"En-Solex": A Novel Solar Exoskeleton for the Energy-efficiency Retrofitting of Existing Buildings

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Abstract. The energy retrofitting of the existing building stock is one of the current challenging strategic objectives on the way to the European target of climate neutrality by 2050. According to the Renovation Wave plan, around 35 million existing buildings need to be upgraded to the highest energy efficiency level by 2030, and innovative technological solutions are required to achieve this ambitious goal. This paper proposes a novel solar exoskeleton for the energy and architectural retrofitting of existing buildings, called En-Solex. The system, which consists of an external steel frame that wraps around buildings like a double skin, combines passive solar gain control (shading and greening) with high-efficiency active solar systems (PV panels) optimised for integration into existing building facades. The energy-saving potential of the system with different façade configurations is evaluated on a multi-family residential building located in a Mediterranean climate. The dynamic energy simulations show that the proposed solution can reduce the energy demand for space heating and cooling by 33.4% and 25.5% respectively. The En-Solex system integration combined with generator replacement results in a maximum heating and cooling reduction equal to 80.7% and 59.6% respectively. The surplus of electricity generated, thanks to the integration of RES, can lead to a net plus target, with the building exceeding its average annual electricity demand.

1 Introduction

The reduction of energy consumption and the increase of energy efficiency in the building sector have been key objectives that the European Community has been pursuing for the past decades. Under the new targets of the European Green Deal for the energy transition from fossil fuels to renewable energy, Europe's goal is to become climate-neutral by 2050 [1].

With the recent "Fit for 55" package adopted to implement the Green Deal, the European Union has set an ambitious target to reduce net greenhouse gas emissions by 55 per cent by 2030 compared to 1990 levels.

To understand the scale of the action required to achieve this target, consider that between 1990 and 2020, EU emissions were reduced by only 20 per cent; Europe is therefore aiming to reduce emissions from 20 per cent to 55 per cent in less than ten years. This calls for a strong energy transition plan involving all sectors of European society.

Among them, the building sector, despite having always been identified as one of the most energy-intensive, is also the one where energy efficiency targets are most easily

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achievable and cost-effective. In fact, the buildings are still responsible for around 40% of the EU's final energy consumption and 36% of its carbon dioxide emissions. The residential sector alone accounts for 26.1% of final energy consumption and 16.6% of gross inland energy consumption [2].

Such significant shares therefore highlight the reasons why European energy policy is increasingly focusing on efficiency measures in this sector. In this sense, the Energy Performance of Buildings Directive (EPBD) introduced in 2010 the obligation to build only Nearly Zero Energy Buildings (NZEB) from 2021 onward (European Parliament, 2010).

Although the number of NZEBs is increasing across Europe [3] they mainly belong to new constructions and still only cover a small part of the total European building stock.

For this reason, already in 2018, the recast of the European Directive 844/2018 [4] paid special attention to the energy renovation of the existing building stock, the largest share in Europe.

This address is further emphasised in the latest draft of the EPDB revision, updated following the "Fit for 55" package, where the energy efficiency improvement of the existing building stock becomes one of the key objectives to be pursued for an effective energy transition in the European Union.

Indeed, a significant amount of the building stock in Europe is more than 50 years old and has been identified as inefficient, requiring the implementation of retrofit measures to reduce energy demand and emissions. Thus, innovative technological solutions are required to achieve this ambitious goal.

Several studies focused on the energy refurbishment of existing buildings to improve their energy performance [5–7]. One primary method for improving energy efficiency in existing buildings is to upgrade passively the thermal efficiency of the building envelope components [8]. This can be achieved by adding additional layers of thermal insulation to reduce heat loss through surfaces and thermal bridges. On the other hand, while making these improvements, it is important to address the problem of overheating during the summer months, especially in hot climates [9,10].

Passive retrofitting is acknowledged as indispensable for the development of low-carbon-impact buildings but it holds the potential to contribute modestly to load shifting on the grid. The use of active retrofitting measures, on the contrary, such as heat pumps and photovoltaic (PV) systems, is considered the most cost-effective solution to cover existing building demand and reduce grid energy load.

However, integrating renewable energy sources (RES) into existing buildings may not effectively cover the energy demand due to limited available surfaces and poor structural load-bearing capacity, particularly in high-density urban areas [11].

Recent research tries to offer holistic solutions to the retrofitting of the existing buildings aiming to improve both their energy and seismic performance. One proposal involves engineered steel exoskeletons for renovating reinforced concrete (RC) framed buildings [12–14]. These solutions mainly require external interventions to reduce occupant interference, minimize renovation needs, and optimize implementation time and costs. Along this line, Evola et al. [15] investigated the energy performance of a prefabricated timber-based retrofit solution which allows reducing the energy need for space heating and space cooling by 66% and 25%, respectively.

Nevertheless, these solutions are hardly able to provide net zero goals in existing building renovation. Given the recent development of district and community level strategies, such as the concept of Positive Energy Districts (PEDs), the deep renovation of the residential building stock could play a key role in the EU renovation wave.

It is therefore essential to provide a new type of intervention that could not only ensure an improvement in the energy performance and efficiency of existing buildings, but also turn retrofitted residential buildings into positive buildings capable of providing surplus energy at the district level [16].

This paper proposes a novel solar exoskeleton for the energy and architectural retrofitting of existing buildings, called En-Solex. The system, which consists of a steel exoskeleton, combining passive solar gain control (shading and greening) with high-efficiency active solar systems (PV panels), can bring existing buildings to net plus target.

2 En-Solex system

The En-Solex system consists of a self-supporting steel frame exoskeleton applied directly to the exterior of the existing building to improve its energy performance and structural safety.

The proposed system aims to increase the surface area available for renewable energy system (RES) integration in existing buildings. This is particularly important as these buildings often have limited space available for solar panels, which are typically restricted to the roof surface.

In addition, the self-supporting frame of the system allows the weight of the panels to be directly supported by the structure, thus avoiding additional loads on the existing structure which are usually unable to withstand additional loads, especially concerning seismic vulnerability.

The system is based on a modular grid of 3m x 3m made of 200mm HEA pillars and 140 mm IPE beams (Figure 1). The frame is made up of a side parallel to the façade of the building to which it is anchored, and an external façade inclined at 5° to the vertical to increase the solar absorption of the photovoltaic systems.

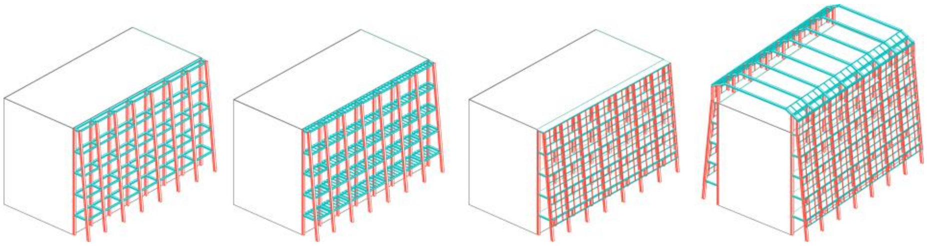

Fig. 1. En-Solex steel frame scheme.

A secondary grid made with steel T-profiles is anchored to the main frame creating a grid of 1 m x 1 m where the several panels are placed. The main frame features wooden horizontals for each floor, adding additional external surfaces have been added to the structure, which can be utilized as balconies or verandas. These surfaces serve as buffer zones between the interior and exterior of the building, improving the indoor thermal comfort of building occupants.

The exoskeleton frame wraps around the building like a second skin, including the roof of the building with a metal frame that can hold the structural load of PV and solar thermal panels. The grid's inner frame, which is in contact with the existing building facade, is designed to integrate thermal insulation sandwich panels made of rock wool with metal cladding.

The thickness of the panels can vary from 6 to 12 cm, depending on the building's energy needs and climatic zone. The thermal transmittance of the sandwich panels can range from 0.612 to 0.383 W/m^{2}K. The outer frame can be equipped with a predefined kit of prefabricated panels.

The kit is designed to be flexible and can be adapted to fit the orientation of existing buildings and the site's climatic conditions. It allows for a free façade design to offer several architectural configurations based on the building's energy demand. Each panel has a surface area of 1 square metre and is equipped with specific anchors for easy attachment to the secondary frame, reducing the time and cost of intervention.

Five different classes of modules have been designed: the En-PV module, which consists of a photovoltaic panel with a total surface area of approximately 1 m^2 and a peak power of 200 W_p; the En-Opaque module which features different opaque panels made of porcelain stoneware, earthenware panel or stone panel, the En-Glass module made of laminated tempered glass, the En-Shade module which provides a wood or aluminium horizontal or vertical brie-soleil; and finally the En-Green module which offers a pre-assembled module for low intensity greenery.

Figure 2 shows some of the façade combinations that can be created using the 1m by 1m panel module in the 3 meters by 3 meter main frame grid.

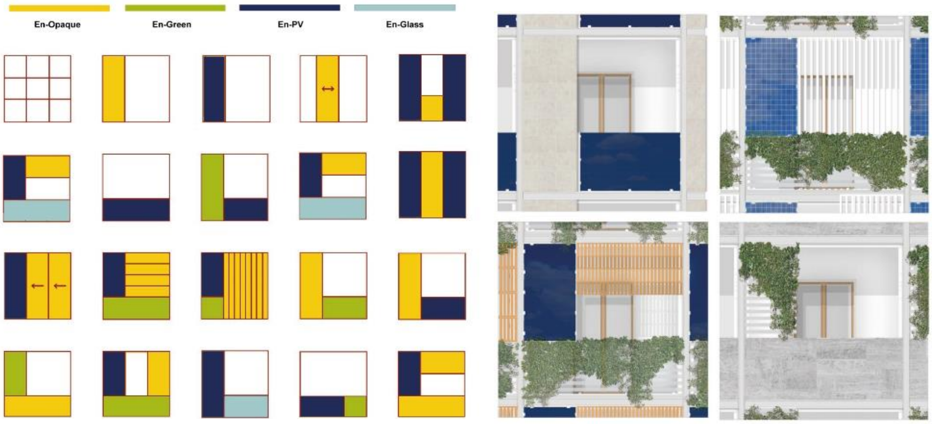

Fig. 2. Possible combinations of different modules and examples of kit configurations.

Both the structural grid elements and the kit modules are designed to be modular and prefabricated. The system can be easily and quickly assembled from the outside of the existing building without affecting building occupancy and reducing the time and cost of its implementation.

The external facade grid's modularity enables easy upgrading and adjustment of the system's facade modules without compromising the overall system. In addition, the proposed retrofitting system can significantly reduce its environmental impact by allowing the system to be simply dismantled and its components reused in other projects.

Figure 3 shows some potential En-Solex system configurations applied to an existing building.

Fig. 3. Examples of possible retrofitted façade using the EN-SOLEX system.

3 Case study

To evaluate the energy performance achievable through the retrofitting system, several energy dynamics simulations were carried out on a multi-storey building in a social housing residential cluster in the city of Bari (Italy).

The case study building is part of a residential apartment block built in the second half of the 1980s, consisting of a total of 7 bar buildings with 6 to 8 storeys. The analysis is carried out on a 6-storey south-facing building (Fig. 4). Each floor consists of two mirrored apartments of 85 square metres for an overall of ten apartments (Fig. 5).

Fig. 4. External view of case study residential buildings cluster.

The building has a reinforced concrete frame structure with a latero-cement slab. The external walls are made of perforated brick (λ=0.4 W/(mK)) without insulation, resulting in an overall thermal transmittance of 1.15 W/m^{2}K. The flat ceiling is made of a latero-cement slab and does not have insulation, and it is equipped with a bitumen waterproof membrane, resulting in an overall thermal transmittance of 1.45 W/m^{2}K.

The windows are made of aluminium frames without thermal breaks and have double glazing filled with air. They are characterized by an overall thermal transmittance of 3.70 W/m^{2}K and a $g_{gl,n}$ of 0.75. The building has an overall net conditioned area of 814 m^2 and an overall net conditioned volume of 2197.5 m^3, resulting in a surface-to-volume ratio of 0.38. The building features an autonomous heating system for each apartment, which includes a standard boiler installed in a non-air-conditioned room.

The system has an average seasonal efficiency (ηH) of 0.85 and feeds water aluminium radiators (Tu=80°C) in each room. For summer air-conditioning, several split air-conditioners with a SEER of 2.7 are installed.

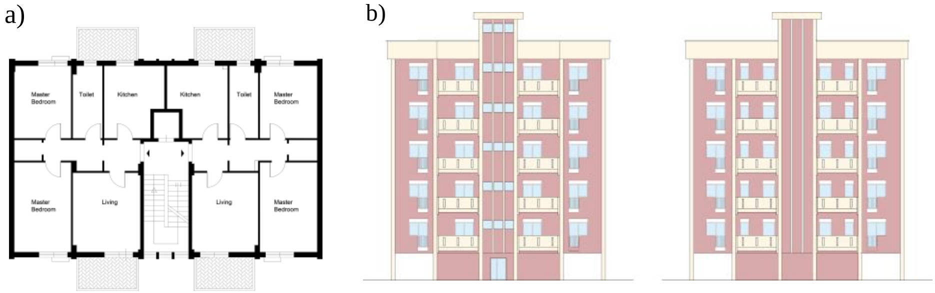

Fig. 5. Typical floor plan of the case study (a); North façade of the building on the left and south façade of the building on the right (b).

4 Methods

Dynamic simulation of the overall building-plant system analysis on an hourly basis was performed in DesingBuilder, a building performance simulation software based on the EnergyPlus simulation engine. IGDG weather data for Bari-Palese were used.

The setpoint temperature was fixed at 20 °C for the heating period and 26 °C for the cooling period according to requirements for residential buildings consistent with category II of UNI EN 16798-1. The heating and cooling system schedule was set to be always available (24 hours per day).

The energy needs for heating, cooling, ventilation, hot water production, lighting, and appliance electrical needs and the PV energy generation were assessed. Scheduled daily occupancy and internal heat gain for the different thermal zones used in the simulation are summarized in Table 1.

The lighting system has a power density of 2.5 W/m^2-100 lux. The infiltration rate of the model is set at 0.5 h^{-1}. Natural ventilation ranges from 5 to 12 vol/h and is activated when the indoor temperature ranges from 21ºC to 25ºC. To prevent overheating or overcooling, a temperature differential of 1ºC between indoor and outdoor temperatures has been set in the simulations. Three different scenarios were performed, each considering different En-Solex façade configurations for the southern façade (Fig. 6).

Table 1- Scheduled daily occupancy and internal heat gain for each room.

Thermal zone	**Occupancy daily time**		**Appliances and occupancy load [W/m^2]**	
	From Monday to Friday	Weekend	From Monday to Friday	Weekend
Master Bedroom	from 10 p.m. to 8 a.m.	from 10 p.m. to 10 a.m.	2.67	3.58
Double bedroom	from 6 p.m. to 8 a.m.	from 10 p.m. to 9 a.m.	2.67	3.58
Living room	from 8 a.m. to 10 a.m. from 4 p.m. to 12 a.m.	from 9 a.m. to 11 a.m. from 4 p.m. to 12 a.m.	9	9
Kitchen-Dining room	from 7 a.m. to 9 a.m., from 12 p.m. to 2 p.m. from 8 p.m. to 10 p.m.	from 7 a.m. to 9 a.m., from 12 p.m. to 2 p.m. from 8 p.m. to 10 p.m.	9	9

The first scenario, RC50, involves a south-facing façade with a RES coverage percentage equal to 50% of the total façade surface area. The southern exoskeleton façade is equipped with a total of 180 En-PV modules for an overall peak power of 36 kW$_p$, 48 En-Opaque modules and 48 En-Glass modules.

The second scenario, RC30, considers a res coverage percentage of 30% of the total façade surface. This façade configuration utilises 108 En-PV modules for a total peak power equal to 21.6 kW$_p$, 120 En-opaque modules and 48 En-Glass modules. The last scenario, RC20, is characterized by a 20% RES coverage percentage with a total of 72 En-PV panels, 156 En-Opaque modules and 48 En-Glass modules.

The façade positioning of photovoltaic modules on the grid and the type of shading modules may vary as required by the building design, following the combinations presented in Figure 2.

All the scenarios are equipped with the same north exoskeleton façade made by the same combination of En-opaque, En-glass and En-Green modules. Even the roof configuration is kept constant among the scenarios. A total of 100 En-PV modules are installed on the roof frame providing a total of 20 kW$_p$.

Additionally, the upper part of the exoskeleton tilted at 30 degrees, allows for the integration of 34 m^2 of solar thermal panels (Fig. 7). All scenarios consider the use of 8 cm thick sandwich panels applied on both sides of the exoskeleton.

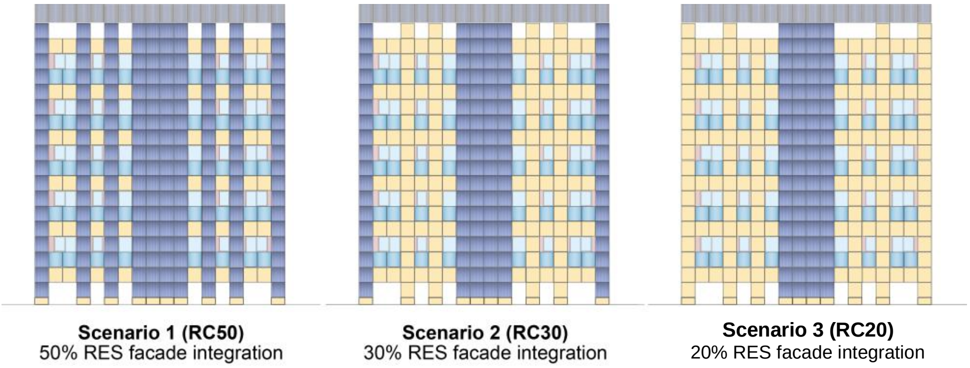

Fig. 6. Analysis of the different scenarios analysed based on the configuration of the south façade of the En-Solex system.

Five simulations were performed. The first simulation analysed the building energy consumption without integrating the En-Solex system, serving as a baseline scenario. The next three simulations evaluated the En-Solex integration based on three different façade configuration scenarios.

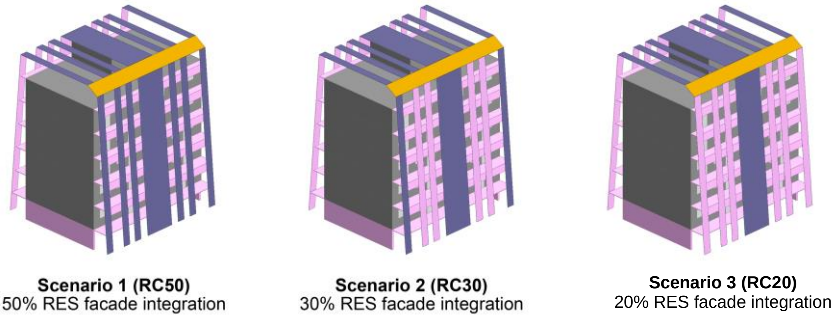

Fig. 7. Design builder 3D model for each analysed scenario.

The final simulation involved the RC50 scenario combined with the replacement of the existing gas boiler with a centralized air-to-water heat pump with fan coil units to achieve complete electrification of the building's energy needs (Scenario RC50+HP). To describe the matching degree between on-site energy generation and the building load, the load match index f_{load},[17] is defined as the average value over an evaluation period of how the on-site generation covers the energy load was evaluated following the Equation 1.

$$f_{load} = 1/N \cdot \Sigma_{year} (min\ [1, g(t)/l(t)]) \tag{1}$$

where $l(t)$ represents the energy load, $g(t)$ *is* the onsite electricity production, and N is the number of samples in the evaluation period. If hourly resolution data is used for a complete year evaluation period, there will be 8760 samples.

Finally, to evaluate the positive target of the building thanks to the retrofitted system integration, the difference between the energy exported from the building to the grid, e(t), and the energy supplied, d(t), known as the net exported energy, represented by ne(t), is evaluated according to Equation 2:

$$ne(t) = e(t)-d(t) \tag{2}$$

5 Results

5.1 Baseline scenario

Based on the dynamic simulation results, the building requires a total energy demand of 76,953.1 kWh/year. Of this, 66% is powered by natural gas (50,730.3 kWh/year), while the remaining 34% (26,223.2 kWh/year) comes from grid electricity (Fig. 8).

The building's heating (H) and domestic hot water (DHW) are supplied by natural gas, accounting for 59% (45,435 kWh/year) and 7% (5,295.3 kWh/year) of the total energy demand, respectively. The other building services are supplied by grid electricity. Cooling (C) accounts for 6% (4.177,3 kWh/year), interior lighting for 7% (5,658.7 kWh/year) and interior equipment for 21% (16,386.9 kWh/year). Table 2 shows the total yearly energy consumption for each building service.

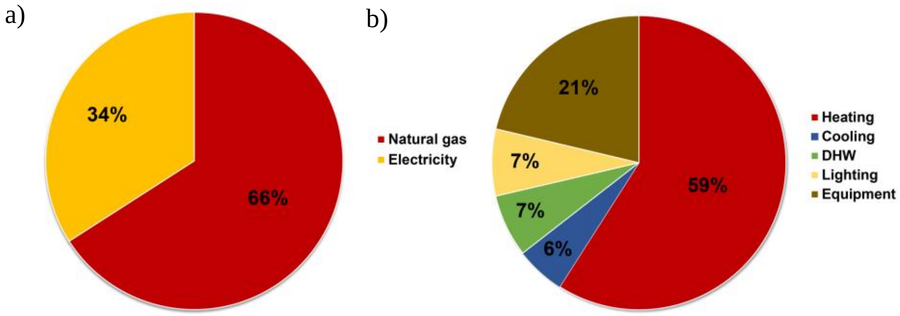

Fig. 8. Baseline building energy demand by a) energy vector and b) by energy service.

Table 2. Yearly energy demand for each building service.

Heating	45,434.9	kWh/year
Cooling	4,177.3	kWh/year
DHW	5,295.3	kWh/year
Indoor Lighting	5,658.7	kWh/year
Equipment	16,386.9	kWh/year
Total energy demand	76,953.1	kWh/year

5.2 En-Solex System scenarios.

Figure 9 shows the monthly comparison of heating and cooling demands between the base case and retrofitted scenarios. The En-Solex system integration leads to a significant reduction in heating and cooling demand in all analysed scenarios. Scenarios RC50, RC30, and RC20 demonstrate a similar reduction in energy demand for both cooling and heating compared to the baseline scenario. The three scenarios show a 33% reduction in heating energy demand compared to the base case of 45435 kWh/year. Cooling demand is also reduced by up to 25.9% (Table 3).

The demand for heating energy is primarily reduced by integrating additional insulation into the external wall. Conversely, the reduction in cooling demand is mainly due to the exoskeleton shading systems reducing summer solar loads.

The En-Solex system integration combined with generator replacement (Scenario RC50+HP) resulted in the maximum heating and cooling reduction equal to 80.7% and 59.6% respectively.

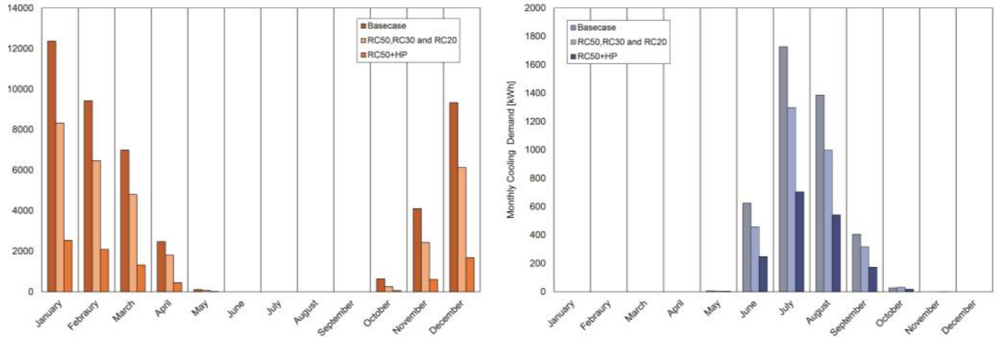

Fig. 9. Monthly heating (a) and cooling (b) demand among analysed scenarios.

When analysing the PV electricity generation, Scenario RC50 generates a total of 55,426.5 kWh/year in terms of PV energy production, while scenario RC30 generates 43,063.4 kWh/year and scenario RC20 generates 36,863.3 kWh/year.

The electricity supplied by PV placed on the roof remains constant in all simulations and accounts for 43.7%, 56.2%, and 65.7% of total generation for scenarios RC50, RC30, and RC20, respectively.

Table 3. Heating and cooling demand comparison among scenarios.

Scenario	Heating demand		Cooling demand	
	kWh/year	Δ%	kWh/year	Δ%
Base case	45,435.0		4,177.2	
RC50	30,277.6	*-33.4%*	3,111.5	*-25.5%*
RC30	30,399.9	*-33.1%*	3,098.0	*-25.8%*
RC20	30,433.6	*-33.0%*	3,094.7	*-25.9%*
RC50+HP	8,774.0	*-80.7%*	1,687.9	*-59.6%*

Compared to the base case electricity demand, the on-site generation exceeds the building energy demand in all scenarios.

Scenario RC50 exceeds the building's electricity demand by 215%, RC30 by 170%, and RC20 by 150%. Meanwhile, scenario RC50+HP, which fully electrifies the building's energy needs, still generates 165.2% more electricity than the building requires, even with higher electricity demand.

Based on the electricity demand of the reference case (Fig. 10), the scenario RC50 covers the monthly electricity demand for the whole year. Scenario RC30 covers the monthly electricity demand from February to December, while scenario RC20 covers the monthly electricity demand from March to October.

Table 4 presents a comparison between building energy demand, building electricity generation, g(t), the amount of exported e(t), delivered electricity d(t) and self-consumed electricity s(t). The data indicates that scenario RC50 exported 170% of the electricity generated, scenario RC30 exported 126.7%, scenario RC20 exported 105.1%, and scenario RC50+HP exported 129.6%. In terms of building energy demand, scenario RC50 self-consumes 43.2% of its total energy requirement while importing the remaining 56.8% from the grid.

Based on the En-solex façade configuration, as the total on-site electricity generation decreases, the amount of electricity from the grid increases, reaching up to 64.5% with scenarios RC50+HP.

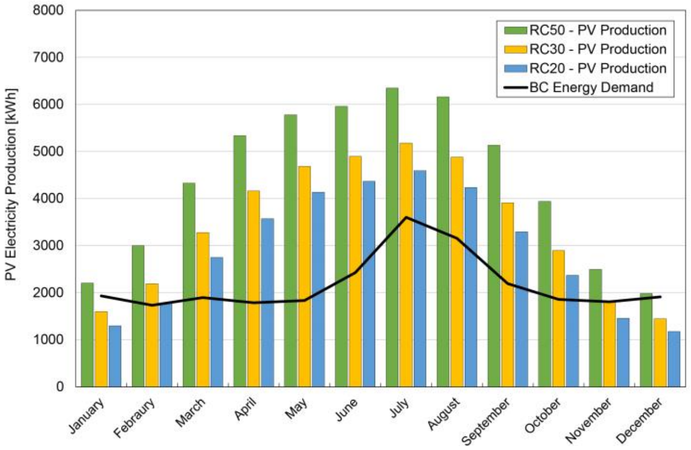

Fig. 10. Comparison of the monthly energy demand between the base case scenario and the retrofitted scenario PV production.

Examining the net electricity balance (ne(t)) between the building and the grid, it is evident that all retrofit scenarios yield a positive balance between the exported and supplied electricity. Specifically, the RC50 scenario results in a net balance of 114.1%, the RC30 scenario 66%, and the RC20 scenario 42.5%.

The RC50+HP (fully electrified) scenario achieves a net balance of up to 65.2%, turning the retrofitted building into a positive one.

Even though the total energy produced on site is much higher than the building's energy needs, hourly production does not match consumption throughout the year, especially in winter. Annual load match index f_{load} on an hourly basis ranges from 41.8% with scenario RC20 to 44.7% with scenario RC50.

Table 4. Generated, exported, delivered and self-consumed electricity for each scenario.

Scenario		**RC50**		**RC30**		**RC20**		**RC50+HP**	
		kWh/year		kWh/year		kWh/year		kWh/year	
Energy Demand	*l(t)*	24,594.8		24,584.6		24,581.9		31,882,5	
Generated El.	*g(t)*	55,426.5	*225.4%*	43,063.4	*175.1%*	36,863.3	*150.0%*	55,426.5	*165.2%*
Exported El.	*e(t)*	42,033.7	*170.0%*	31,114.2	*126.7%*	25,831.1	*105.1%*	41,320.9	*129.6%*
Delivered El.	*d(t)*	13,973.3	*56.8%*	14,818.6	*60.3%*	15,392.9	*62.6%*	20,548.3	*64.5%*
Self-consumed El.	*s(t)*	10,621.5	*43.2%*	9,766.0	*39.7%*	9,189.0	*37.4%*	11,334.2	*35.5%*
Net exported El.	*ne(t)*	28,060.4	*114.1%*	16,325.7	*66.0%*	10,438.1	*42.5%*	20,772.7	*65.2%*

6 Conclusions

This paper proposes a novel solar exoskeleton for the energy and architectural retrofitting of existing buildings, called En-Solex. The system, which consists of an external steel frame, combines passive solar gain control (shading and greening) with high-efficiency active solar systems (PV panels) optimised for integration into existing building facades.

The dynamic simulation of the integration of the En-Solex system with a case study of existing buildings shows how the system can reduce the energy demand for space heating and cooling by 33.4% and 25.5% respectively. The integration of the En-Solex system combined with generator replacement results in a maximum heating and cooling reduction of 80.7% and 59.6% respectively. In addition, thanks to the integration of RES, the system results in a surplus of electricity generated, leading the existing building to a net plus target. Scenario RC50 exceeds the building's electricity demand by 215%, RC30 by 170%, and RC20 by 150%. Meanwhile, scenario RC50+HP, which provides complete electrification of building energy needs, even with higher building electricity demand, still provides 165.2% of electricity generation higher than building requirements. The system not only improves the energy performance and efficiency of existing buildings, but also transforms retrofitted building into positive buildings capable of providing surplus energy at the district level.

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