# Scaling Positive Energy Districts Through Integrated Active Exoskeleton Retrofits: A REC-Driven Application to a Social Housing Cluster

*Roberto* Stasi[1*], *Francesca* Vecchi[2], *Simona* Semeraro[2], *Francesco* Ruggiero[2] and *Umberto* Berardi[2]

[1]Department of Experimental Medicine (DiMeS), University of Salento, Lecce, Italy
[2] Department of Architecture, Construction and Design (DArCoD), Polytechnic University of Bari, Bari, Italy

**Abstract.** The transition toward climate-neutral cities requires large-scale building retrofits combined with collective renewable self-consumption. This study assesses the energy performance of en-SOLEX, a modular solar exoskeleton retrofit system, applied to a social housing district in Bari (Italy). The system transforms energy-intensive buildings into net-positive producers while increasing self-consumed electricity, improving the feasibility of Renewable Energy Communities (RECs), particularly in social housing contexts where energy sharing can reduce energy poverty. When integrated within a REC, en-SOLEX significantly enhances collective self-consumption and mitigates increased demand from electrification. The self-consumption index (SCI) rises from 65% in a rooftop PV scenario to 74–91% with en-SOLEX, reaching up to 98% under electrified conditions. The self-sufficiency index (SSI) also improves, achieving up to 43% in non-electrified cases and remaining positive under full electrification. Compared to diffuse rooftop PV, concentrating generation on selected buildings reduces structural constraints, minimizes retrofit interventions, and simplifies decision-making, key barriers in social housing RECs. Overall, the study shows that combining deep retrofits, façade-integrated PV and REC-based energy sharing provides a scalable and inclusive approach to achieving Positive Energy Districts that are aligned with EU decarbonisation targets.

## 1 Introduction

The transition toward climate-neutral cities represents one of the most pressing challenges for urban sustainability, with the existing building stock playing a decisive role. In the European Union, buildings account for approximately 40% of final energy consumption and over one third of greenhouse gas emissions, with residential buildings constituting the largest share [1]. Despite ambitious policy frameworks such as the European Green Deal, the "Fit for 55" package, and the recast Energy Performance of Buildings Directive (EPBD), progress in decarbonising existing buildings remains slow, particularly in dense urban districts

---

[*] Corresponding author: roberto.stasi@unisalento.it

characterised by ageing construction, high energy demand, and limited potential for on-site renewable energy generation.

A substantial portion of European residential buildings was built during the post-war period, prior to the introduction of energy efficiency regulations [2]. These buildings, often located in peripheral urban neighbourhoods, exhibit poor thermal performance, obsolete systems, and limited architectural adaptability [3]. Retrofitting such stock is further complicated by spatial constraints, restricted roof availability for photovoltaic (PV) installations, and social considerations, including affordability and the need to avoid tenant displacement. As a result, conventional building-level retrofit strategies, focused primarily on envelope insulation or system upgrades, are frequently insufficient to achieve deep decarbonisation or to enable meaningful integration of renewable energy at large scale [4].

In response to these limitations, recent research has explored integrated retrofit solutions capable of simultaneously reducing energy demand and expanding renewable energy generation capacity. Among these, external solar exoskeletons have emerged as a promising approach for dense urban contexts. Acting as self-supporting secondary structures, solar exoskeletons can host building-integrated photovoltaics (BIPV), provide passive solar control through shading, and accommodate additional insulation layers, all while being installed from the outside and minimising interferences with the occupants [5].

However, achieving climate-neutral urban districts requires moving beyond isolated high-performance buildings toward coordinated, district-scale energy strategies [6]. Even when deeply retrofitted, individual buildings often struggle to reach energy self-sufficiency due to temporal mismatches between energy demand and renewable production, particularly in Mediterranean climates where cooling demand peaks in summer and solar availability is seasonally uneven. This challenge has driven increasing interest in Renewable Energy Communities (RECs), which enable collective self-consumption and local energy sharing among multiple buildings within a defined urban area [7]. By aggregating diverse demand profiles and pooling renewable generation, RECs can improve local renewable utilisation, reduce grid dependency, and enhance economic and social benefits at the neighbourhood scale [8]. Despite the growing body of literature on both deep building retrofits and RECs, these two domains remain largely disconnected. Retrofit studies typically assess performance improvements at the single-building level, while REC analyses often assume static building characteristics and focus on energy sharing mechanisms [9]. Consequently, there is limited understanding of how advanced retrofit solutions, particularly those that significantly alter both demand profiles and renewable generation capacity, interact with REC operation and influence collective self-consumption, surplus production, and overall system viability [10].

The present study evaluates the integration of a modular solar exoskeleton retrofit system within a district-scale REC framework. Focusing on a social housing district in Bari, Southern Italy, representative of Mediterranean suburban contexts, the study evaluates how the deployment of a prototype solar exoskeleton system, named en-SOLEX, through a concentrated RES integration strategy, can simultaneously reduce energy demand, increase on-site renewable electricity generation, and enhance collective self-consumption at the district scale. The analysis addresses typical urban constraints, including limited rooftop availability and high residential energy demand, while exploring the potential of façade-integrated BIPV and passive design strategies to enable net-positive energy balances.

## 2 Case Study

The case study focuses on a social housing neighborhood built in the first half of the 1980s in the city of Bari, Southern Italy. Bari is characterized by a temperate dry-summer climate (Csa) according to the Köppen climate classification and falls within the ASHRAE 3A warm–humid climate zone. **Fig. 1** illustrates the location of the selected district and the boundaries of the REC. The study area is situated in the Japigia district and comprises 18 residential buildings, ranging from six to eight above-ground floors, with a total of 226 housing units and approximately 900 residents, based on 2021 ISTAT data. The district is also identified by ISTAT as an area of social and economic vulnerability.

The buildings exhibit homogeneous construction and building services characteristics and have not undergone major refurbishment interventions since their original construction. The structural system consists of reinforced concrete frames. The building envelope is composed of double-leaf perforated brick masonry with a lightly insulated cavity. Windows systems are characterized by aluminum frames with double glazing.

Space heating is provided by conventional natural gas–fired boilers supplying aluminum radiators. No centralized cooling systems are installed; cooling demand, where present, is met by standalone room air-conditioning units. All buildings are connected to a single primary substation. No renewable energy systems are currently installed within the district.

**Fig. 1.** Geographic location of the case study social housing district in Bari and boundaries of the Renewable Energy Community.

## 2.1 En-SΘLEX system

The en-SΘLEX system (**Errore. L'origine riferimento non è stata trovata.**) is an integrated retrofitting system prototype made of a self-supporting steel-frame exoskeleton. Installed externally and independent of the original structure, the system is designed to enhance building energy performance primarily by increasing the available surface area for the integration of renewable energy sources (RES), a critical limitation in medium- and high-rise buildings where roof space alone is often insufficient [11]. The exoskeleton consists of a modular steel frame composed of H-shape beams and columns connected through bolted plate joints.

The system is conceived for application to post-Second World War reinforced concrete buildings, which represent approximately 50% of the European building stock. These structures, commonly located in suburban areas, are typically characterized by high energy demand, low thermal comfort, limited architectural quality, and significant seismic vulnerability.

The design specifically targets row multi-family residential buildings, identified through typological analysis based on the TABULA project classification [12]. In particular, the system is developed for buildings belonging to TABULA class 6, comprising multi-family buildings constructed between 1976 and 1990. This typology is generally characterized by a regular rectangular plan, a modular structural grid, a central staircase, and two apartments per floor.

The system consists of two main structural components: an inner frame aligned with the existing façade, serving as the anchoring interface, and an outer frame inclined by 5° from the vertical to enhance PV performance while limiting ground-level encroachment. A secondary steel grid with a 1 m × 1 m module supports the installation of façade elements and functional panels.

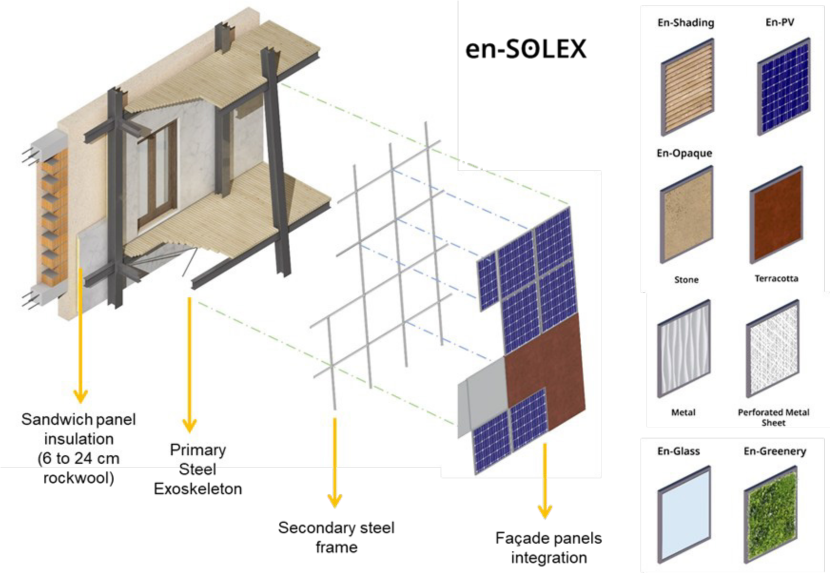


**Fig. 2.** The “en-SΘLEX” system facade design [5].

At each floor level, wooden horizontal beams are integrated to create additional semi-outdoor spaces, such as balconies, verandas, or greenhouses. The exoskeleton also extends to the roof through a truss system capable of supporting PV and solar thermal panels. As the structure is entirely self-supporting, it transfers no additional loads to the existing building, an essential aspect given the limited structural capacity and seismic vulnerability of the target building stock. The modular façade system allows for multiple predefined configurations tailored to building orientation, climatic conditions, and energy demand.

Five panel typologies have been developed: (i) En-PV modules integrating photovoltaic panels (approximately 1 $m^2$, 200 $W_p$); (ii) En-Opaque modules for fixed shading; (iii) En-Glass modules using laminated tempered glass; (iv) En-Shade modules with adjustable horizontal or vertical brise-soleil; and (v) En-Green modules for low-intensity greenery integration. The combination and placement of these modules are optimized according to façade orientation and seasonal performance requirements.

All structural and envelope components are modular and prefabricated, enabling rapid external installation without disrupting building occupancy. The system allows for future upgrades, partial replacement, and reconfiguration of façade elements. Moreover, its reversibility and dismantlability support component reuse and reduce environmental impacts. Finally, the exoskeleton structure can accommodate additional functions, such as external elevators or fire escape routes, contributing to improved accessibility and safety in existing buildings.

Results from previous study [5] showed that the integration of the system alone leads to a reduction in space heating and cooling energy demand of 33.4% and 25.5%, respectively.

The integration of renewable energy sources within the en-SΘLEX exoskeleton enables surplus electricity generation, allowing the retrofitted building to achieve a net-positive energy balance up to 215% building’s electricity demand. The export of surplus electricity to the grid further enables energy sharing at the district scale, supporting the energy transition of existing urban clusters.

By concentrating RES integration on selected buildings and enabling energy sharing within the REC, the en-SΘLEX approach can offer a more feasible and scalable pathway for decarbonising existing urban districts compared to diffuse PV deployment. This strategy reduces structural risks, limits economic and organisational complexity, and enhances the effectiveness of collective self-consumption mechanisms at the district scale.

**Fig. 3.** Examples of possible retrofitted façade using the en-SΘLEX system [5].

## 3 Methodology

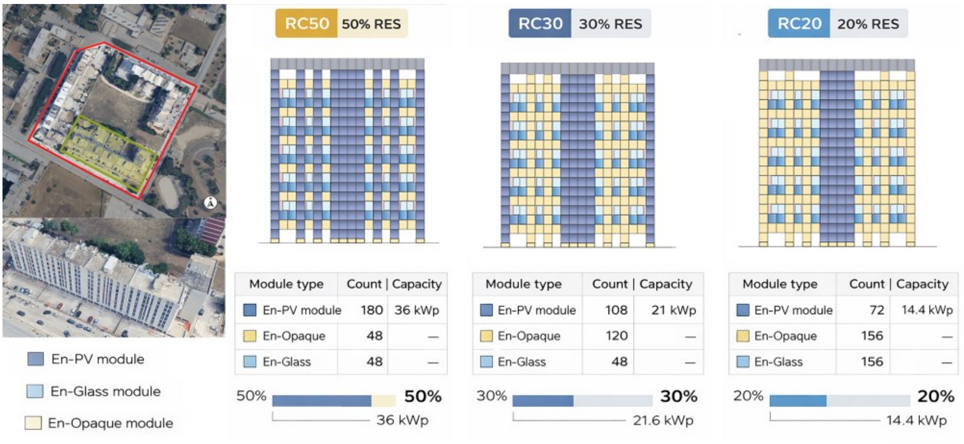
This study aims to evaluate the impacts of community-scale retrofitting strategies within the framework of a REC applied to a social housing residential district. By shifting the analytical focus from individual buildings to the district scale, the research examines how concentrated integration of RES in residential retrofits can enhance local self-consumption and energy self-sufficiency through energy-sharing mechanisms within a REC, in contrast to diffuse RES deployment, typically employed in REC assessment evaluation.

The methodological framework is based on an Urban Building Energy Modelling (UBEM) approach, encompassing the generation of building geometries and the characterization of construction and energy system properties. To address the limitations of single-building approaches in achieving energy autonomy, the model incorporates a behaviour-aware representation of residential energy demand. Occupancy presence and activity schedules are refined to capture temporal variability and behavioural heterogeneity, which are critical drivers of hourly electricity demand and strongly influence the performance of collective self-consumption in aggregated building systems.

Energy simulations are conducted using the City Energy Analyst (CEA), an open-source, bottom-up, physics-based UBEM tool specifically designed for district-scale applications [13]. CEA applies dynamic energy balance methods accounting for solar gains, heat transfer, internal gains, and HVAC system performance, employing resistor–capacitor network models to represent building thermal behaviour. Hourly demand and generation outputs enable the assessment of virtual energy sharing in accordance with the Italian REC regulatory framework.

Based on district-level energy demand, two demand scenarios are analysed: a baseline scenario representing the existing building stock, characterized by low-performance envelopes and conventional energy systems, and a retrofit scenario combining envelope improvements with the adoption of high-efficiency, predominantly electric energy systems. Retrofit measures are designed in compliance with the Italian Minimum Energy Performance Requirements (DM 26/06/2015), which define maximum allowable U-values for building components and minimum efficiency standards for energy systems in existing buildings renovation actions. Each energy demand scenario is coupled with two PV generation strategies. The first strategy considers a diffuse PV deployment across all district buildings, typical configuration of REC analysis evaluation, with panels installed on roof surfaces exceeding an annual solar irradiation threshold of 1,200 kWh/m²·year, consistent with Mediterranean climatic conditions. A maximum coverage ratio of 0.9 limits the usable roof area for PV installation. Rather than assuming a uniform panel tilt angle, PV azimuth and inclination are optimised for each individual roof to maximise energy yield. Under these geometric and climatic constraints, a total installed PV capacity of 460 $kW_p$ is achieved.

The second PV generation strategy evaluates the application of the en-SΘLEX system to selected buildings, aiming to achieve concentrated RES integration and limit the number of retrofitting projects. To maximise on-site electricity production, this strategy prioritises the deployment of En-PV modules on façade surfaces, accounting for building energy demand and different window-to-wall ratio (WWR) configurations. Three alternative en-SΘLEX configurations are analysed for the south-facing façades of 5 selected buildings of the district (**Errore. L'origine riferimento non è stata trovata.**).



| Module type | Count | Capacity |
|---|---|---|
| En-PV module | 180 | 36 kWp |
| En-Opaque | 48 | — |
| En-Glass | 48 | — |

| Module type | Count | Capacity |
|---|---|---|
| En-PV module | 108 | 21 kWp |
| En-Opaque | 120 | — |
| En-Glass | 48 | — |

| Module type | Count | Capacity |
|---|---|---|
| En-PV module | 72 | 14.4 kWp |
| En-Opaque | 156 | — |
| En-Glass | 156 | — |

**Fig. 4.** En-SΘLEX system south facade configurations based on different WWR.

In the RC50 configuration, photovoltaic modules cover 50% of the south-facing façade area. This configuration integrates 180 En-PV modules, corresponding to a total installed capacity of 36 $kW_p$, together with 48 En-Opaque and 48 En-Glass modules. En-Glass modules are primarily used as parapets, while the remaining grid areas are equipped with En-Opaque modules. The second scenario, RC30, assumes a RES coverage equal to 30% of the total façade area. This configuration integrates 108 En-PV modules, corresponding to a total installed capacity of 21.6 $kW_p$, together with 120 En-Opaque modules and 48 En-Glass modules. It is suitable for buildings with a WWR of up to 60%.

The final scenario, RC20, features a reduced RES coverage of 20% of the façade area, comprising 72 En-PV modules, 156 En-Opaque modules, and 48 En-Glass modules. This configuration is designed for buildings with higher glazing ratios, accommodating window-to-wall ratios of up to 80%.

All scenarios share an identical configuration for the north-facing façade, consisting of a fixed combination of En-Opaque, En-Glass, and En-Green modules. Although the northern façade does not directly contribute to energy performance and may not be cost-effective as a standalone measure, it is required to structurally support the roof exoskeleton and to ensure architectural coherence of the retrofit. The roof configuration is kept constant across all scenarios, with 100 En-PV modules installed on the roof frame, providing an additional 20 $kW_p$ of photovoltaic capacity. Overall, the en-SΘLEX configurations result in installed PV capacities ranging from a minimum of 172 $kW_p$ (RC20) to a maximum of 280 $kW_p$ (RC50).

Solar irradiation calculations are performed within CEA using the DAYSIM engine, which computes hourly solar irradiation for each roof surface while accounting for roof geometry and orientation, shading from surrounding buildings, surface albedo (set to 0.25 to reflect urban conditions), and local weather data. Table 1 show all the scenarios analysed with the corresponding ID and PV integration strategies.

**Table 1.** Scenarios overview based on energy demand and PV generation system.

| ID scenario | Energy Demand | PV generation |
|---|---|---|
| CER | Baseline | Roof diffuse PV |
| CER+ | Retrofitted | |
| RC20 | Baseline | En-SOLEX 20% RES |
| RC30 | | En-SOLEX 30% RES |
| RC50 | | En-SOLEX 50% RES |
| RC20+ | Retrofitted | En-SOLEX 20% RES |
| RC30+ | | En-SOLEX 30% RES |
| RC50+ | | En-SOLEX 50% RES |

## 3.1 Simulation inputs

The geometric and thermo-physical features of the baseline buildings were derived from the national TABULA/EPISCOPE database [12], using the Multi-Family House archetype from the 1976–1990 construction period, selected for their consistency with the typical residential stock of southern Italian urban fabrics during that era. The building geometries are defined in a shapefile (.shp), containing information on building heights, footprint areas, and number of floors. These geometries are enriched with construction archetypes and the corresponding thermal properties are varied depending on the retrofit scenario.

In the Baseline configuration, the envelope properties, including both the thermal transmittance (U-values), are derived directly from the TABULA/EPISCOPE dataset for the Italian residential building stock (archetypes IT.MidClim.MFH.06 and construction period 1976–1990). The Multi-Family House (MFH) typology features 0.25 m hollow brick masonry walls with low insulation, resulting in a U-value of 0.80 W m$^{-2}$K$^{-1}$. The floor and roof slabs are made of reinforced brick-concrete systems, yielding U-values of 0.98 W m$^{-2}$K$^{-1}$ and 0.75 W m$^{-2}$K$^{-1}$, respectively. Windows are composed of air-filled double glazing mounted in metal frames without thermal break, with a U-value of 3.70 W m$^{-2}$K$^{-1}$. The heating season is assumed from November 15th to March 31st. Considering the HVAC systems, the Baseline scenario assumes a conventional natural gas boiler serving both space heating and domestic hot water (DHW) production, with a thermal efficiency of 66%, as derived from the TABULA database. Mechanical cooling is not present in baseline scenario.

The retrofitted scenario adopts a full electrification strategy, replacing the gas boiler with a reversible air-to-air heat pump capable of providing both space heating and cooling. Domestic hot water production is also electrified, either through integration within the heat pump system or via a dedicated electric storage tank. System performance is modelled assuming a coefficient of performance (COP) of 3.5 in heating mode and an energy efficiency ratio (EER) of 3.0 in cooling mode. Envelope thermal transmittance are assumed in compliance with the Italian Minimum Energy Performance Requirements (DM 26/06/2015) for the specific climatic zone (Table 2).

Following the study by Vecchi et al. [14], household types are randomly assigned to buildings based on floor area and census characteristics. Each household type is associated with a specific occupancy and activity schedule, which is customised in the City Energy Analyst (CEA) according to the hourly probability of activity occurrence.

Schedule development is based on data from the national Time Use Survey (TUS) and census information provided by the Italian National Institute of Statistics (ISTAT). Census data, combined with building heated floor areas, are used to aggregate household types within each census section. The assignment criteria include the number of employed and retired occupants, household composition, and the average floor area per inhabitant (m²/inhabitant).

**Table 2.** Properties of envelope components and energy system by scenario.

| **Scenario** | **U-value (W m$^{-2}$K$^{-1}$)** | | | | **Heating** | **Cooling** |
|---|---|---|---|---|---|---|
| | **Wall** | **Roof** | **Floor** | **Window** | | |
| Baseline | 0.8 | 0.75 | 0.98 | 3.7 | NG-fired boiler with radiators (η = 66%) | n.a. |
| Retrofitted | 0.36 | 0.32 | 0.38 | 2 | Heat pump air-air (COP=3.5) | Heat pump air-air (EER=3.0) |

## 3.2 REC assessment

To evaluate the technical assessment of the energy flows within the REC the following indicators are selected adapting from the studies by [15]. Building within REC boundaries are defined aligning the ISTAT census sections with the primary cabin areas made available by GSE. Having a REC composed of N buildings, each building n has an electricity demand $E_{demand}^{n}(t)$ and can generate renewable power $E_{pv}^{n}(t)$ from its PV systems at hourly timestamp t. The electricity generated by the PV panels of the building can be consumed instantaneously – in this case, simplified hourly - in the same building behind the meter. The self-consumed energy $E_{selfconsumption}^{n}(t)$ in each building n at time interval t is calculated as show in Eq. (1):

$$E_{selfconsumption}^{n}(t) = \min(E_{demand}^{n}(t), E_{pv}^{n}(t)) \tag{1}$$

Virtual energy sharing is assumed for intra-building energy exchanges, based on the Italian framework. Within the REC boundaries, the solar surplus generated by each member can access to a premium tariff if self-consumed by other REC members in the same hourly timestep. Therefore, applying virtual energy sharing, buildings can share the surplus energy (after physical self-consumption) with other buildings which are simultaneously registering electricity deficit. The electricity surplus $E_{surplus}$ in Eq. (2) and Eq. (3) at timestep t for each building n and the whole REC are calculated as:

$$E_{surplus}^{n}(t) = E_{pv}^{n}(t) - E_{selfconsumption}^{n}(t) \tag{2}$$

$$E_{surplus}^{REC}(t) = \sum_{n=1}^{N} E_{surplus}\,(t, n) \tag{3}$$

The electricity deficit $E_{deficit}$ in Eq. (4) at timestep *t* for each building *n* and the whole REC in Eq. (5) are calculated as:

$$E_{deficit}^{n}(t) = E_{demand}^{n}(t) - E_{selfconsumption}^{n}(t) \tag{4}$$

$$E_{deficit}^{REC}(t) = \sum_{n=1}^{N} E_{deficit}\,(t, n) \tag{5}$$

From energy sharing among members, the collective self-consumption ($CSC_{shared}^{REC}(t)$), at hourly time interval t can be calculated as the minimum between the overall energy surplus or deficit in the community, as shown in Eq. (6):

$$CSC_{shared}^{REC}(t) = \min(E_{surplus}^{REC}(t), E_{deficit}^{REC}(t)) \quad (6)$$

From this evaluation, the following indicators can be calculated:

- self-consumption index (SCI), which is the self-consumed PV generation out of the total PV generation, in Eq. (7);

$$SCI = \frac{\sum_{n=1}^{N} E_{selfconsumption}(t,n) + CSC_{shared}^{REC}(t)}{\sum_{n=1}^{N} E_{pv}(t,n)} \quad (7)$$

- self-sufficiency index (SSI), which is the self-consumed PV generation related to total electricity demand, in Eq. (8).

$$SSI = \frac{\sum_{n=1}^{N} E_{selfconsumption}(t,n) + CSC_{shared}^{REC}(t)}{\sum_{n=1}^{N} E_{demand}(t,n)} \quad (8)$$

Virtual energy sharing is modelled on an hourly basis, consistent with both the temporal resolution of the UBEM simulations and the Italian REC regulatory framework, which defines collective self-consumption according to hourly simultaneity between generation and demand. The grid constraints and detailed network operation (e.g., voltage limits, line congestion, or transformer capacity) are not explicitly modelled in this study.

## 4 Results

Results in **Errore. L'origine riferimento non è stata trovata.** provide a detailed analysis of how different retrofit and photovoltaic integration strategies influence energy performance at both building and district scales within the REC. Beyond absolute values, a comparative analysis of percentage variations between scenarios reveals key insights into the effectiveness, robustness, and scalability of concentrated renewable energy source integration enabled by the en-SΘLEX system. From a demand perspective, the transition from the baseline to the electrified retrofit scenario leads to a substantial increase in annual electricity demand, rising from approximately 580 MWh to nearly 950 MWh (+64%). This increase reflects the electrification of space heating and domestic hot water production and the space cooling new demand highlighting a critical trade-off of deep decarbonisation strategies: while thermal energy demand is reduced, electricity demand becomes dominant. This shift reinforces the need for retrofit approaches that simultaneously reduce demand peaks and expand on-site renewable generation capacity.

In terms of PV generation, the diffuse rooftop scenario achieves the highest installed capacity (460 $kW_p$) and annual production (≈368 MWh). However, when compared to en-SΘLEX-based configurations, the marginal benefit of this higher capacity is less pronounced than expected. The RC50 scenario, for instance, reaches approximately 336 MWh/year with a 39% lower installed capacity (280 $kW_p$), indicating a significantly higher utilisation efficiency of the installed PV systems. Compared to RC20 and RC30, RC50 increases annual PV generation by approximately 58% and 33%, respectively, confirming that higher façade coverage directly translates into greater renewable output, albeit with diminishing returns in terms of self-consumption.

A key qualitative difference between rooftop-only and en-SΘLEX scenarios lies in the temporal distribution of PV generation. While rooftop PV systems are typically optimised for a single south-facing orientation and peak around solar noon, the en-SΘLEX system integrates PV modules on vertical façades oriented toward south-east and south-west. This configuration broadens the daily generation profile by shifting part of the production toward morning and late-afternoon hours. As a result, PV generation under en-SΘLEX scenarios shows a flatter and more distributed curve, which aligns more closely with residential demand patterns and contributes to higher collective self-consumption rates. This effect partially explains why en-SΘLEX scenarios achieve comparable or superior REC performance despite lower installed capacities.

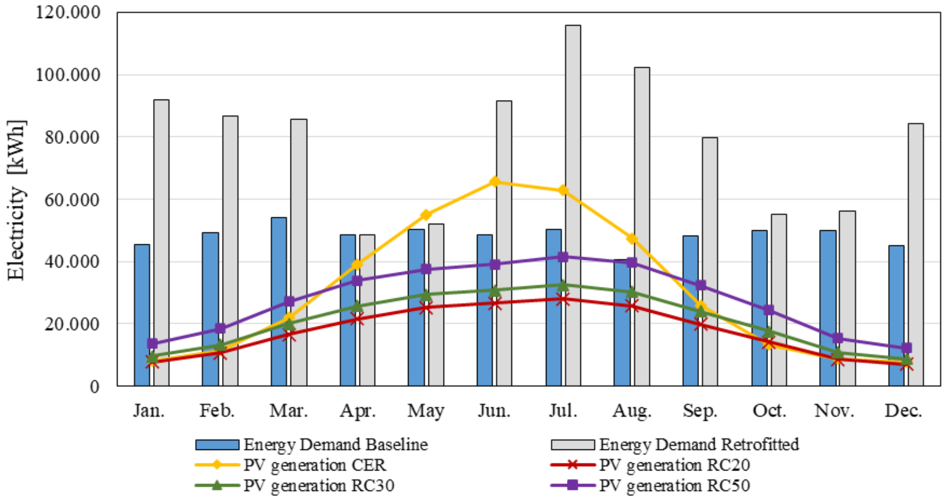


**Fig. 5.** En-SΘLEX system south facade configurations based on different WWR.

Temporal matching is clearly reflected in the self-consumption index (SCI) values (Table 3). At the REC level, SCI increases from 65% in the diffuse rooftop scenario to 91% in RC20 (+40%) and remains high in RC30 (86%, +32%). Although SCI decreases to 74% in RC50 due to increased surplus generation, it remains higher than the diffuse scenario, confirming that concentrated façade-based integration enhances local utilisation of renewable electricity. In fully electrified scenarios, SCI values further increase, reaching up to 98% in RC20$^+$, despite the higher electricity demand. This indicates that electrification, when combined with distributed PV generation across façades and REC-level energy sharing, can improve simultaneity between demand and generation rather than exacerbate mismatches.

**Table 3.** SCI and SSI values for baseline and retrofitted scenarios based on different PV generation scenarios.

| | $E^{REC}_{demand}$ | $PV^{REC}_{gen}$ | $E^{REC}_{self\ cons}$ | $E^{REC}_{surplus}$ | $E^{REC}_{deficit}$ | **CSC** | **SCI** | **SSI** |
|---|---|---|---|---|---|---|---|---|
| | *kWh* | *kWh* | *kWh* | *kWh* | *kWh* | *kWh* | *%* | *%* |
| CER | 580,413.8 | 367,633.6 | 235,022.1 | 132,611.5 | 345,391.6 | 3,890.1 | 65% | 41% |
| CER$^+$ | 949,730.5 | | 308,502.7 | 59,130.9 | 641,227.8 | 7,355.9 | 86% | 33% |
| RC20 | 580,413.8 | 212,017.5 | 102,423.3 | 109,594.2 | 477,990.5 | 91,010.0 | 91% | 33% |
| RC30 | | 253,285.9 | 106,282.2 | 147,003.7 | 474,131.6 | 110,664.8 | 86% | 37% |
| RC50 | | 335,557.9 | 111,149.9 | 224,408.0 | 469,263.9 | 138,425.7 | 74% | 43% |
| RC20$^+$ | 949,730.5 | 212,017.5 | 147,878.2 | 64,139.3 | 801,852.3 | 59018.4 | 98% | 22% |
| RC30$^+$ | | 253,285.9 | 159,049.9 | 94,236.0 | 790,680.6 | 83,118.2 | 96% | 25% |
| RC50$^+$ | | 335,557.9 | 173,587.4 | 161,970.5 | 776,143.1 | 131,452.8 | 91% | 32% |

The self-sufficiency index (SSI) reveals complementary dynamics. While diffuse rooftop PV achieves an SSI of 41%, en-SΘLEX scenarios range between 33% and 43% in non-electrified cases. Notably, RC50 increases SSI by approximately 31% compared to RC20, reflecting the impact of higher façade PV coverage. In electrified scenarios, SSI values decrease due to increased demand, yet remain positive, confirming that a significant share of electricity demand is still met locally. This highlights a critical insight: under high electrification levels, SCI becomes a more meaningful indicator than SSI for evaluating REC performance, as it captures the effectiveness of local energy circulation rather than absolute autonomy.

The comparison between building-level and REC-level performance further reinforces the importance of aggregation (Table 4). In RC20, building-level SCI increases from 48% to 91% at the REC level (+89%), while in RC30 and RC50 the REC-level SCI exceeds building-level values by 44% and 124%, respectively. These gains demonstrate that en-SΘLEX equipped buildings act as strategic energy nodes, supplying surplus electricity to neighbouring buildings with complementary demand profiles. Without REC aggregation, a significant share of façade-generated electricity would be exported to the grid; with energy sharing, it is retained within the district.

**Table 4.** SCI and SSI values comparison based on Building and REC level.

| | **SCI** | | **SSI** | |
|---|---|---|---|---|
| | Building Level | REC Level | Building Level | REC Level |
| CER | 64% | 65% | 40% | 41% |
| CER$^+$ | 84% | 86% | 32% | 33% |
| RC20 | 48% | 91% | 50% | 33% |
| RC30 | 42% | 86% | 52% | 37% |
| RC50 | 33% | 74% | 55% | 43% |
| RC20$^+$ | 70% | 98% | 44% | 22% |
| RC30$^+$ | 63% | 96% | 47% | 25% |
| RC50$^+$ | 52% | 91% | 51% | 32% |

Beyond performance metrics, these results have important implications for social housing retrofit strategies. Concentrated RES integration through the en-SΘLEX system avoids the need for diffuse rooftop interventions, which are often constrained by insufficient structural capacity, fragmented ownership, and economic barriers. By decoupling PV installation from existing roof structures and concentrating investments on a limited number of buildings, the system reduces technical risk and simplifies decision-making processes. At the same time, the façade-based SE–SW PV configuration improves generation distribution throughout the day, enhancing self-consumption and reducing reliance on grid imports during peak residential demand periods.

Overall, the results indicate that the en-SΘLEX system, when integrated within a REC framework, provides not only higher-quality renewable generation but also a more resilient and socially inclusive pathway toward Positive Energy Districts. In social housing contexts, this approach supports energy poverty mitigation by increasing access to locally generated, low-cost electricity, stabilising energy expenses, and enabling collective benefits that would be difficult to achieve through isolated, building-level interventions alone.

Notwithstanding the promising results, several limitations of the proposed approach should be acknowledged. First, the REC performance assessment is based on the current Italian regulatory framework, which defines collective self-consumption according to hourly simultaneity and assumes virtual energy sharing without explicitly modelling distribution grid constraints (e.g., voltage limits, line congestion, or transformer capacity). This simplification may lead to an optimistic estimation of energy exchange potential and may limit the transferability of results to contexts characterised by different regulatory schemes or network conditions. From a modelling perspective, the UBEM approach relies on archetype-based envelope properties and probabilistic occupancy schedules. While appropriate for district-scale analysis, these assumptions cannot fully capture household-level behavioural variability, rebound effects, or long-term socio-technical adaptations.

Moreover, the study focuses primarily on energy performance indicators (SCI and SSI) and does not include a comprehensive techno-economic assessment, life-cycle environmental analysis, or detailed structural and constructability evaluation beyond the conceptual self-supporting design of the exoskeleton.

Finally, the findings are based on a single Mediterranean social housing district; differences in climate, urban morphology, and governance structures may affect scalability in other contexts. Future research should therefore incorporate detailed grid modelling, storage and demand-side flexibility strategies, multi-year climate sensitivity analyses, full cost–benefit and life-cycle assessments, and comparative applications across diverse climatic zones. Further investigation into governance models, benefit distribution mechanisms, and energy poverty mitigation effects is also needed to validate the robustness and scalability of the proposed framework.

## 5 Conclusions

This study assessed the integration of deep energy retrofitting and concentrated renewable energy source deployment within a Renewable Energy Community framework, using a Mediterranean social housing district as a case study. By adopting a district-scale perspective supported by Urban Building Energy Modelling, the analysis demonstrated how coordinated retrofit strategies can overcome the limitations of single-building approaches in dense residential contexts.

The results show that diffuse rooftop photovoltaic deployment, although capable of maximising installed capacity, is often constrained by structural, economic, and organisational barriers. In contrast, the en-SΘLEX solar exoskeleton enables concentrated RES integration on selected buildings through a self-supporting structure, decoupling PV installation from existing load-bearing limitations. Despite lower installed capacity, façade-integrated PV, distributed across south-east and south-west orientations, achieves comparable renewable generation while improving the temporal alignment between production and residential demand.

When combined with REC-based energy sharing, the en-SΘLEX system significantly increases collective self-consumption and mitigates the effects of electrification-driven demand growth. The results confirm that collective self-consumption is a more meaningful performance indicator than self-sufficiency under advanced electrification scenarios, as it better captures the efficiency of local energy circulation.

Beyond energy performance, the proposed approach offers relevant social benefits. Concentrating RES integration reduces the number of retrofit interventions and simplifies decision-making processes, which are critical barriers in social housing estates and in general in REC adoptions. The REC framework enables surplus renewable electricity to be shared among residents, supporting energy affordability and contributing to energy poverty mitigation. Overall, the study demonstrates that coupling solar exoskeleton retrofitting with RECs represents a scalable and socially inclusive pathway toward Positive Energy Districts, aligning urban retrofit strategies with European decarbonisation and social equity objectives. Future research should include regulatory sensitivity analyses, integrated grid and storage modelling, techno-economic and life-cycle assessments, and investigations into governance and social acceptance mechanisms to support broader transferability and practical deployment.

## Acknowledgements

This research was conducted within the frame of the research agreement "ReNew Urban-esoscheletri per la riqualificazione energetica e sismica di edifici esistenti" between Sud Montaggi S.r.l. company and Department of Civil Architecture, Built Environment and Design of Polytechnic University of Bari.

The authors recognize the financial contribution of the following projects: PRIN - HERA – "Holistic Energy Recovery Agent tool for sustainable urban clusters" and PRIN PNRR 2022 NETPLUS – "Neighborhood Energy Transition: towards Positive energy baLance and carbon neUtral diStricts", " TECH2", Project No. F/350388/02/X60, CUP B99J25000000005, financed by the Ministry of Enterprises and Made in Italy (MIMIT) under the framework of the ``Innovation Agreement" dated 03/09/2024 and National Center for Sustainable Mobility (MOST) - "Digital twin nella gestione di vettori energetici nuovi per l'accoppiamento edificio-trasporti in ambito urbano", funded by the Italian Ministry of University and Research (MUR) within the National Recovery and Resilience Plan (PNRR), Mission 4, Component 2, Investment 1.4, CUP: D93C22000410001.

## Symbology

*Acronyms*
BIPV – Building-Integrated Photovoltaics
CEA – City Energy Analyst
COP – Coefficient of Performance
CSC – Collective Self-Consumption
DHW – Domestic Hot Water
EER – Energy Efficiency Ratio
EPBD – Energy Performance of Buildings Directive
HVAC – Heating, Ventilation and Air Conditioning
ISTAT – Italian National Institute of Statistics
MFH – Multi-Family House
NG – Natural Gas
PED – Positive Energy District
PV – Photovoltaic
REC – Renewable Energy Community
RES – Renewable Energy Sources
SCI – Self-Consumption Index
SSI – Self-Sufficiency Index
TABULA – Typology Approach for Building Stock Energy Assessment
TUS – Time Use Survey
UBEM – Urban Building Energy Modelling
WWR – Window-to-Wall Ratio

*Symbols*
$\eta$– System efficiency [-]
N – Number of buildings within the REC
$n$– Generic building within the REC
$t$– Time step (hourly resolution)

$E_{d,n,t}$– Electricity demand of building $n$at time $t$[kWh]
$E_{g,n,t}$– PV electricity generation of building $n$at time $t$[kWh]
$E_{sc,n,t}$– Self-consumed electricity in building $n$at time $t$[kWh]
$E_{sur,n,t}$– Electricity surplus of building $n$at time $t$[kWh]
$E_{def,n,t}$– Electricity deficit of building $n$at time $t$[kWh]
$E_{sur,REC,t}$– Total REC electricity surplus at time $t$[kWh]
$E_{def,REC,t}$– Total REC electricity deficit at time $t$[kWh]
$E_{CSC,t}$– Collective self-consumed electricity within the REC at time $t$[kWh]
$E_{g,tot}$– Total PV electricity generation within the REC [kWh]
$E_{d,tot}$– Total electricity demand within the REC [kWh]
U – Thermal transmittance [W·m$^{-2}$·K$^{-1}$]

## References

1. F. Asdrubali, U. Berardi, and R. Stasi, Sustainability Certifications, Labels and Tools in the Built Environment 4 (2025). https://doi.org/10.1201/9781032705149-2
2. R. Stasi, F. Ruggiero, and U. Berardi, E3S Web of Conferences **343**, 01004 (2022). https://doi.org/10.1051/E3SCONF/202234301004
3. D. A. Pohoryles, D. A. Bournas, F. Da Porto, A. Caprino, G. Santarsiero, and T. Triantafillou, Journal of Building Engineering **61**, 105274 (2022). https://doi.org/10.1016/J.JOBE.2022.105274
4. A. La Scala, Infrastructures 2025, Vol. 10, Page 268 **10**, 268 (2025). https://doi.org/10.3390/INFRASTRUCTURES10100268
5. R. Stasi, F. Ruggiero, and U. Berardi, Energy Build. **333**, 115416 (2025). https://doi.org/10.1016/J.ENBUILD.2025.115416
6. I. Šironja, M. G. Antić, and T. Capuder, Energy **338**, 138911 (2025). https://doi.org/10.1016/J.ENERGY.2025.138911
7. G. Russo, L. Pompei, G. F. Giuzio, G. U. Magni, D. Groppi, G. Cipolla, F. Vecchi, R. Stasi, S. Semeraro, D. Astiaso Garcia, U. Berardi, and A. Buonomano, Renewable and Sustainable Energy Reviews **223**, 116007 (2025). https://doi.org/10.1016/J.RSER.2025.116007
8. G. Aruta, F. Ascione, N. Bianco, and G. M. Mauro, Energy **282**, 128377 (2023)
9. A. Fichera, E. Marrasso, C. Martone, G. Pallotta, M. Sasso, and R. Volpe, Build. Environ. **281**, 113193 (2025). https://doi.org/10.1016/J.ENERGY.2023.128377
10. A. Buonomano, C. Forzano, G. F. Giuzio, R. Maka, A. Palombo, and G. Russo, Renewable and Sustainable Energy Reviews **226**, 116411 (2026). https://doi.org/10.1016/J.RSER.2025.116411
11. R. Stasi, F. Ruggiero, and U. Berardi, E3S Web of Conferences **523**, 01008 (2024). https://doi.org/10.1051/E3SCONF/202452301008
12. I. Ballarini, S. P. Corgnati, and V. Corrado, Energy Policy **68**, 273 (2014). https://doi.org/10.1016/J.EGYR.2024.03.048
13. F. Vecchi, R. Stasi, and U. Berardi, Energy Reports **11**, 3941 (2024). https://doi.org/10.1016/J.EGYR.2024.03.048
14. F. Vecchi, S. Semeraro, R. Stasi, F. Guarino, and U. Berardi, 493 (2026). https://doi.org/10.1007/978-981-95-1826-5_52
15. S. Chaudhry, A. Surmann, M. Kühnbach, and F. Pierie, Energies 2022, Vol. 15, Page 8902 **15**, 8902 (2022). https://doi.org/10.3390/EN15238902