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Research Article/ Review Article/ Perspective Article (Remove where relevant)

A Smart Multifunctional Modular Facade Panel for Building Renovation: A Comparative Assessment across European Climates of Energy Efficiency and Thermal Comfort

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Abstract

This study presents a comprehensive comparative assessment of a multifunctional modular facade panel for building renovation, integrating HVAC (Heating, Ventilation, and Air Conditioning) and photovoltaic (PV) systems. Three panel versions are analyzed: a conventional metal-framed version, a slim version with reduced thickness, and a timber framed version featuring bio-based materials. In addition to conventional thermostatic HVAC control, a thermal comfort control approach based on the Predicted Mean Vote (PMV) index is evaluated. Various wall panel configurations are explored by altering key components, including the insulation layer, the PV area (BIPV), and HVAC control strategies. These are virtually tested through scenario analysis on a case study building with different pre-renovation envelope thermal conditions. Four representative European climate clusters—Mediterranean, Oceanic, Continental and Nordic—are selected to investigate optimal renovation strategies in terms of energy performance and thermal comfort. Subsequently, building-level simulations are conducted using TRNSYS software to evaluate the performance of modular panels on a typical multifamily residence envelope with varying external wall U-values under different climatic conditions. A parametric study of 480 cases highlights key trade-offs between insulation, PV integration, and HVAC control methods. Notably, PMV-based control may occasionally lead to improved energy efficiency and occupant comfort compared to conventional thermostatic control. Overall, this study underscores the potential of multifunctional modular facade panels to enhance building performance in diverse European climates.

Keywords: Integrated HVAC Systems, PMV-controlled HVAC, Modular Facade Panel, Building Renovation, Energy Efficiency, Thermal Comfort

Highlights

- Building performance and NZEB compliance are strongly climate dependent.
- PV contribution is decisive for NZEB compliance across EU climates except Mediterranean
- The ECCI index shows comfort gains are nearly energy-free in mild climates but costly in colder regions.

1 Introduction

The building sector contributes substantially to global energy use and greenhouse gas emissions, with existing European buildings accounting for a major share of operational energy consumption. Meeting the targets of the European Green Deal and the EPBD necessitates improved energy performance, yet façade renovations are hindered by technical, economic, and architectural limitations—particularly in dense or heritage contexts—highlighting the need for efficient, easy-to-install, climate-adaptive solutions that boost indoor environmental quality.

Multifunctional façade systems, integrating insulation, renewables, and active control in prefabricated modules, offer a compelling avenue for deep renovation. These systems can significantly reduce heating and cooling demand and enhance comfort, though their success depends on local climate, building type, and occupant behavior. For example, ALvarez-Alava et al. demonstrated effective solar harvesting within prefabricated modular façades (Alvarez-Alava et al., 2023). Evola et al. reported over 50% reductions in primary energy for Mediterranean buildings using such modules (Evola et al., 2021).

Another promising innovation is the integration of decentralized HVAC components directly into façade panels. Adamovský et al. proposed adaptable, lightweight prefabricated systems that facilitate rapid renovation and high energy performance (Adamovský et al., 2022). Meanwhile, Zhu et al. developed a hybrid control system optimizing thermal comfort through PMV index (Predicted Mean Vote) - based feedback, enabling façade adaptivity (Zhu et al., 2015).

These advancements underline the potential of multifunctional façade systems to deliver deep renovation benefits—merging energy efficiency, ease of deployment, and occupant-centric comfort—aligned with Europe’s climate and energy objectives. In this regard, the present study conducts a comparative assessment of a multi-functional modular façade panel for building renovation, integrating both HVAC and photovoltaic systems. Three variants—a conventional metal framed panel, a slim-type version and a timber framed bio-based version—are evaluated implemented on a typical central-European residential apartment. Beyond standard thermostatic HVAC control, a PMV based comfort control strategy is investigated. A series of parametric simulations via TRNSYS explores 480 variations in insulation, BIPV area, and control approaches across four representative European climates (Greece, France, Austria and Sweeden).

2 SmartWall - A modular solution for deep retrofit

SmartWall is a multifunctional retrofitting solution composed of prefabricated wall panels that incorporate thermal insulation, optionally, a slim profile fan coil unit for heating cooling and ventilation, and high efficiency windows. Photovoltaic modules can be externally mounted on either the façade or the roof of the building. This wall system allows for both exterior or interior installation depending on spatial constraints and architectural preferences.

Designed as a modular plug-n-play wall panel, SmartWall integrates flexible piping and electrical conduits to facilitate instant on-site connection to both the existing and the additional HVAC and electrical infrastructure, thereby significantly reducing installation time. To reduce the integration side effects and the occurring thermal bridges, a 20 mm VIP layer is by design positioned in the rear side of the fan coil unit to maintain consistent thermal performance across the entire SmartWall panel.

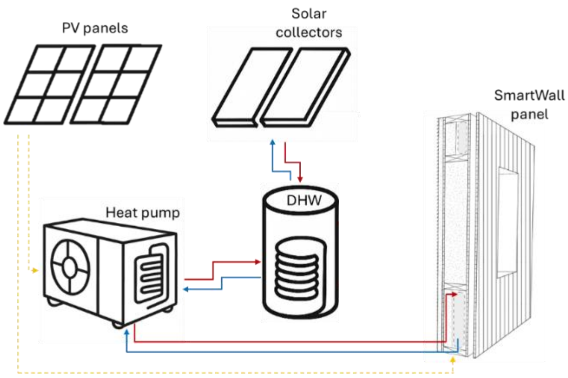

Figure 1.HVAC supply system for SmartWall network and DHW

The façade panel is equipped with triple-glazed low-emissivity windows consisting of a wood/aluminum frame (thermal transmittance, Uf = 1.4 W/(m^2·K)) and argon-filled triple glazing (Ug = 0.58 W/(m^2·K)), yielding an overall window thermal transmittance of Uw = 0.89 W/(m^2·K). The source of the HVAC system is a low-temperature air-to-water heat pump for heating and domestic hot water supply (Figure 1). The integrated slim-type fan coil distributes conditioned air within each room. Domestic hot water production is also supported by a 3.2 m^2 vacuum solar panel.

Apart from the energy and HVAC support system – which is common in all SmartWall applications – the thermal characteristics vary according to each wall design and layer configuration. Three wall designs are examined in this study following the real and virtual cases implemented within the frame of EU HORIZON - funded projects PLURAL, GREENEST and REHOUSE(Gerogiannis et al., 2024; Katsigiannis et al., 2022, 2023):

- The conventional version: metal-framed wall panel with conventional insulation (Figure 2 - left)
- The "eco-friendly" version: timber-framed wall with timber-based layers and bio-based insulation (Figure 2 – mid).
- The slim-type version: a thinner SmartWall type with high performance insulation (Figure 2- right).

Metal-framed SmartWall is supported by two frames fabricated from Hollow Rectangular Section (HRS) steel profiles (50 × 30 mm, 1.8 mm thickness). Thermal break spacers are installed at all fixing points except along the bottom edge, where structural constraints require HRS steel spacers. The insulation system comprises a 160 mm mineral wool core, supplemented by a 30 mm mineral wool layer with aluminium foil between the existing envelope and the new panel. The internal surface is finished with a 12.5 mm gypsum board coated with a multifunctional layer, or a cement board for external applications. Material specifications and thermal properties are presented in Table 1.The wall panel reaching a total thickness of 160 mm, including the fan coil unit, achieves an overall thermal transmittance of 0.23 W/m^2·K.

The second SmartWall configuration utilises timber-based materials with lower embodied energy for improved environmental performance. It consists of two lightweight timber frames, interconnected by horizontal timber supports and secured to the existing masonry through multiple anchoring and fixing points. Insulation is mainly provided by wood fibre blow-in material and additional softwood layers. The outer assembly combines Oriented Strand Board (OSB) and weatherboards with a ventilated cavity, as illustrated in Figure 2. The complete panel (with total thickness of 240 mm), including the integrated mechanical components, achieves a thermal transmittance of 0.17 W/m^2·K.

Finally, in the case of the slim type SmartWall is characterised by strict design requirements of a 70 mm total thickness. The frame is a 3 mm L-shape steel component with a 47 mm thermal break. The outer part is a gypsum board of 12.5 mm, and the main insulator is VIP, achieving a total thermal transmittance of 0.22 W/m^{2}K. It should be mentioned that due to the small thickness of the wall panel the fan coil unit is anchored on the internal surface and not integrated in the wall assembly.

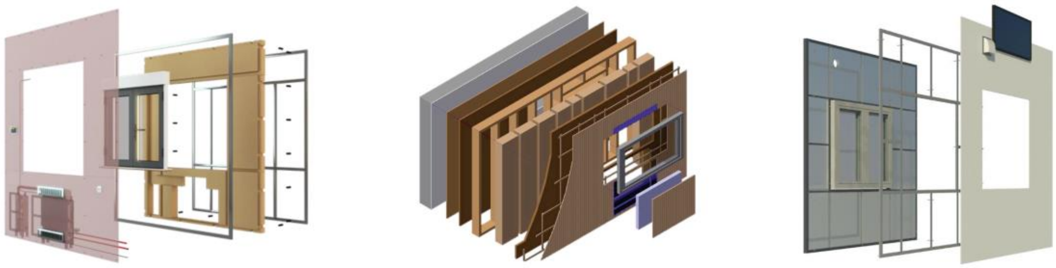

Figure 2. Examined SmartWall applications: Metal-framed (left), timber-based (mid) and slim-type (right)

Table 1. Thermal properties of SmartWall-incorporated materials

SmartWall type	Material	Thermal conductivity (W/mK)	Thickness (mm)	Specific Heat Capacity (J/KgK)
Metal-framed (Uvalue=0.23 W/m^{2}K)	Steel	60.5		434
	Gypsum board	0.20	12.5	980
	Mineral Wool	0.035	160	1030
	Mineral Wool with aluminium foil	0.035	30	1030
	VIP[1]	0.0075	20	800
Timber-based (Uvalue=0.17 W/m^{2}K)	Timber frame and studs	0.13		1200
	Weatherboard	0.13	20	2100
	Wood-fiber board	0.048	60	2100
	Wood fiber blow-in insulation	0.038	100	2100
	OSB (Oriented Strand Board)	0.13	22	1700
	Softwood fiber insulation	0.036	60	2100
	VIP[1]	0.0075	20	800
Slim (Uvalue=0.22 W/m^{2}K)	Steel	60.5		434
	Cement board	0.35	12.5	900
	Mineral wool	0.035	27.5	1030
	VIP[2]	0.0075	30	800

[1] *VIP layer used in the rear side of the integrated fan coil unit to minimize thermal bridges*

[2] *VIP layer as additional insulation layer to reduce wall U value*

3 Methodology

The implementation of the SmartWall solution alternatives is assessed in this study aiming to quantify the impact of such retrofitting solution in various circumstances. In specific, a parametric analysis is conducted via TRNSYS to assess the influence of key parameters: photovoltaic (PV) area representing renewable energy contribution, HVAC control strategy, and the existing wall's thermal transmittance (U-value). Four representative European climate zones (Mediterranean, Oceanic, Continental and Nordic) are considered to cover a wide range of environmental conditions (Maduta et al., 2023). Indicative corresponding weather and energy data are used from Greece, France, Austria and Sweden respectively.

The approach followed a systematic simulation framework. Each renovation solution is modelled with varying PV capacities and the two HVAC control alternatives. These configurations are tested under multiple conditions of the existing envelope in terms of heat losses. Additionally, the complete set of combinations are simulated across the four representative EU climate zones, generating a multi-dimensional dataset.

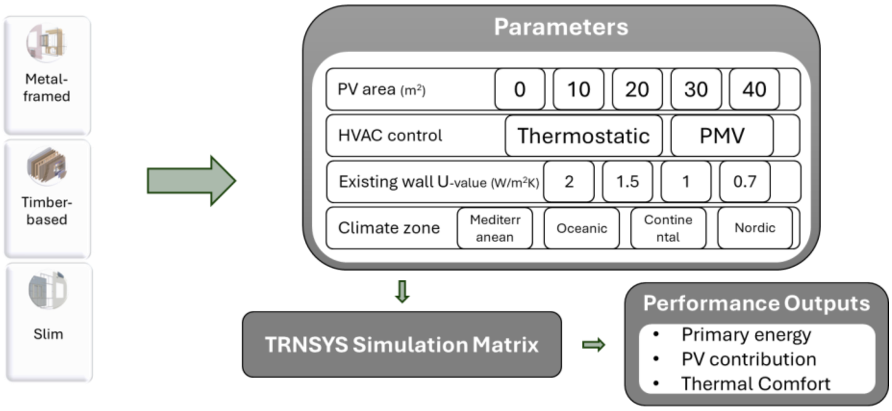

Figure 3. Methodological scheme for the comparative assessment of three SmartWall alternatives

The outcome of the 480 simulated cases is analyzed based on primary energy per floor area, the proportion of demand met by PV generation, and—where relevant—indoor comfort indicators. The methodology enabled a comparative evaluation of the renovation solutions' energy efficiency, PV contribution, and adaptability to diverse climatic contexts, identifying the NZEB-compliant designs by providing an evidence-based foundation for selecting optimal modular retrofit strategies.

3.1 Case study

The examined renovation solution is applied to one floor of a five-storey, post-war residential building with originally low thermal insulation. This section, representative of common European multi-family typologies, consists of four apartments, 71 m^2 each, arranged around an unconditioned central corridor (Figure 4). Table 2 summarises general building data and modelling assumptions. Since the focus is monopolized by the renovated surfaces (external walls), the horizontal boundaries (floor and ceiling) are considered as adiabatic surfaces. Operational parameters followed steady-state nominal values with correction factors, in line with the Greek Regulation on the Energy Performance of Buildings. Occupancy, lighting, and plug load nominal values are listed in Table 2, with corresponding normalization factors of 0.75, 0.10, and 0.50.

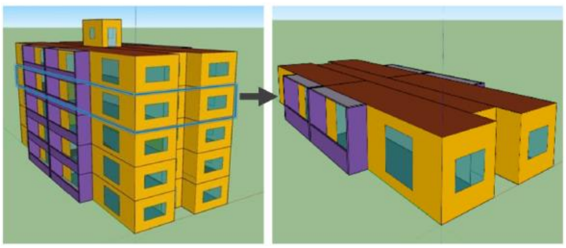

Figure 4.Building geometry of the simulated case

Table 2. Building information and operational characteristics

Description		Operation	
Type	Typical floor of multi-family building	Users	0.05 p/m^2
Gross floor area	282 m^2	Lighting	6.4 W/m^2
External wall area	270 m^2	Electrical devices	4 W/m^2
Bearing structure	20%	Ventilation heat recovery	75%
Window to wall ratio	22%	Infiltration	0.6 ACH
		Shading control	70% shade (in cooling season & Tout<28°C)

3.2 TRNSYS implementation

TRNSYS model considers all incorporated systems including HVAC (heat pump, fan coils, auxiliary equipment), solar supported DHW production and PV panels set-up with inverter and batteries (Figure 5). In order to ensure consistency and comparability of results across the four examined European climates (Greece, France, Austria, and Sweden), the heating and cooling systems were dimensioned for each case. Specifically, the nominal capacities of the heat pump and fan-coil units were systematically adjusted to account for the increasing thermal demand in colder climates.

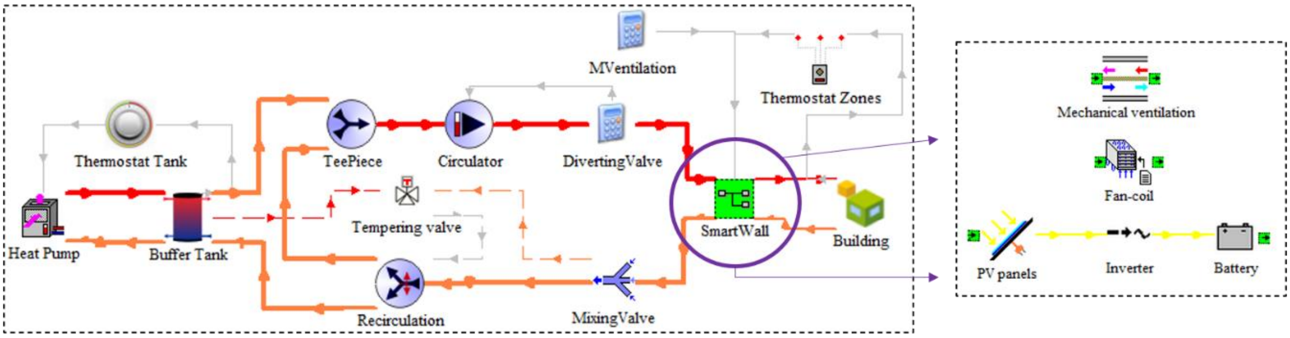

Figure 5. Systems simplified set-up and the SmartWall module as a macro-component

The examined two alternatives in terms of **HVAC control** is the simple zone thermostat and a PMV-based control. The thermostatic control is modelled by a zone setpoint of 21°C and 25°C with deadband 1°C for heating and cooling season respectively. That said, the fan coil unit in each thermal zone is set to regulate the temperature between 20-22 °C during winter period and 24-26 °C in cooling mode. In the PMV-based control, instead of using the zone thermostat, the PMV index is calculated each timestep based on Fanger's equation (Fanger, 1970). Apart from operative temperature, PMV considers radiant temperature, relative humidity, air speed within the zone, clothing factor and the metabolic rate of the occupants. The thermally acceptable conditions are indicated when PMV is close to zero ranging from -0.7 to 0.7. Negative PMV implies a cool sensation for the occupant while the positive values indicate excessively perceived heat. According to this input, a signal is generated to control the triple-stage fan coil unit. This control determines not only the mode (heating/cooling) and the temperature setpoint, but also the load ration of the fan.

Regarding the calculations, the relative air speed is assumed to be equal to 0.1 m/s, the metabolic rate is set equal to 1.2 met and external work equal to 0, assuming sedentary activity. Temperature is directly controlled by the systems, while relative humidity is indirectly controlled. As for the clothing factor, the ASHRAE standard is being used that indicates a daily value based on the ambient temperature at 6 a.m. (ASHRAE STANDARDS COMMITTEE 2013–2014, 2013).

3.3 Key Performance Indicators

To assess the outcome of the parametric simulations three main KPIs are considered: the primary energy, the thermal discomfort hours (TDH) and the Energy Cost of Comfort Improvement (ECCI). The primary energy for each case is calculated based on the amount of final energy consumed corresponding to each national electricity mix, the amount of on-site produced electricity from PVs and the Primary Energy Factors (PEF) (Balaras et al., 2023):

- 2.1 for Greece (Mediterranean),
- 2.3 for France (Oceanic),
- 1.63 for Austria (Continental) and

- 1.6 for Sweden (Nordic).

The PEF for the electricity produced from the on-site PV system and exported to the grid is 1.6.

The TDH is the index used to assess the overall thermal comfort conditions in each simulated case. The TDH corresponds to the hours of thermal discomfort virtually experienced by the occupant within a simulated period (of a year). The comfortable levels are defined based on the PMV index and more specifically class C, meaning PMV values below -0.7 and above 0.7.

To quantify the trade-off between energy need and thermal comfort, a performance indicator termed ECCI is introduced. The ECCI is defined as the ratio of the additional annual primary energy consumption between the thermostatic and the PMV-based control strategies to the corresponding percent (%) reduction in TDH. It therefore expresses the energy cost (kWh/m^2·a) required to improve the thermally comfortable occupancy hours by 1%.

4 Results- Key Findings

Three SmartWall applications are examined throughout 480 building scenarios focusing on energy performance and thermal comfort. The renovation alternatives are evaluated in terms of the vulnerability of the existing building case meaning the pre-renovated envelope's insulation as well as the climatic conditions. In Figure 6, all distinct simulation scenarios are illustrated revealing the clusters that correspond to the influence parameters: climatic conditions, type of SmartWall, the pre-renovated external wall Uvalue, the HVAC control, and the PV panel area. For instance, the first climatic zone cluster (first 120 scenarios-red markers) refers to Mediterranean, the second to Oceanic, the third to Continental and the fourth to Nordic. Similarly, the presentation of results follows the parametrization depicted in Figure 3. The primary energy consumption depicted in Figure 6 occurs from the aggregate of energy consumed for heating, cooling and DHW including the contribution from the on-site PV production.

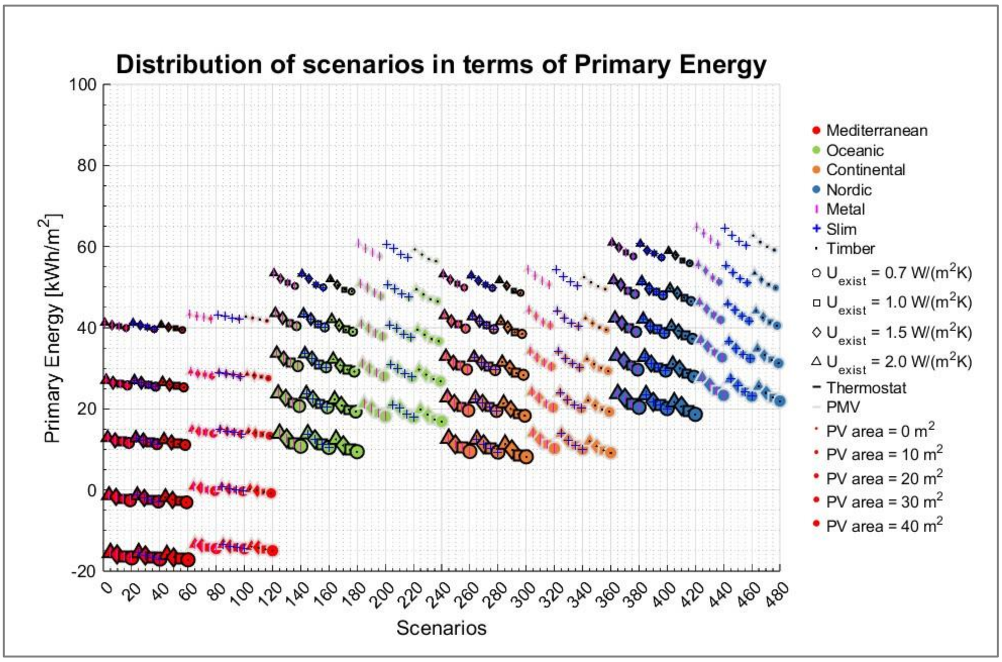

Figure 6. Primary energy consumption of renovated cases

From a holistic perspective, the distribution of the primary energy consumption highlights the relative influence of the examined parameters. Despite the PEF impact, which reduces the primary energy in the northern EU clusters (Continental and Nordic), climate conditions emerge as the dominant factor with Nordic scenarios showing the highest consumption and Mediterranean cases the lowest, reflecting the strong influence of heating demand. Among the renovation solutions, despite the 26% difference of the SmartWall Uvalue, the primary energy occurred remains in similar levels among all three types. The HVAC Control strategy has a clear effect, indicating that the PMV-based regulation yielding slightly higher consumption than the thermostat-based operation. In more energy intensive climatic conditions, the “energy cost” of thermal comfort is significantly higher. Finally, PV integration provides a systematic stepwise reduction in primary energy, with larger PV areas (up to 40 m^2) delivering the most significant gains. Overall, climate and renovation solution dominate performance outcomes, while HVAC control and PV integration introduce further improvements, and the effect of the pre-renovation envelope remains comparatively minor.

Isolating the worst-case scenarios from Figure 6 in terms of the Uvalue of the pre-renovated state (Uvalue=2W/m^2K) and the less effective SmartWall type (metal-framed with Uvalue=0.23W/m^2K) Figure 7 occurs. The NZEB thresholds[1] are depicted from the dashed horizontal lines: Greece (Mediterranean, red, 50 kWh/m^2), France (Oceanic, 30 kWh/m^2), Austria (Continental, 20 kWh/m^2), and Sweden (Nordic, 55 kWh/m^2). Notably, the marker size denotes the PV area (0–40 m^2), and the outline color indicates the HVAC control (black: thermostatic, grey: PMV).

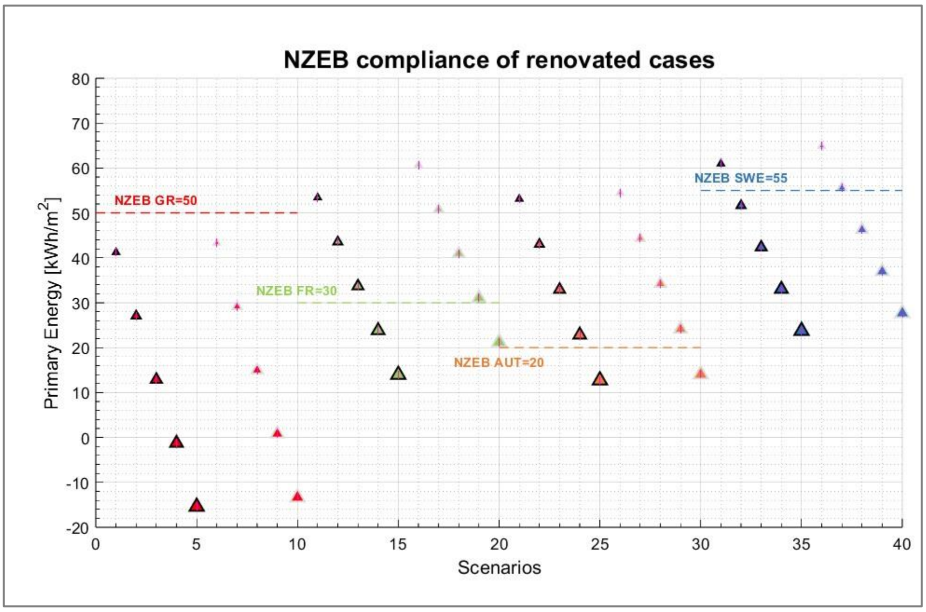

Figure 7. Primary energy per EU climatic zone and NZEB compliance

Figure 7 highlights the strong influence of both climate-specific NZEB definitions and renovation strategies on compliance. In the mediterranean cases, the NZEB state can be achieved even without the installation of PVs. In the oceanic climate, several cases meet the proposed levels with the condition of sufficient PV contribution (30 m^2 combined with thermostatic control or 40 m^2 of PV with PMV-controlled HVAC). In the continental cases, the stringent Austrian requirement (20kWh/m^2) makes compliance considerably more challenging with only scenarios of 40 m^2 PV area falling below the threshold. The Nordic limit (55 kWh/m^2) is comparatively lenient, allowing most scenarios to

[1] *https://www.energycharter.org/fileadmin/DocumentsMedia/EU4Energy/AM-NZEB-A.Baggioli-17.10.19.pdf*

achieve NZEB compliance with the contribution of at least 10 m^2 of PV. Overall, the decisive role of PV integration in reducing primary energy demand is clearly stated, while the comparison between thermostatic and PMV-based HVAC control indicates only modest differences, which may nonetheless be critical in borderline cases.

Among all cases the PMV-based control increases the primary energy by 5-7% compared to the thermostatic, while the TDH index is improved by 25 to 63%. It should be noted that the energy impact of HVAC control seems to be more significant in the heating intensive cases. However, as noted in Table 3, in the mediterranean cases the PMV control is more efficient during summer season.

Table 3. Primary energy consumption for heating/cooling in thermostatic and PMV-based HVAC control - Mediterranean climate

Control	Primary energy - Heating [kWh/m^2]	Primary energy - Cooling [kWh/m^2]
Thermostatic	9.6	44.3
PMV-based	16.9	39.6

The quantified outcome occurred in terms of the ECCI is presented in Table 4. The results highlight a clear climate dependency: in the Mediterranean and the Continental climate, primary energy consumption remains very low, and comfort improvements can be achieved with negligible additional energy use, as shown by the almost flat slope. These cases present moderate trade-offs, where reducing discomfort requires a tangible but still balanced energy increase. By contrast, the Nordic and the Oceanic climate exhibit the steepest slope, revealing that even modest comfort gains are accompanied by significant increases in primary energy demand, reflecting the mainly the heating intensity of the comfort improvement. Overall, the analysis indicates that while improving comfort is relatively inexpensive in milder climates, in colder regions the energy penalty can become substantial, requiring careful consideration when balancing comfort targets with NZEB compliance.

Table 4. Energy Cost of thermal comfort improvement for the four EU climatic zones

Climate	Control	Thermal Discomfort	Primary Energy	ECCI
Mediterranean	Tstat	25.95%	20.13	0.03
	PMV	1.06%	20.91	
Oceanic	Tstat	50.99%	38.96	0.11
	PMV	0.33%	44.42	
Continental	Tstat	59.59%	41.05	0.01
	PMV	0.45%	41.92	
Nordic	Tstat	63.74%	50.43	0.06
	PMV	0.42%	54.05	

5 Discussion - Conclusions

This study investigated the performance of three SmartWall renovation solutions across 480 scenarios, accounting for climatic conditions, envelope vulnerability, HVAC control strategy, and PV integration. By combining energy performance and thermal comfort analysis, the methodology provided a holistic assessment of how envelope retrofits interact with operational and climatic parameters to influence NZEB compliance and user comfort.

The analysis of 480 building scenarios highlights the central role of climate in shaping the energy and comfort performance of façade renovation strategies. Across all cases, climatic conditions proved to be the dominant factor, with Mediterranean buildings consistently achieving the lowest primary energy demand and Nordic scenarios the highest, reflecting the strong influence of heating loads. By contrast, the differences among the three SmartWall types, despite a 26% variation in U-value, were relatively minor, indicating that insulation upgrades alone have limited effect compared to broader climatic drivers.

NZEB compliance analysis revealed strong dependency on both national thresholds and PV integration. Mediterranean buildings could often comply without PV, whereas Oceanic cases required at least 30–40 m^2 of PV to meet the French standard. The Austrian requirement for Continental climates proved the most challenging, with compliance only achievable under maximum PV integration, while the more lenient Swedish limit enabled most Nordic cases to reach NZEB levels with limited PV. Importantly, the “energy cost” of thermal comfort improvement varied significantly: comfort gains in mild climates could be achieved with negligible energy penalties, while colder climates, particularly Nordic, required substantial additional energy for even modest comfort improvements.

HVAC control strategies introduced additional nuance. PMV-based regulation consistently increased primary energy consumption by 5–7% compared to thermostatic control, yet yielded significant comfort improvements, with TDH reductions of up to 63%. This effect was especially pronounced in heating-dominated climates, whereas in Mediterranean contexts PMV control performed more efficiently during summer cooling.

The quantified ECCI results further underline the climate dependency of comfort–energy trade-offs. In Mediterranean and Continental climates, comfort improvements incurred only marginal energy costs, whereas Oceanic and Nordic scenarios exhibited steep energy penalties for comparable comfort gains. These findings highlight that while SmartWall retrofits combined with PV integration offer a robust pathway to NZEB compliance, the balance between comfort and efficiency is highly climate-sensitive. In colder regions, strategies must carefully weigh comfort targets against the significant energy costs of achieving them.

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Data Availability Statement

All simulation inputs/outputs are available from the corresponding author upon reasonable request and institutional approval.

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study, in the analysis or interpretations of data, the writing of the manuscript, or in the decision to publish the results.

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