the simultaneous operation of space heating/cooling and DHW production, a separate tank is assigned for each circuit (DHW, space conditioning).

The supply water is conditioned by the heat pump and stored in a dedicated tank (100 L buffer for each apartment) before being circulated to the fan coil. This arrangement connects the heat pump to the load side, enabling its use for both space heating or cooling, while also improving its operation by minimising frequent start-stops.

A similar storage tank (150 L for each apartment) is utilised for DHW, receiving hot water from both solar collectors and the heat pump. It provides hot water to the building's taps based on a dynamic load profile. The DHW system includes a solar collector component, which utilises incidence angle modifiers (IAMs) to heat water specifically for DHW purposes. A small pump circulates the fluid, considering the temperature difference between the collector and the tank. When the hot water from the solar collector is insufficient, the heat pump for space heating is activated. The control strategy for DHW combines a forced hourly profile with thermostatic control of the water temperature in the tank. The stored water temperature is regulated at different set points throughout the year, with a total of 2.5 hours of heating distributed during the day.

In terms of power generation, a photovoltaic (PV) array component is included in the model. This component can simulate different types of PV panels, such as monocrystalline, polycrystalline, or thin-film, and incorporates a maximum power point tracker (MPPT). Ten high-performance PV modules (21% efficiency) are connected, covering a total installed area of 20 m^2. A sequence of batteries and an inverter are also incorporated for power storage and transformation, respectively, converting the DC power generated by the PV panels into AC power required by most household devices. The power is either consumed by the load or fed back to the grid if there is an excess. The assumed interaction with the utility follows a hybrid net-metering regime, where any excess power produced is directed to the national grid and subtracted from later electrical consumption.

The existing state of the examined two-apartment floor is also developed via TRNSYS. Apart from the aforementioned building component (type56), the regimes include a separate electrical radiator for heating and a split-type A/C unit for cooling. A hot water circuit with a 3 kW electric heater supplies both apartments with DHW via a buffer tank of 200 L. The set-up of the system is illustrated in FIG 12.

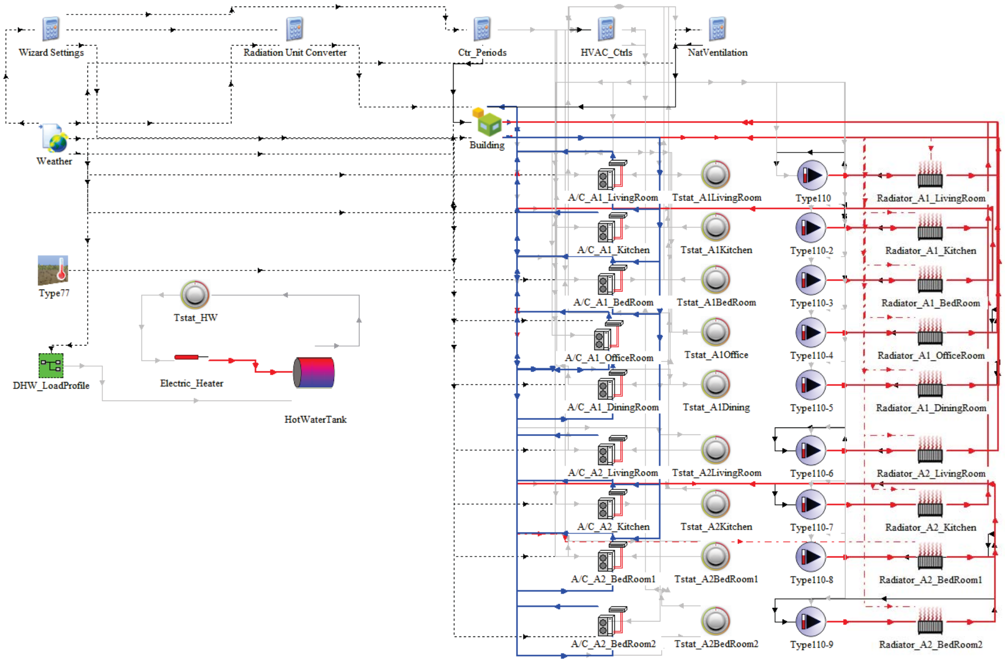

FIG. 12 Overview of TRNSYS model for the heating and cooling system of the existing state

According to Greek regulations for residences, the building operates 18 hours per day and 365 days annually. The internal gains due to occupants, electrical equipment and lighting are considered dynamically based on hourly profiles proposed by ASHRAE (90.1) and (Mitra, Steinmetz, Chu, & Cetin, 2020), as presented in FIG 13.

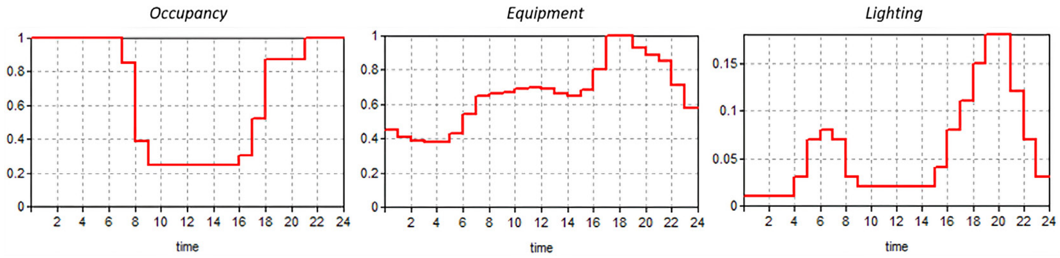

FIG. 13 Hourly profiles for occupancy, equipment and lighting

The simulations were conducted for a one-year period with a 10-minute timestep, considering a preparatory month to avoid side effects from initial values. Other simulation assumptions and boundary conditions regarding the building and its operation are summarised in TABLE 3.

TABLE 3 Operational characteristics of the pilot building

Occupancy	5 P/100 m^2 of floor area	**DHW consumption**	50 L/(day·P)
Ventilation/ Infiltration	15 m^3/(h·P)	**Heating setpoint**	20° C
	0.75 m^3/(h·m^2)	**Cooling setpoint**	26° C
Electrical equipment	2 W/m^2		
	6.4 W/m^2		

3.3 KPIS DEFINITION

Specific Key Performance Indicators (KPIs) have been selected in order to better comprehend and assess the impact of the SmartWall application as a retrofitting solution. The area of interest is restricted to the energy performance with reference to the thermal comfort conditions. The energy KPIs used are the primary energy, the renewable energy ratio, and the thermal energy demand. For thermal comfort, the Predicted Mean Vote (PMV) has been taken into account.

The primary energy consumption (PE$_c$), besides being a major metric within the Energy Performance of Buildings Directive (EPBD – Directive 2010/31/EU), is one of the most crucial KPIs regarding the energy assessment of building renovation scenarios. For the residential sector, this indicator concerns the total energy that is consumed annually for heating, cooling, ventilation, and domestic hot water. The primary energy can be normalised per unit floor area [kWh/m^2/yr] and defined by the following equation:

$$PE_c = \frac{\sum(f_p x\ E_{del})}{A_b} \tag{1}$$

where, PE$_c$ is the primary energy consumption in [kWh/m^2/yr] and is the sum of delivered energy in [kWh/yr], with being the primary energy factor and the delivered energy. It is calculated as the balance of the delivered energy required to meet the energy demands of considered end-uses of the building (heating, cooling, ventilation, DHW), and A$_b$ is the total area of the building in [m^2]. A derivation of the appropriate energy performance indicators is necessary because of the potential different fuel sources, i.e. thermal and electrical energy consumption. In the examined case, the primary energy factor is 2.5 for electricity consumed and 2 for the subtracted amount of energy that is exported to the grid (the on-site produced electricity from PVs has a primary energy factor equal to 1), based on prEN 15603.

The Renewable Energy Ratio (RER) is defined as the ratio of the energy from Renewable Energy Systems (RES) and the energy consumption of the building or the apartment over a period of time. It can be determined for thermal needs (heating and cooling) and electricity needs as a whole or separated. The energy from the renewable sources can be calculated by the difference between the total energy consumption and the non-renewable energy of the considered energy flow carrying renewable energy (thermal solar, photovoltaics, heat pumps).

The function escrybes the renewable energy ratio is:

$$RER = \frac{E_{p,ren}}{E_{p,tot}} \tag{2}$$

where, $E_{p,ren}$ is the renewable primary energy and $E_{p,tot}$ is the total primary energy use.

Thermal energy demand TE_d refers to the energy delivered in each conditioned zone in order to maintain the desirable temperature conditions, and it is directly linked with the building's thermal losses. It is calculated as the sum of heating and cooling energy demands.

Last but not least, Predicted Mean Vote (PMV) is the index for the thermal comfort assessment before and after the renovation. According to ASHRAE standard 55 – 2013 and EN ISO 7730, the comfort zone is defined by the combination of six major variables of thermal comfort, indoor thermal environmental factors and personal factors, that produce acceptable thermal environment conditions for the majority of the occupants within a space (Gilani, Khan, & Pao, 2015). Normally, PMV (see equation [3]) is calculated based on four measurable parameters quantities (air velocity, air temperature, mean radiant temperature, and relative humidity) and three assumed parameters (clothing, metabolic rate, and effective mechanical power) (Arakawa Martins, Soebarto, & Williamson, 2022).

$$\begin{aligned} PMV = {} & (0.303\, exp\, -\, 0.0336\, M\, +\, 0.028)\, \times \{ (M - W) - 3.5\, \times\, 10 \\ & - 3\, [5733 - 6.99\, (M - W)\, -\, p\_a\,] - 0.42\, (M - 58.5) - 1.7\, \times 10 \\ & - 5\, \times\, M\, (5867 - p\_a\,) - 0.0014 M\, (34 - t\_a\,) - 3.96\, \times\, 10 - 8\, f\_cl\, [(t\_cl \\ & +\, 273\,)\, 4 - (\, t\_r\, + 273\,) 4] - f\_cl\, \times\, h\_c\, (\, t\_cl - t\_a\,)\} \end{aligned} \tag{3}$$

where, M- the metabolic rate (W/m^2) of the body surface area

W- the effective mechanical power (W/m^2)
I_{cl} – Thermal resistance of clothing (m^{2}K/W)
f_{cl} – is the clothing surface area factor
t_a – is the air temperature (°C)
t_r - is the mean radiant temperature (°C)
v_{ar} – is the relative air velocity (m/s)
p_a – is the water vapour partial pressure (Pa)
h_c – is the convective heat transfer coefficient [W/(m^{2}K)]
t_{cl} – clothing surface temperature (°C).

In the examined model, the required assumptions for the calculation of PMV are summarised in TABLE 4.

TABLE 4 Assumptions for PMV calculation

Metabolic rate	1.2 met
Effective mechanical power	0
Rel. air velocity	0.1 m/s
Clothing factor (winter/summer)	1/0.5

Based on PMV calculations, the thermal discomfort index has also been determined, meaning the percentage of the aggregated period of time that the PMV exceeds 0.5 (too hot) or falls below -0.5 (too cold) within the simulation period.

4 RESULTS

Based on the simulations conducted at the building level, FIG 14 provides a visual representation of how SmartWall's passive characteristics contribute to minimising heat losses through the envelope. The required thermal energy to counterbalance the losses (TE_d) is equal to 131.4 kWh/m^2 for the existing state, 37.9 kWh/m^2 for the renovation scenario with metal framed SmartWall and 36.9 kWh/m^2 for the timber-based. A demand reduction of 71% is observed for the metal and 72% for the timber SmartWall despite the difference in the U-values (0.25 W/m^{2}K for metal framed SmartWall and 0.13 W/m^{2}K for the timber-based SmartWall). The impact on the heating needs is clearly more effective compared to the reduction in cooling demand due to the significant solar and internal gains that are not significantly reduced after the renovation. Nevertheless, it can be highlighted that the implementation of SmartWall panels as a renovation solution overall enhances the thermal performance of the building envelope and improves the efficiency of the heating and cooling systems.

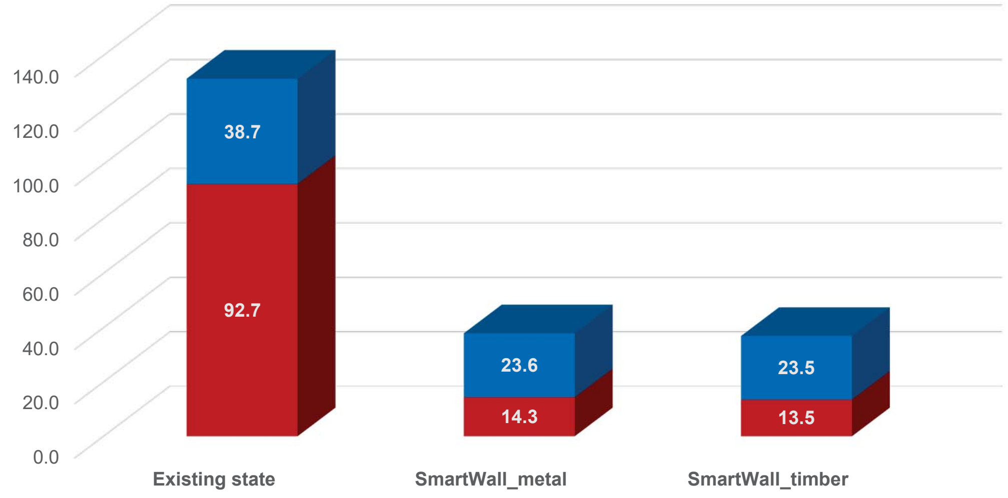

FIG. 14 Heating and cooling demand for the existing state and the two renovated envelopes

FIG 15 presents the Primary Energy consumption (PE_c) for heating, cooling, and DHW, comparing the existing state with the application of two SmartWall alternatives. The reduction of the energy consumption is similarly substantial for both SmartWall designs – approximately 65.5 and 64 kWh/m^2 for the metal and timber-based SmartWall – reaching 80% (without the contribution of PV). As illustrated in FIG 15, the primary energy reduction can reach 88% when the SmartWall is combined with 20 m^2 PV panels. The contribution of RES (Renewable Energy Ratio – RER) in both renovation cases is 36% – since the installed systems are identical and the consumption is not significantly different. Of the 36% of RES, the solar thermal system for DHW is responsible for 15%, whereas the remaining 21% refers to PV production.

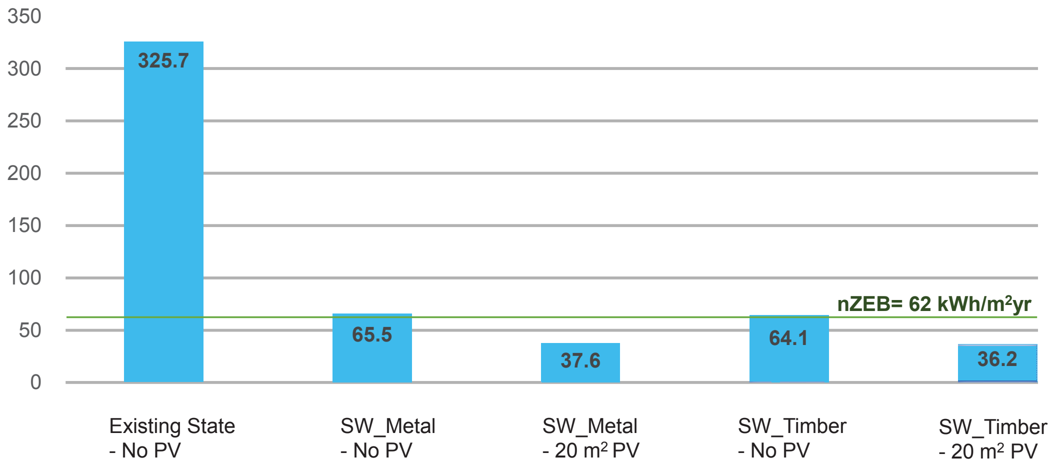

FIG. 15 Primary Energy consumption for existing and renovated state (with and without installed PV) in kWh/m^2/yr

The limit of the examined building to reach nZEB, based on national building regulation (KENAK), is 62 kWh/m^2. It can be observed that the nZEB state is feasible in all examined renovated cases with incorporated PV panels. The SmartWall application without installed PV marginally fail to reach the nZEB limitation. On the other hand, it is worth mentioning that the timber-frame SmartWall application presents a similar performance towards the nZEB state compared to the metal-frame alternative.

Focusing on the renovation solution provided, FIG 16 demonstrates the energy profile of the simulated storey using a metal-framed SmartWall. Energy also refers to electrical equipment and lighting consumption, as well as the PV production (with negative values) throughout the simulated year. 65% of the total required electricity of examined apartments refers to heat pump consumption, from which 24% accounts for heating, 28% for cooling and 13% for DHW. The rest of the end-use refers to electrical and lighting equipment (34%) and auxiliary systems (1%) (fan coils, circulation pumps, etc.). Power production from installed PV is significant throughout the year, while the total amount of self-consumed (62%) and exported to the grid (38%) electricity sufficiently counterbalances the total consumption during the months with high solar potential. Similar results are provided for the timber-framed SmartWall.

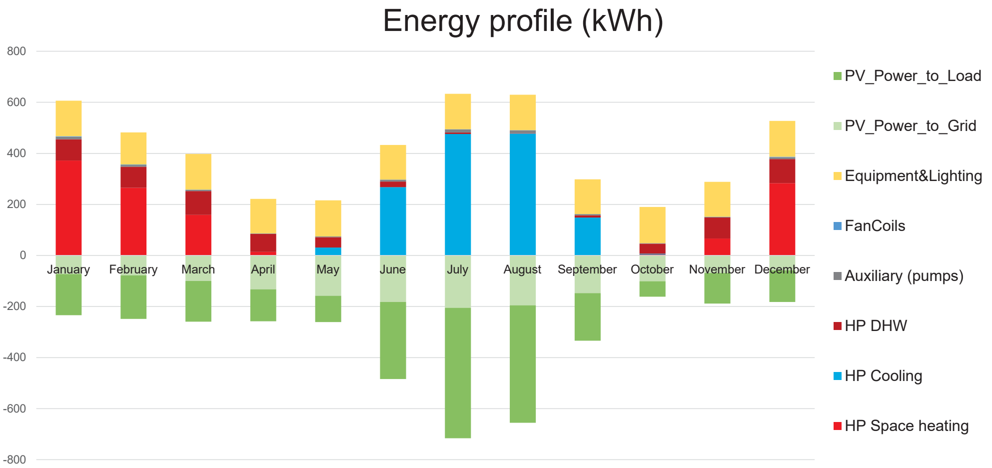

FIG. 16 Energy profile of renovated state for pilot building - SmartWall with metal frame

As far as thermal comfort is concerned, two box-plot figures (FIG 17 and FIG 18) illustrate the PMV deviation in the monitored zones. The highlighted (with cyan colour) thermal zones correspond to the conditioned zones, whereas the rest refer to other auxiliary rooms (WC, corridors, etc.) without any installed heating or cooling system. The red line of each column depicts the median PMV value in each zone, while the top and bottom edges of each box visually represent the upper and lower quartiles, respectively (the upper quartile corresponds to the 0.75 quantile and the lower quartile corresponds to the 0.25 quantile). The lines (whiskers) that extend above and below each box connecting the minimum with the maximum value represent a much less dense data range.

In the existing state of the pilot building, all conditioned zones present median PMV values near zero, indicating satisfactory thermal comfort levels for the occupants. The vast majority of values are within the comfort zone. The discomfort index is 9.14%, meaning that in less than 10% of the simulated period, thermal conditions were outside the acceptable PMV levels (less than -0.5 or higher than 0.5).

Similarly to the existing state, the renovated scenarios present satisfactory thermal comfort levels for the conditioned zones. In specific, the SmartWall-conditioned rooms present smaller deviations (box heights) within the comfort levels, indicating a slightly more acceptable indoor environment compared to the existing state. The thermal discomfort index is calculated below 5% for both renovation scenarios, meaning 3.9% and 4.2% for the metal and the timber-based SmartWall, respectively.

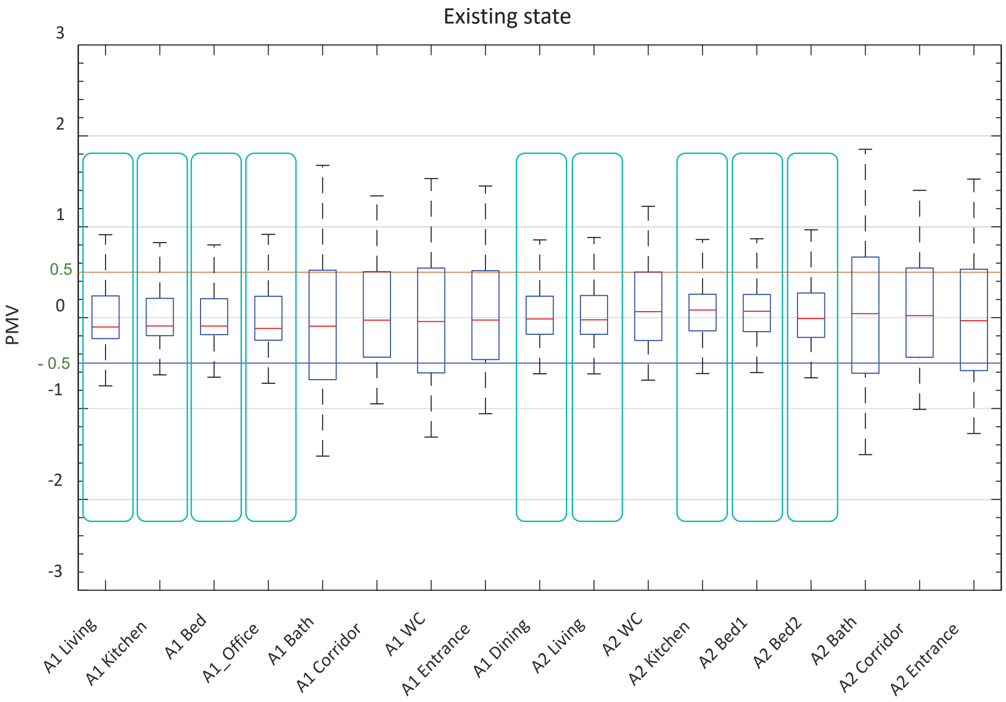

FIG. 17 Thermal comfort deviation - Existing state

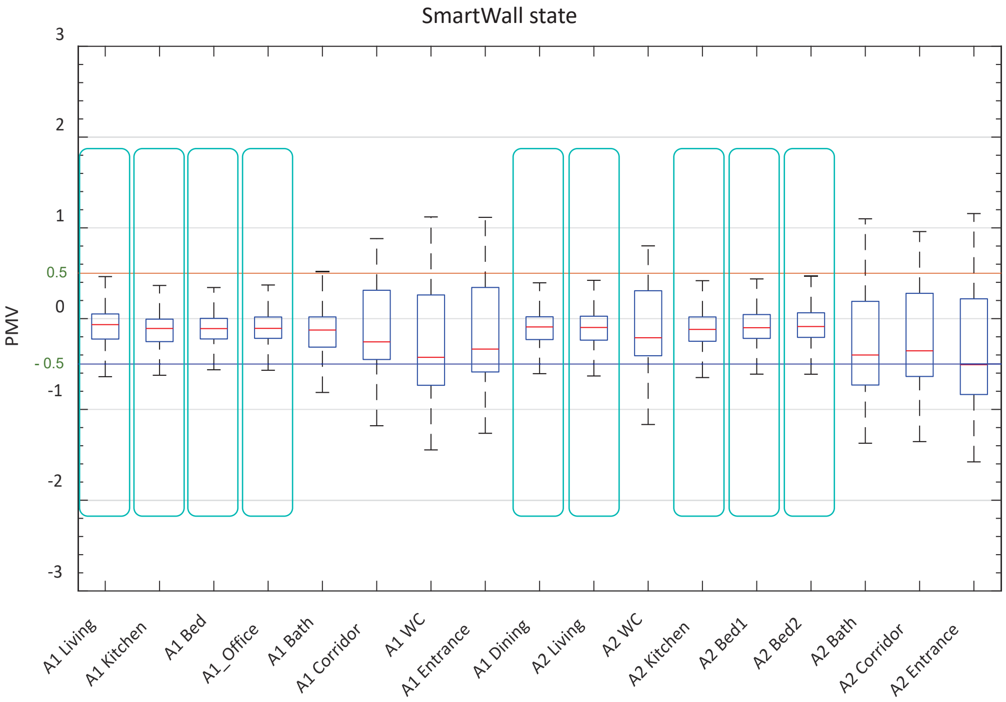

FIG. 18 Thermal comfort deviation - Renovated state

5 DISCUSSION – CONCLUSIONS

The present work examined the deep retrofitting solution of SmartWall – a multifunctional prefabricated façade panel with integrated HVAC components. Two different SmartWall designs incorporating conventional (metal frame, mineral wool, gypsum board, etc.) or more environmentally friendly (timber frame, OSB, wood fibre blow-in insulation, etc.) materials are considered renovation scenarios for a storey of a multi-family building located in Attica, Greece. The energy performance of the renovated floor was assessed, taking into account the indoor thermal comfort conditions. The outcome of the evaluation is summarised in the following highlights.

- SmartWall application achieved a simultaneous upgrade in both the building envelope – by reducing heat losses – and the efficiency of HVAC systems.
- The demands for heating and cooling presented a reduction of 71% after the renovation with SmartWall compared to the existing (poorly insulated) state.
- Timber-based type, despite the lower U-value, proved to be marginally more efficient in terms of thermal performance since its application resulted in a higher reduction of thermal energy demand in the examined case.
- A similar SmartWall application in Berlin with a thicker insulation layer (240 mm) is presented in (Katsigiannis et al., 2022), highlighting a heat loss reduction of 77%. This indicates the effectiveness of such façade upgrades in diverse climates with varying heating intensities.
- nZEB state can be achieved with both SmartWall alternatives with incorporated PV considering the limits of national building regulation. Excluding the PV installation, the renovation marginally fails to reach the nZEB state.
- Thermal comfort conditions are within the acceptable levels for all examined cases. However, the thermal discomfort index, which corresponds to the occupancy hours outside the acceptable range, presented an improvement by ca. 5% in the renovated scenarios compared to the existing state.

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