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Energy assessment of a residential building renovated with a novel prefabricated envelope integrating HVAC components

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Abstract. Off-site prefabrication systems continuously gain attention in the building industry as they combine fast construction with fewer and more sustainable resources as well as minimize disturbance for occupants. In this direction, adaptable off-site prefabricated envelope components with embodied HVAC systems have been developed as an effective renovation solution. They can minimise thermal losses through the envelope while at the same time integrated HVAC systems efficiently maintain indoor thermal comfort conditions. In this study, a “Plug-and-Play” prefabricated envelope component incorporating HVAC systems is examined as a solution for the deep renovation of a typical single-family residence in Berlin, aiming to reach NZEB state. This versatile modular system, called SmartWall, can be installed either to the exterior or the interior side of the external wall, incorporating timber-based frame, boards and insulation, high-performance windows and a slim-type fan coil. The evaluation of this prefabricated system is investigated with respect to its energy performance both at component and building level, as well as its calculated embodied energy. The results indicate a reduction of 89% total primary energy highlighting that NZEB state can be ensured if the SmartWall application is combined with sufficient photovoltaic modules. The climate change potential contribution of such retrofit indicates a significant amount of embodied energy, which is nevertheless counterbalanced by the operational energy savings within the first few years after the implementation.

Keywords: NZEB, deep renovation solution, prefabricated all-in-one envelope kit, TRNSYS building simulation

1. Introduction

In Europe, the residential sector is responsible for 26% of energy consumption from which approximately 80% is consumed for heating/cooling and DHW [1]. The need for more energy efficient residences seems to be urgent considering the urbanization trends in Europe as well as the condition of existing buildings in urban areas. According to EU Building Stock Observatory [2] most residential buildings were built before thermal standards were introduced, meaning poorly or even non-insulated

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facades. The latter, in combination with the low renovation rate of existing buildings, hinders reaching EU-energy targets [3]. Towards this goal, successful retrofitting solutions should not only upgrade the building energy performance to reach NZEB standards, but additionally take into account renovation time and cost to facilitate their market and user uptake. Off-site prefabricated construction is either way attracting a fresh wave of interest and investment on the back of changes in the technological and economic environment [4]. Prefabricated holistic technologies that ensure time and cost reductions and combine the envelope improvement with high-performance energy systems for heating, ventilation and cooling, could offer various attractive “Plug-and-Play” products.

The high expectations of NZEB state, through deep renovation schemes, require efficient integrated HVAC and renewable systems as well as full exploitation of heat recovery and passive systems. Smart windows, multi-functional coatings and adaptive control systems also play a crucial role in the energy balance and optimization of the multifunctional façade panel. The integration of HVAC systems into multifunctional façades is a key technology that numerous EU-funded projects have dealt with. Many of them aim to assess what is feasible or technically suitable by integrating various combinations of heat pumps, convectors, ventilation (mostly mechanical) and heat recovery systems, embedded RES, thermoelectrical parts and smart control systems [5].

Implemented all-in-one façade solutions that have been explored and developed within the EU funded research framework demonstrate the extended work done on renovation to reach NZEB state. State-of-the-art technologies are used for prefabricated modules in several deep renovation projects, such as MORE-CONNECT, BERTIM, E2VENT, iNSPiRe and 4RinEU [3]. In some cases, prefabricated modules combine HVAC units and integrated RES that are designed as a prefabricated box i.e., to fit on the roof as in MORE-CONNECT project or as integrated roof modules as developed in BERTIM [6] [7]. In some cases high-efficiency HVAC systems are incorporated into the wall assembly (MORE-CONNECT, E2VENT and 4RinEU) and/or they even utilise high-performance photovoltaic, energy storage and heat recovery systems (MORE-CONNECT, E2VENT, iNSPiRe and 4RinEU) [8] [9] [10] in order to drastically decrease the primary energy use.

In the frame of PLURAL project [11], similarly to the aforementioned technologies, an all-in-one prefabricated deep renovation solution has been developed. This prefabricated kit called “SmartWall” which is designed and built with high thermal performance materials, incorporates a HVAC distribution system, aiming to reduce thermal losses through the envelope as well as increase the heating, cooling and ventilation efficiency.

In this paper, a three-level evaluation has been followed. A component-level analysis is conducted in order to determine via COMSOL the thermal bridges occurring from the integration of the HVAC distribution component and the window. Secondly, a building-level simulation is performed via TRNSYS evaluates the energy of a deep refurbished detached house located in Berlin, where the all-in-one SmartWall solution is virtually implemented. Last but not least, the embodied energy and the corresponding Greenhouse Gas emissions of such retrofitting solution have been calculated.

2. System and simulation overview

2.1. SmartWall description

SmartWall is a multifunctional wall system that combines several technologies including fully prefabricated walls with timber-based frame and insulation materials, slim-type fan coil for heating and cooling and high-performance windows. It can be installed either to the building’s exterior as a façade wall, or to the interior in case there are space or aesthetical restrictions. Photovoltaics can be installed either on the external wall or alternatively on the roof, if the building geometry includes balconies or volumes that shade the vertical external surfaces. It is versatile and easily adjustable to any dimension up to 4m on height per module and can be decorated with any kind of finishing material. SmartWall can be applied in every climate within Europe, while it is more effective for climates with significant cooling demand. As a modular “Plug and Play” panel (Figure 1 and Figure 2), the SmartWall is constructed containing flexible piping and electrical wiring connections that can accommodate either the existing or a new heating/cooling system and electrical services (switches, plugs etc.), significantly reducing the on-site installation time.

The effectively insulated façade combined with high performance double or triple pane low-e windows - with mechanical ventilation with heat recovery (70%) within the frame - are in most cases enough to convert the renovated building towards NZEB status. Windows can also be combined with smart blinds operation for optimum visual and thermal comfort conditions. Secondly, almost all materials are selected with respect to their thermal and environmental-friendly behaviour. Moreover, SmartWall implementation can lead to complete energy autonomy by means of high-performance PV panels installed either on the roof or on the external surface of the SmartWall.

Figure 1. Internal and external side of SmartWall

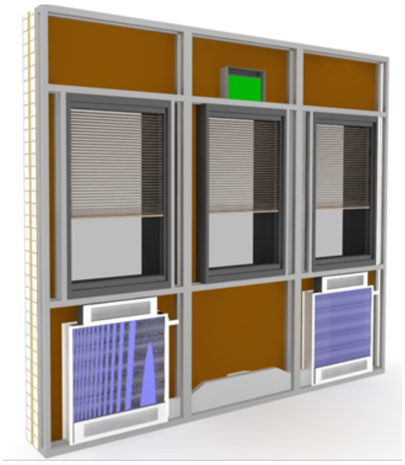

Figure 2. SmartWall incorporating slim-type fan coil, openings and other components

2.1.1. Material and design characteristics. In order to anticipate almost every building's requirement, the SmartWall has been developed with "generic" dimensions of 120 cm (l) x 300 cm (h) x 37.2 cm (w). The dimensions of a SmartWall panel, in case of an actual implementation depend on several parameters such as the height of each storey of the building, 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.

The frame of the SmartWall panel consists 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 soft wood are used for the insulation layers while OSB (Oriented Strand Board) and weather boards are combined with a ventilated layer to complete the wall assembly as presented in Figure 3. A typical SmartWall also includes a window, with dimensions 97.5 cm × 101.75 cm and a fan coil unit with dimensions 90.5 cm × 88.6 cm ×11 cm. The incorporated fan coil occupies a significant part of the insulation layer; therefore a 20 mm thick Vacuum Insulation Panel (VIP) is installed at the rear side of the fan coil, resulting in a homogenous thermal transmittance for the whole SmartWall area. The total area of Smart Wall is 3.6 m^2, where the opaque area is equal to 2.6 m^2 and the window area equal to 1.0 m^2. The windows consist of an aluminium frame and double pane glazing with argon fill with U_{value} equal to 1.2 W/m^2K.

The materials used in the SmartWall assembly as well as their thermal properties taken into account for the simulation process are presented in Table 1.

Two wall panel versions are considered for the current simulation analysis. One “blank” panel with all the aforementioned layers without any integrated components or openings (type 1) and the SmartWall panel which incorporates the HVAC systems and the windows (type 2).

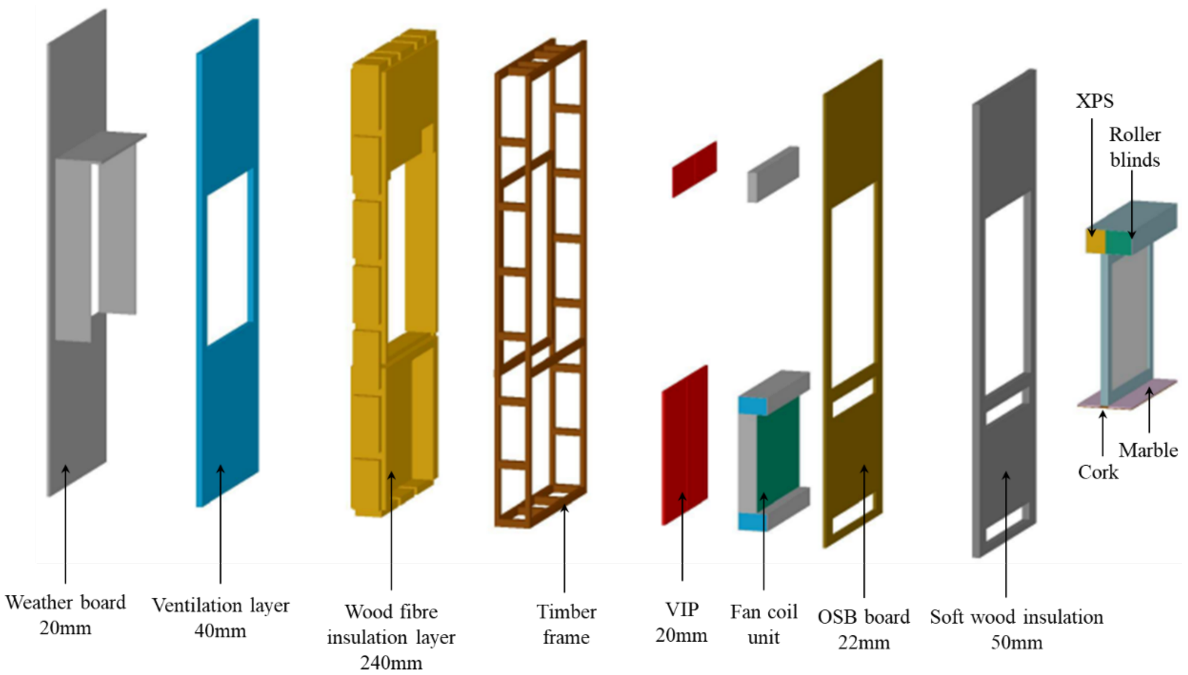

Figure 3. Configuration of SmartWall

Table 1. Thermal properties of materials used in SmartWall

SmartWall material	Density (kg/m^3)	Specific Heat Capacity (J/kgK)	Thermal conductivity (W/mK)
Clay plaster	1680	1450	0.58
Climate board	500	1450	0.14
Oriented Strand Board (OSB)	595	1700	0.13
Wood-fiber insulation	40	2100	0.038
Wood-fiber board	270	2100	0.048
Soft wood insulation	60	2100	0.036
VIP	195	800	0.006
Timber batten-counter batten (for rear ventilation)	560	1500	0.12
Weather board	500	1450	0.14

2.1.2 Energy system characteristics. In the current study, the SmartWall is combined with a low temperature air-to-water heat pump for both heating and hot water production. The slim-type fan coil, incorporated in the SmartWall, is responsible for distributing the conditioned air inside each room. The heat pump suppling the building with domestic hot water is assisted by a vacuum solar panel of 3.2 m^2 area. A 20 m^2 photovoltaic system is also installed on the roof of the building for electricity production. An overview of the layout of the SmartWall auxiliary systems is presented in Figure 4.

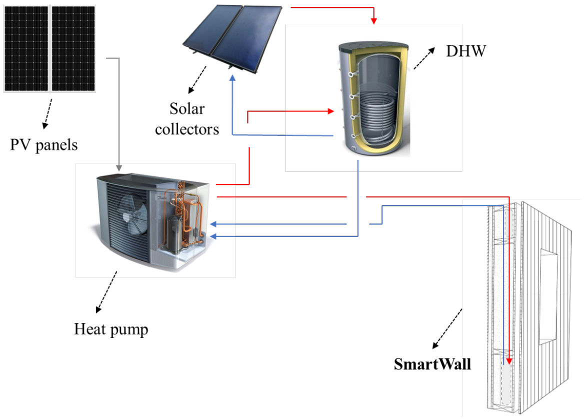

Figure 4. Example of SmartWall auxiliary system

2.2. *Modelling of the system*

For this study, a two-step simulation methodology is followed. Initially, a component level analysis held in COMSOL, for the calculation of the wall thermal transmittance including the effect of thermal bridges caused by all integrated components (window, fan coil etc.) on SmartWall (type 2). Then, a building-level assessment simulated in TRNSYS is performed, where a typical detached house located in Berlin is renovated using SmartWall. The outcome of the component level analysis that calculates the equivalent U-value of SmartWall is used as an input for the simulation of the whole building. In the building level analysis, the renovated state of the building is compared to its existing state, in order to quantify the impact of envelope upgrade with the SmartWall system.

2.2.1. Component level approach – COMSOL simulation. The analysis of the building envelope according to ISO 10211:2007 *[12]* is a steady state approach aiming to the calculation of the equivalent thermal transmittance (U-value) or equivalent thermal resistance (R-value) taking into account all thermal bridges. The SmartWall panel structure along with the presence of fan coils at the space between the rectangular frames creates non-negligible thermal bridges.

For the component level analysis, each SmartWall type is simulated by means of the commercial CFD package COMSOL in steady state conditions. The boundary conditions consider indoor and outdoor temperature 20 and 0 °C respectively, while the heat transfer coefficient (h_{out} and h_{in}) is assumed 25 W/(m^{2}K) for external and 7.69 W/(m^{2}K) for internal environment. Thermal properties of the assigned materials are presented in Table 1. The fan coil is assumed to consist of a 3 mm thick steel box and the volume inside the metal box have properties similar to unventilated air layer. The fan coil inlet and outlet are also assumed to be made by a 3mm thick PVC box with unventilated air. By using symmetries of the geometry of SmartWall, the size and computational time is significantly reduced.

The total heat flow, Φ, which passes through each configuration, is obtained by the simulation results. Hence, the equivalent U-value, U_{eq}, is calculated by the following equation:

$$U_{eq,SmartWall} = \frac{Q}{A_{SmartWall}(T_{in} - T_{out})} \tag{1}$$

For the geometries which include window or glass door, the equivalent U-value is calculated by the equation:

$$U_{eq,SmartWall} \cdot A_{SmartWall} = U_{eq,Wall} \cdot A_{Wall} + U_{Window} \cdot A_{Window} \tag{2}$$

where Q_{wall} is the total heat flow that passes the external surfaces and A_{wall} the area of Smart Wall without the window, U_{win} and A_{wind} are the U-value and the area of window (including the glass and the frame).

The thermal transmittance of SmartWall without any impact of thermal bridges (U_{clear}) is calculated equal to U_{clear}=0.106 W/(m^2K). Figure 5 presents the simulated geometry of SmartWall panel and the temperature contour at steady state conditions. As shown in the contour illustration, the VIP layer creates a significant temperature gradient behind the fan coil improving the thermal performance of the prefabricated wall panel. In order to determine the appropriate VIP thickness, a parametric analysis has been conducted ranging from 0 to 30 mm. The outcome (Figure 6) indicates that the most effective thickness for the VIP is 20 mm in terms of energy and cost. The presence of window, metal boxes (for roller blinds) and fan coil create significant thermal bridges, increasing the wall U-value by 28%, from 0.109 W/(m^2K) (of blank type (a)) to 0.139 W/(m^2K) (SmartWall, type 2). For the whole building simulation, the thermal conductivity of the incorporated materials is modified such a way to achieve the above thermal transmittance [13] [14].

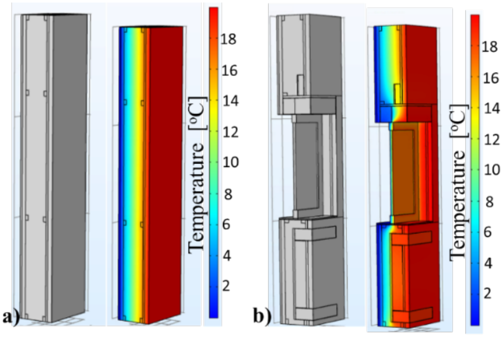

Figure 5. Model of SmartWall blank type1 (left) and type 2 with integrated components (right) temperature contour at steady state conditions

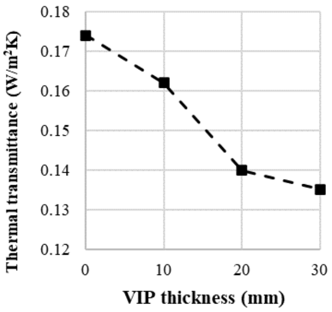

Figure 6. Parametric analysis of VIP thickness effectiveness

Building level approach – Operation (TRNSYS simulation). The TRNSYS software has been used in order to simulate SmartWall components and their supply systems, while quantifying their potential of upgrading the building energy performance. Its libraries offer a wide variety of useful components, whilst the dynamic energy analysis is capable of accurately simulating transient HVAC system's behavior. An overview of the model set up in TRNSYS is depicted in Figure 7. The main components of the model as well as their functionality presented, are developed in three main segments with respect to the active systems.

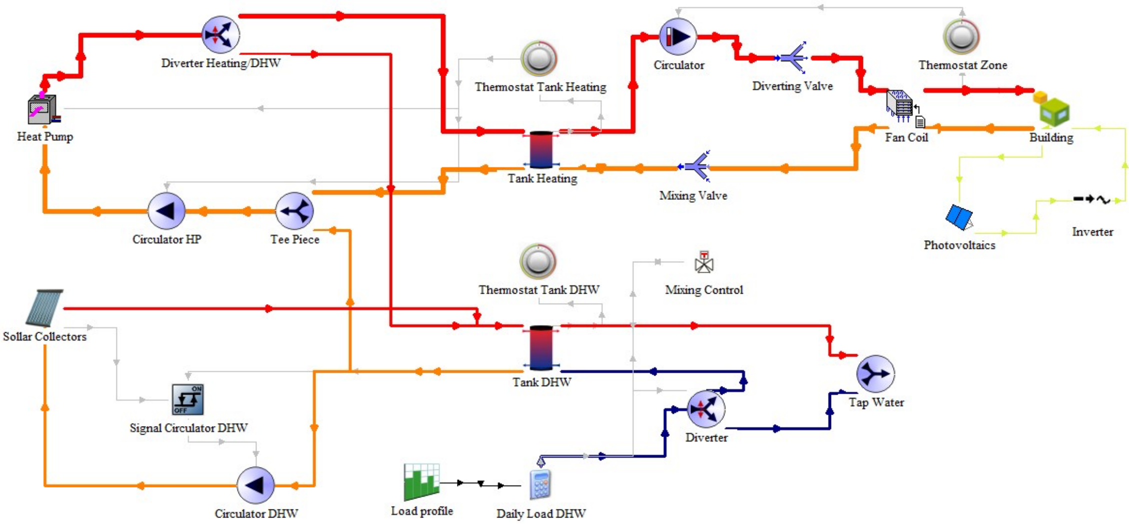

Figure 7. SmartWall system modelled in TRNSYS studio

The building unit (Type56) incorporates all parameters and regimes concerning the building i.e., the geometry and operation (occupancy, heating schedules etc.) and elements' characteristics (walls, roof, floor, windows etc.). The distribution inside the zones is accomplished by the fan coil unit and its corresponding thermostat. One variable speed 2-pipe fan coil with rated capacity of 2.18 kW for heating, is assigned to each thermal zone. It is the responsible terminal device to supply conditioned air in the zone, in accordance to thermostat's control signal. The circulating water arriving to the fan coils is conditioned in an air-to-water heat pump. A single-stage, low temperature heat pump is used with rated capacity of 9.37 kW for heating and. It is the main source for heating water for both space heating and DHW, maintaining the water inside the tanks in different temperature amplitudes throughout the year, for economic and environmental purposes. The used tank stores hot water (300 L capacity) from the heat pump, which is sent to the fan coil. It connects the source side with the load side, while enabling the use of the same heat pump for both space heating and DHW, along with improving its operation mitigating the constant start-stops.

A similar storage tank (300 L) is used for DHW receiving hot water from both solar collectors and heat pump, providing it to building taps for consumption in accordance with a dynamic load profile. An evacuated tube solar collector component enables incidence angle modifiers (IAMs), which heats water for DHW. A small pump circulates the fluid taking into account the medium's temperature difference between the collector and tank. When the hot water from the solar collector is not enough, the same heat pump that supports the space heating switches on. Its DHW contribution control combines a forced hourly profile with a thermostatic control of the water temperature into the tank. Specifically, it regulates the stored water temperature at different set points over the year, by heating it for a total of 2.5 hours distributed through the day during the heating period and continuously (whenever it is necessary) during cooling season.

Aiming to model the power generation, a PV array component is considered. This detailed component can model monocrystalline, polycrystalline or thin-film PV panels, while encompassing a maximum power point tracker (MPPT). Ten PV high-performance modules are connected in series, for a total of 20 m^2 installed area. Additionally, an inverter is necessary for power transforming purposes. It converts the DC power produced from the PV, to AC needed from almost every device in a house, whilst sending it to the load and/or feeds it back to the grid if there is excess power produced. The model does not consider any battery used for electricity storage. Interaction with the utility is assumed to operate under a net-metering regime, where the excess power produced is directed to national grid and subtracted from later electrical consumption.

2.2.2. Building level approach - Life Cycle perspective. The environmental impact of the additional capital equipment due to the SmartWall implementation is assessed in terms of its potential contribution to climate change (*in* CO$_2$eq) and the primary energy demand.

Table 2. Aggregated material inventory for capital infrastructure

Infrastructure		**Systems (fan coil, heat pump & PV)**	
SmartWall material	**Weight (kg)**	**SmartWall material**	**Weight (kg)**
Clay Plaster	2855.9	Metal Sheet (Fan Coil)	270
Climate board	2124.9	Reinforcing steel	120
OSB	4501.5	copper	35.2
Wood fiber insulation	6055.2	steel, low alloyed	32
Weather/soft wood fiber board	3131.4	tube insulation	16
Fleece	1054.5	lubricating oil	2.7
Drainage layer	4218.2	polyvinylchloride (PVC)	1.6
Root resistant membrane	249.4	refrigerant R32	4
Vacuum Insulation Panel	34.41	PV panels	20 (m^2)

The functional unit for comparative life assessment from cradle to gate was 1 m^2 floor area per year. Table 2 summarises the materials that have been added to the existing situation. Primary data were collected from SmartWall developers. For modelling the background processes, e.g. extraction of the materials, waste treatment etc., the study relied on generic data from EcoInvent v3.1 *[15]*. The system was modelled in SimaPro version 8.1.

3. **Building Case**

The examined building is a detached single-family house built in 1965 in Berlin, Germany. It consists of two floors and an unheated basement, and it is ranked as Energy Class F based on national building certification. An overview of current and renovated state and the positioning of the SmartWall are shown in Figure 8 and Figure 9, respectively.

Figure 8. Pre-renovated state

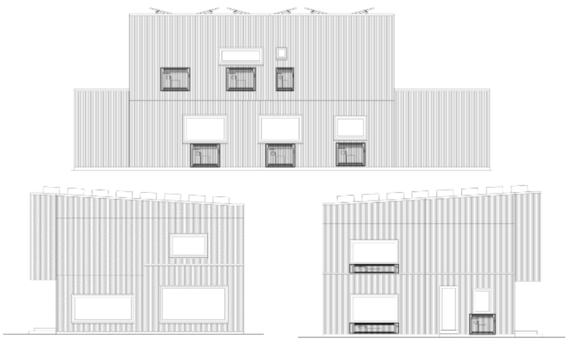

Figure 9. Renovated state with SmartWall panels

In the proposed deep renovation, some critical interventions at the building envelope and its HVAC systems with the implementation of the SmartWall component have taken place. Apart from the external walls where SmartWall panels are installed (with U-value 0.107 W/(m^2K) for type 1 and 0.139 W/(m^2K) for type 2), one roof level with the installed PV and one green roof have been additionally insulated with total U_{value} of 0.06 W/(m^2K) and 0.13 W/(m^2K) respectively. Each simulated room is considered as a unique thermal zone, with independent thermostatic control set for the boundary thermal comfort conditions at 20°C and 26°C, for heating and cooling period respectively. It has been verified via the simulation that the cooling need of the building is negligible. For heating and DHW, an oil boiler is used in the existing (pre-renovated) state, whereas in the renovated state the aforementioned system heat pump - solar collector is used.

The existing structure is depicted in Figure 8, while some general information and the assumed occupant profiles of the building are summarized in Table 3 with the corresponding values of both the existing and renovated state. During cooling period natural ventilation has been configured and an hourly DHW load profile has been assumed according to ASHRAE 90.1.

Table 3. Building case characteristics

Description			**Operation**	
	Existing	Renovated	Occupants	6
Gross Floor Area	267 m^2	284 m^2		
External Wall Area	272 m^2	279 m^2	Lighting	6.4 W/m^2
Windows opening Area	62 m^2	59 m^2		
Windows to Wall Ratio	23%	21%		
Gross Roof Area	159 m^2	176 m^2	Electrical devices	4 W/m^2
Total Volume	742 $m^3{}_1$	786 $m^3{}_2$		

Ventilation	0.5 h^{-1}	0.4 h^{-1}

4. Results

The outcome from the building level simulations indicates that the renovation solution with SmartWall panels significantly upgrades both the thermal performance of the envelope as well as the efficiency of the systems used for heating and DHW. Figure 10 illustrates the contribution of SmartWall's passive behaviour to the reduction of heat losses through the envelope.

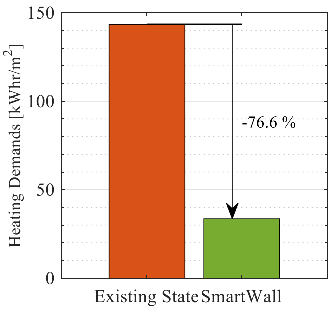

Figure 10. Heating demand reduction

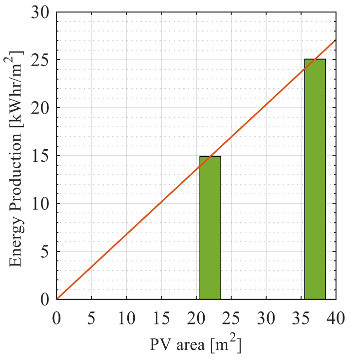

Figure 11. PV production to match ZEB state

Towards NZEB state, the renovated state of Berlin case appears to be within the NZEB standards, as proposed from EU directives [16]. The PV system produces 3,850 kWh/y or 13.6 kWh/m^2 annually (Figure 11). Based on the available contribution from photovoltaics, the annual energy consumed for HVAC and DHW can be fully covered by a PV system with area of 22 m^2. Moreover, as depicted in Figure 11., in case the PV panels area increased to 38 m^2 the whole consumption would have been covered, including the electricity needed for electrical equipment and lighting.

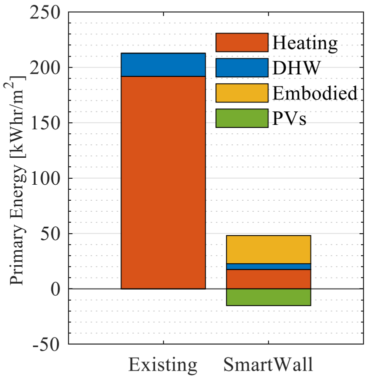

Figure 12. Primary Energy reduction

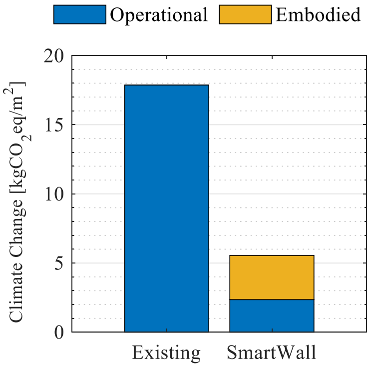

Figure 13. Potential contribution to Climate Change

Compared to the existing state, the presence of SmartWall decreases the demands for heating 77%, due to the energy upgrade of building envelope. Moreover, taking into account both the improvement of envelope's passive behavior (through the insulation) and the incorporated high-efficiency systems, the primary energy used for space heating and DHW is decreased by 89% (Figure 12). The final primary energy consumed in the renovated scenario is 22.7 kWh/m^2. The consumption of the oil boiler in the existing state, reaches 192 kWh/m^2 for space heating and 21 kWh/m^2 for DHW. The corresponding primary energy for the renovated state is 17.5 kWh/m^2 for heating and approximately 5 kWh/m^2 for DHW considering both the heat pump and the solar collector meaning a reduction of 91% and 75% respectively. The additional amount of embodied energy calculated in annual basis is 25.5 kWh/m^2 (considering a life span of 20 years). As far as the Greenhouse Gas emissions are concerned, Figure 13 shows that the primary energy saved during 20 years after the renovation, corresponds to a reduction of approximately 15.5 kgCO$_2$eq/m^2.

5. Discussion - Conclusions

The present study examined the thermal behavior of the SmartWall, a multifunctional prefabricated façade panel, as well as its impact when used as the "Plug and Play" kit for the renovation of a heating intensive residence in Berlin. The analysis developed at three levels: the energy performance at component level and building level as well as the embodied energy calculation at environmental level. The outcome of the evaluation is summarized in the following highlights.

- A single intervention to the façade achieves a simultaneous upgrade in both the envelope and the HVAC systems of the renovated building without aesthetically affect the building.
- In spite of the presence of the integrated fan coil system inside the SmartWall, which creates significant thermal bridges, the installation of 20mm thick VIP behind the fan coil reduces their impact. The total heat losses through the envelope were reduced by 77%.
- A reduction of 89% in primary energy could be achieved or a final consumption of 7.5 kWh/m^2 when taking into account the electricity produced from the PVs.
- SmartWall application can be used as just one deep renovation solution and lead to NZEB state, while the occurring energy savings can excessively counterbalance the embodied energy.
- The embodied energy in the capital equipment is not insignificant, although its inclusion in the assessment does not change the overall conclusion. The finding that the savings during the operation, which correspond to the overall primary energy reduction, are partially counterbalanced by the needs in capital equipment is in line with other research on energy saving innovations. For instance, IPCC concludes that capital infrastructure is the most determining factor for renewable energy systems' environmental performance. [17] The findings thus highlight the need for holistic assessments that account for the life cycle of a technical system in order to avoid environmental tradeoffs and rebound effects [18].

Given the domination of materials in the overall impacts, their treatment and recycling at the end-of-life of the plants is consequently important since it could lead to environmental savings due to the avoided production of materials. This calls for further research into the end-of-life treatment options and the maximization of recycling of construction and demolition waste. Last but not least, a technoeconomic assessment of such renovation solution would give a useful insight in future research.

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