# Building energy retrofit: a multi-technology and low-impact renovation package

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***Abstract* – Energy retrofit and decarbonization of buildings constructed before 1990 is a key priority, since they still represent the majority of the European stock, having high energy consumption due to poor-performing envelopes, obsolete HVAC systems, and limited integration of renewable energy sources. To such aim, the EU-funded RE-SKIN project, which stands for Renewable and Environmental-Sustainable Kit for building INtegration, consists in a multifunctional retrofit toolkit composed of envelope technologies and smart HVAC systems that work synergistically to transform conventional buildings into energy-efficient and climate-resilient constructions. Based on a whole-building performance approach, the toolkit is designed to achieve high levels of energy efficiency and environmental sustainability, especially in areas of Europe experiencing increasing energy demand due to climate change. Interoperable building technologies and installations are also integrated: envelope solutions (thermal insulation and windows) ensure a reduction of thermal loads, while technical systems (BEMS, BIPVT, heat pump, fan-coils, power controller, storage systems) ensure energy efficiency and RES exploitation. The toolkit provides energy savings, optimization of energy fluxes, improved comfort, integration with the electrical grid, and circularity in material use. This paper describes the preliminary results of the toolkit application on two case studies, showing that the zero emission and net zero targets are fully achievable.***

***Keywords—Circular economy; building energy retrofit; ZEmB;***

## I. Introduction

The building sector, which is currently responsible for 39% of global energy related carbon emissions (28% from operational emissions, and the remaining 11% from materials and construction) [1] plays a strategic role and represents a promising lever in decarbonization, energy transition and sustainable development strategies.

Of course, the construction of new buildings with low carbon emissions mainly contributes to reducing the overall energy and carbon impact of the construction sector. However the problem remains for the existing building stock, especially for the fraction constructed pre-1990, which represents 70% of the total [2]. These buildings still have a rather long useful life but are definitely not adequate for modern energy and environmental challenges. Furthermore, their operation is still mainly related to the combustion of fossil fuels (e.g. natural gas, diesel, etc.), resulting in a local environmental impact.

In this sense we have to undertake a global campaign to retrofit the existing building stock, moving from the current renewal rate, about 1% annually, to a significant increase necessary to redevelop the entire building stock by 2050 of about 3-4% [3–5]. Moreover, the current retrofit interventions are mostly carried out according to an unbundled and fragmented approach, which results in the mere addition of ameliorative envelope or HVAC solutions rather than in their systemic and effective integration.

In addition to this, it should be noted that the improvement of the envelope performance rises concerns about the overall environmental performance of building, since it typically shift the environmental burden from the operational impacts to the embodied impacts associated with construction materials and systems [6]. On the other side the widespread replacement of traditional fossil-fuel-based boilers with electric heat pumps, alongside the increasing deployment of non-dispatchable renewable energy systems [7–9], presents several critical challenges. While these technologies are essential for achieving the decarbonization of the building sector, their implementation, if not supported by robust energy management strategies, may lead to a substantial increase in stress on the grid, potentially causing grid overload. Specifically, in the absence of integrated systems capable of harmonizing on-site generation and consumption, the growing electricity demand linked to widespread heat pumps use, especially during heating or cooling peak periods, could exacerbate power imbalances, as a large portion of the required energy might be drawn directly from the grid rather than being met through local renewable generation [10,11]. At the same time, the fraction of non-dispatchable renewable electric energy that is not self-consumed must be fed into the grid, with a consequent risk of overgeneration during peak solar hours, potentially leading to grid congestion, voltage instability, and even curtailment of renewable energy [12].

Thus, the RE-SKIN project has been funded in the framework of Horizon Europe with the aim to achieve the decarbonization goals avoiding all the issues abovementioned, concretely tackling technical, economic, and environmental aspects related to the energy retrofit of existing buildings [13,14].

RE-SKIN, which stands for *Renewable and Environmental-Sustainable Kit for building INtegration*, consists in multifunctional retrofit toolkit composed low-impact envelope technologies and advanced HVAC systems that work synergistically to reduce the $CO_{2\text{-eq}}$ emission up to 90% in operation phase, while simultaneously avoiding burden shifting related to embodied energy. In the present study, the application of the toolkit to two demonstration cases has been preliminary analyzed, highlighting its potential for significant energy and environmental performance improvement associated with the operational phase. A further study will address the estimation of overall emissions, including the environmental impacts of construction materials, through a comprehensive Life Cycle Assessment (LCA) approach.

## II. RE-SKIN PROJECT

The RE-SKIN project was developed in continuity with the European H2020 HEART project, compared to which it is intended to achieve a higher level of innovation [15]. Specifically, the project is dedicated to the development of comprehensive, sustainable, and multifunctional renovation solutions tailored to a particularly demanding geographical context: Central and Southern Europe (from 500 to 3000 HDD about) [16]. This region presents a wide spectrum of environmental conditions and is characterized by the need to address complex building performance challenges, including heating, cooling, and overheating, often exacerbated by the intensifying impacts of climate change [17]. The targeted area includes Central and Northern Italy, Andorra, North Macedonia, Northern Greece, France, Central and Northern Spain, Southern Germany, Northern Portugal, Albania, Serbia, Kosovo, Montenegro, Croatia, Bosnia and Herzegovina, Austria, the Czech Republic, Southern Hungary, Northern Bulgaria, Liechtenstein, and Slovakia.

The project is fully in line with the EU Renovation Wave strategy [18], which aims to improve the energy performance of buildings and, consequently, reduce the related consumption of energy and resources, with a view to a circular economy.

More precisely, RE-SKIN's target focuses on a specific share of the European building stock: multi-storey, brick-and-masonry residential, public and tertiary buildings of the second half of the 20th century. The large number of these constructions, their poor energy performance and the considerable similarities across countries make it an optimal objective for a wide-ranging intervention strategy. The corresponding amount roughly sums up to 1,000,000 residential buildings and around 500,000 public and tertiary buildings, for a total net floor area estimated of about 1.4 billion $m^2$.

Based on these premises, RE-SKIN's general objectives may be summarized as follows:

- enabling a large-scale nZEB cost-effective renovation in Europe, based on circular economy principles and also caring for architectural value;
- promoting total energy efficiency, optimising the shares of embodied, operational and renewable energy;
- promoting and exploiting energy-efficient technologies that are at the same time environmentally friendly;
- maximizing the energy performance of the building envelope, combining both passive and active features in a multifunctional package;
- enhancing synergies between envelope technologies and technical systems, also enhancing the role of BEM and ICT technologies;
- strengthening Smart Grid interactivity;
- being in full compliance with the technical screening criteria of the EU Taxonomy in order to attract sustainable investments in the post-project stage;
- applying and experimenting all the categories of the product life cycle in the perspective of the circular economy;
- pursuing the resilience of the system by including in the building performance also features able to cope with climate change and major disruptive events (strategy of climate change adaptation).

In detail, the RE-SKIN project develops an integrated, multifunctional system for the energy retrofit of existing buildings, comprising intervention on the envelope (roof and façade) and on the HVAC system.

The façade retrofit is based on the application of a self-supporting thermal cladding with bio-based insulation, designed for rapid, scaffold-free installation. It also houses wiring/piping for new technical systems. A wide range of finishes accommodates diverse architectural needs. Both roof and façade employ advanced, weather-resistant, waterproof materials suitable for extreme climates. The existing windows can be retrofitted using advanced techniques (e.g. glazing substitution, window films application, etc.) or substituted with low-embodied energy new windows in case retrofitting is not technically feasible.

The solution for roof retrofit incorporates a building-integrated hybrid photovoltaic-thermal (BIPVT) system that generates electricity and heat while providing thermal and acoustic insulation. It includes refurbished PV modules that supply electricity to building loads. The mounting structure housing photovoltaic modules replaces traditional roofing materials and ensuring aesthetic integration and waterproofing.

The air heated by the hybrid roof supports heating and domestic hot water (DHW) via a solar-assisted heat pump, and excess heat is dissipated through natural ventilation, aiding summer cooling. More specifically, the HVAC system includes an air-to-water DC heat pump connected to a hybrid photovoltaic-thermal system and to decentralized DC waterloop heat pumps (WLHP) installed in each room, enabling both heating and cooling via the building's hydronic network. In addition, an energy storage system composed by repurposed Electric Vehicles (EVs) batteries is also included, to store PV electricity [19]. All AC/DC power fluxes, including grid interfacing, are managed by a multi-input multi-output power converter.

The different hardware components will be complemented by a cloud-based platform, which optimizes the total energy performance and actively involves end-users in the building management. The platform will support control and energy management operations but also intervene at an early stage of the decision-making and design phases to select the most suitable system configuration, in terms of costs, consumption, embodied energy and emissions throughout the whole building's life cycle.

Designed under circular economy principles, the system prioritises recycled, repurposed, refurbished and bio-based materials to optimise energy efficiency and minimise environmental impact. It is scalable across Europe, enhancing both active and passive building energy performance year-round. A summary scheme of the main technologies adopted in the proposed toolkit is shown in the figure below (Fig. 1).

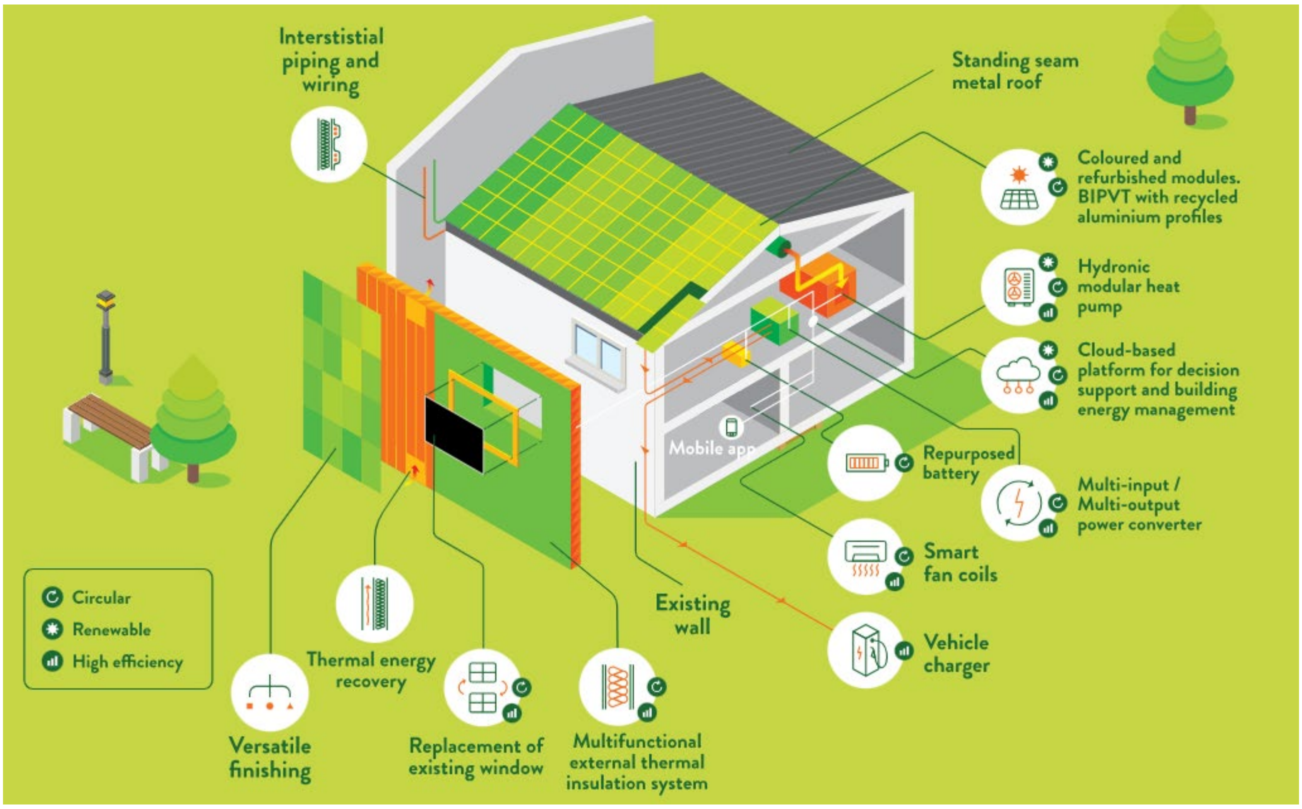

Fig. 1. RE-SKIN project – toolkit

## III. Case studies Assessment

In the initial phase of the project, building energy simulations (BESs) are carried out on two case studies aiming to assess the energy performance of the solutions proposed. The analyzed buildings are those that will be retrofitted within the project. In order to allow the complex energy simulation of the multifunctional kit, Grasshopper and Ladybug Tools software are used in combination. It should be noted that the latest is based on the EnergyPlus calculation engine which represents one of the main reference tools for detailed and accurate building energy analysis [20,21].

The two case study buildings have been specifically selected based on their high representativeness in relation to the whole target application context. These are located in Milan (Italy) and in Burgas (Bulgaria), which are characterized by 2477 and 2576 heating degree-days, respectively.

More in detail, the Italian one was built in 1965, it is a small building with 2 stories (about 340 $m^2$) with a surface-to-volume ratio (S/V) of about 1.52. The structure is made of uninsulated brick walls, uninsulated pitched tiles roof and simple double-glazing windows with PVC frames and an average window-to-wall ratio (WWR) of about 12 %. In terms of technical systems, a centralized gas boiler with radiators provides the heating demand and domestic hot water. The energy consumption of the building before retrofit, estimated according to the energy bills, is about 262.3 $kWh/m^2y$ (183.5 $kWh/m^2y$ and 78.8 $kWh/m^2y$ for heating and DHW, respectively).

The retrofit intervention of the Italian case involves the insulation solution for walls and roof described in Section 2, the application of solar control films on windows exposed to the East, South and West, while on North windows the application of a low-emissivity film. Moreover, regarding technical systems, the intervention includes the replacement of the existing boiler and radiators with the RE-SKIN air-to-water heat pump and WLHP terminals, which provide both heating, cooling. The HP also provides DHW, having a total nominal power of 18 kW both for heating/DHW and cooling. Furthermore, a BIPVT system characterized by 80 PV modules (active surface of 130 $m^2$) will be installed on the south pitched roof, with a peak power of about 20.8 $kW_p$ that will be connected to a battery energy storage system of about 18 kWh.

The Bulgarian case, on the other hand, was built in two phases (between 1936 and 1966) and it is a school building with 2 floors (about 321 $m^2$) with a S/V ratio of about 1.25. The structure is made of solid brick walls with exterior thermal insulation, an uninsulated pitched roof with tiles and double-glazing windows with an average WWR of about 23 %. In terms of the technical systems, a centralized gas boiler with radiators provides the heating demand, while DHW is not available in the school. The energy consumption of the building before retrofit (heating), according to the energy bills, is about 75.5 kWh/m$^2$y.

The retrofit intervention of the Bulgarian case includes the RE-SKIN insulation for walls and roofs, already described in Section 2, the retrofit of existing windows by replacing the double glazing with more performant ones, the replacement of the existing boiler and radiators with the air-to-water heat pump (nominal power of 18 kW both for heating and cooling) and WLHP terminals in each space. In this case, the BIPVT system is characterized by 39 modules (active surface of 64 m$^2$) installed on the south roof with a peak power of 10.14 kW$_p$ and connected to a battery energy storage system of about 35 kWh.

Both buildings were not equipped with a centralized air-conditioning system, thus ensuring poor summer comfort conditions. Just the Bulgarian building had some rooms air conditioners in the offices.

The following table reports the main information related to the two building case studies.

TABLE I
RE-SKIN- MAIN INFORMATION RELATED TO THE TWO BUILDINGS BEFORE AND AFTER THE RETROFIT INTERVENTION

| | **Italian case study** | | **Bulgaria case study** | |
|---|---|---|---|---|
| | *Pre-retrofit* | *Post-retrofit* | *Pre-retrofit* | *Post-retrofit* |
| **Envelope - average U-value (W/m$^2$K)** | | | | |
| **Windows** | 2.0 | 2.0* | 2.9 | 1.1 |
| **Walls** | 1.32 | 0.18 | 0.32 | 0.15 |
| **Roofs** | 0.33 | 0.20 | 1.09 | 0.15 |
| **Floors** | 1.86 | 1.86 | 0.27 | 0.27 |
| **Technical systems** | | | | |
| **Heating system** | Centralized gas boiler with radiators $\eta_{overall}$= 0.82 | Air-to-water heat pump with WLHP $\eta_{overall}$ = 4.80 | Centralized gas boiler with radiators $\eta_{overall}$= 0.80 | Air-to-water heat pump with WLHP $\eta_{overall}$ = 4.64 |
| **Cooling system** | N.A | Air-to-water heat pump with WLHP** $\eta_{overall}$ = 5.11 | Air cond. system with split units*** $\eta_{overall}$= 3.50 | Air-to-water heat pump with WLHP** $\eta_{overall}$ =4.94 |
| **DHW system** | Centralized gas boiler | Centralized served by the Air-to-water heat pump | N.A. | N.A. |
| **PV system** | - | 80 modules (20.80 kW$_p$) | - | 39 modules (10.14 kW$_p$) |

*The U$_w$ of north windows is slightly lower due to the application of low-emissivity film.
** Only some occupied rooms are served by the system.
*** All the occupied rooms are served by the system.
N.A.: not available

Detailed pre-retrofit modelling of the two case studies has been done, through the definition of thermal zones for all different spaces (rooms, stairs, unheated spaces, attics, etc.) and the application of envelope thermal features reported in Table I. After that, in the Italian BES model, a constant Air Change per Hour (ACH) and a mean internal heat gain equal to 0.5 h$^{-1}$ and 4 W/m$^2$ respectively, according to the typical residential profile, have been assumed. The heating period has been considered from January to mid-April and from mid-October to December, based on the national Climatic Zone E, with an average setpoint of about 22°C, as depicted from the analysis of the indoor climate data monitored through dataloggers.

In the Bulgarian BES model, an ACH of 0.7 h$^{-1}$ for both the office and classroom spaces was assumed. Additionally, a constant value of 6 W/m² for the overall internal heat gains was considered in the office rooms, while for the classrooms was assumed constant 2 W/m² for electrical equipment/lighting. Regarding the average occupancy density of classrooms, it was set equal to 0.32 people/m$^2$, according to the information provided by the building manager. It should be noted that for the ACH and the occupancy density of the classrooms, those conditions were maintained for 10 hours per day (from 07:00 to 17:00) which represents the time when the school is usually open. For the rest of the time, these parameters have been reduced to simulate the unoccupied hours (e.g. the ACH is reduced to 0.3 h$^{-1}$ and the occupancy density is null). The heating period has been assumed to be from January to May and from November to December based on data obtained through interviews with the building owner. During these periods, the heating system operates daily from 5:30 AM to 2:30 PM, ensuring that the building maintains a setpoint temperature of about 23-24°C, while for the rest of the hours it falls to 18-19°C. These data were estimated on the basis of a monitoring activity of internal conditions.

In the following figure, a view of the buildings and BES models developed is shown.

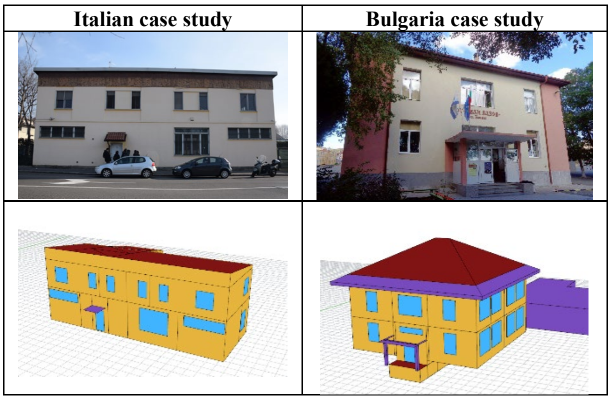


Fig. 2. Photo and view of the building energy simulation model of the two case studies

The model calibration and validation have been done by comparing the energy consumption collected from the bills (before retrofit) with the simulated one. Such procedure includes the following improvements to the model:

- set of a specific weather file related to the same year of the bills;
- implementation of the thermal bridges into the energy model through Therm software;
- optimization of the temperature set-points according to the indoor temperature monitoring data;
- set-up of the real building operation mode.

In such regard, the discrepancy between measured and simulated energy consumption complied with respect to the validation thresholds proposed by the ASHRAE Guideline 14 [22], as reported in Table II.

TABLE II
VALIDATION RESULTS OF THE BUILDING ENERGY SIMULATIONS

| **Index** | **Italian case study** | **Bulgaria case study** | **Validation thresholds according to ASHRAE Guideline 14** |
|---|---|---|---|
| NMBE [%] | -4.6 | +2.9 | ±5 |
| CV(RMSE) [%] | 11.1 | 12.4 | 15 |

After that, the validated BES models were implemented by adding the features of the RE-SKIN retrofit interventions to calculate the expected energy consumption. Then, it was converted into primary energy consumption by adopting the conversion factor of 2.42 for electricity delivered from the grid and 1.05 for natural gas.

Consequently, a summary of the energy savings achievable in the two case studies is provided in the following table.

TABLE III
ENERGY CONSUMPTION OF THE TWO BUILDINGS BEFORE AND AFTER THE RETROFIT INTERVENTION

| | **Italian case study** | | **Bulgaria case study** | |
|---|---|---|---|---|
| | *Pre-retrofit* | *Post-retrofit* | *Pre-retrofit* | *Post-retrofit* |
| Primary energy consumption - Heating [kWh/m$^2$ y] | 183.5 | 38.1 | 75.4 | 12.8 |
| Primary energy consumption - Cooling [kWh/m$^2$ y] | 0 | 20.3 | 1.2 | 23.5 |
| Primary energy consumption - DHW [kWh/m$^2$ y] | 78.8 | 22.8 | - | - |
| Primary energy consumption – Total [kWh/m$^2$ y] | 262.3 | 81.2 | 76.6 | 36.3 |
| Primary energy consumption – Total [kWh y] | 89,182 | 27,608 | 24,563 | 11,652 |
| Electric energy consumption – Total [kWh y] | 0 | 11,408 | 159 | 4,815 |
| Energy supplied by PV system [kWh y] | - | 21,610 | - | 10,658 |
| $CO_2$ emissions [kg/$CO_2$] | 17,819 | 0 | 4,905 | 0 |

The obtained results indicate that both the Italian and Bulgarian cases achieve a significant reduction in primary energy consumption, even excluding the contribution of photovoltaic energy. In particular, in the first case it goes from 89,182 kWh/y (262.3 kWh/m²·y) to 27,608 kWh/y (81.2 kWh/m²·y), corresponding to a reduction of 69%, while in the second case it drops from 24,563 kWh/y (76.6 kWh/m²·y) to 11,652 kWh/y (36.3 kWh/m²·y), corresponding to a reduction of 53%. These values refer to the building envelope and system interventions, excluding energy use for auxiliary systems, which can be considered both low in absolute terms and substantially unchanged between the pre- and post-renovation scenarios. Considering then also the contribution of the renewable electricity generated on-site, in both cases the yearly net energy balance is 0. The photovoltaic system, in fact, supplies 21,610 kWh/y and 10,658 kWh/y for the Italian and Bulgarian buildings, respectively, which is more than 100% of the final electric energy consumption in both cases. While the excess energy produced (10,202 kWh/y and 5843 kWh/y for the Italian and Bulgarian cases, respectively) is sold to the electric grid.

The discrepancy in performance between the two case studies can be attributed to some factors, such as the differences in the S/V, WWR, user profiles of the spaces, the use of DHW as well as the higher capacity of the photovoltaic system in the Italian case. Furthermore, it is important to highlight the positive outcomes achieved in both scenarios, since in the post-retrofit configuration, cooling is assumed to all rooms, whereas in the pre-retrofit condition, cooling was either absent or limited to a few spaces (in the Bulgarian case).

Despite some differences between the two case studies, the performance data are comparable and serve as a robust benchmark for evaluating project outcomes.

In terms of energy savings, a significant contribution is given by improvements in the building envelope. In both cases case, more than an half of the overall energy demand is reduced through the external walls and windows intervention.

It is important to highlight that in both cases, the PV systems are designed to maximize electricity production. Moreover, the inclusion of electric storage supports load shifting and peak shaving, improving on-site self-consumption and minimizing the risk of grid overloading. The results obtained indicate that for both retrofitted buildings, the target of reaching a zero-emission building according to the new European directive 2024/1275 [23] has been achieved. In addition, the excess of electricity produced on-site through renewable sources compared to the building's needs makes these two case studies suitable for classification as Positive Energy Buildings (PEB).

Finally, the renovation solutions led to a substantial reduction in $CO_2$ emissions while reaching the zero local emission target, reflecting the environmental impact of the retrofitting measures. In both case studies, the operational $CO_2$ emissions in the post-retrofit scenario are equal to zero, reducing with respect to the pre-retrofit scenario by approximately 17,819 and 4,905 kg/$CO_2$ per year for the Italian and Bulgarian case respectively. These values underscore the role of deep renovation strategies and renewable integration in cutting greenhouse gas emissions and supporting EU climate goals.

In should be noted that, the avoided $CO_2$ emissions resulting from the excess photovoltaic (PV) energy production contribute to compensating, at least in part, the embodied energy associated with the retrofitting interventions. Such aspect will be further addressed in future studies.

Currently, the Italian case study building is being retrofitted and the works on Bulgarin one will start in summer 2025.

It must be also noted that the preliminary evaluations reported in this work must be validated/fine-tuned after the end of retrofit works, through a detailed post-retrofit monitoring activity.

## IV. CONCLUSION

The results obtained from the application of the RE-SKIN retrofit toolkit in two representative European buildings clearly demonstrate the effectiveness of an integrated, systemic approach to deep renovation. The combination of envelope enhancements, high-efficiency HVAC systems, and on-site renewable energy generation enables both case studies to achieve a net-zero balance in overall primary energy consumption, demonstrating the effectiveness of integrated energy retrofitting strategies . These reductions are particularly notable given the different building typologies, climates, and initial performance levels.

A significant portion of the energy savings in both case studies can be attributed to interventions in the building envelope. Additionally, the integration of photovoltaic (PV) systems combined with energy storage facilitated a high degree of on-site renewable energy generation, achieving a significant coverage in both case studies. This approach substantially decreased dependence on the electrical grid. Moreover, the adoption of energy storage systems enhanced energy management capabilities by enabling load shifting and peak shaving, thereby improving system flexibility and promoting compatibility with smart grid infrastructures.

These technical outcomes are further reinforced by substantial environmental benefits. Annual operative $CO_2$ emissions in the post-retrofit scenario are equal to zero, avoiding approximately 17,819 kg/$CO_2$ emission in the Italian case and 4,905 kg/$CO_2$ in the Bulgarian one. Such results confirm the RE-SKIN project's capacity to deliver measurable progress toward decarbonization goals.

Beyond performance metrics, RE-SKIN introduces a replicable retrofit strategy based on modular, low-invasiveness technologies and a cloud-based decision support platform. Its architecture supports both design optimization and real-time operation management, fostering better interaction between buildings, users, and the grid. The toolkit's scalability makes it particularly suited for application across the widespread stock of mid-20$^{th}$ century European buildings, offering a viable pathway for upgrading energy performance at scale.

In conclusion, the RE-SKIN project demonstrates a feasible and impactful model for deep renovation that not only improves energy efficiency and environmental sustainability but also supports the evolution of buildings into smart, self-regulating systems aligned with EU energy and climate targets.

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