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Highlights

- Harmonised framework compares Positive Energy District pathways in two districts
- Full electrification phases out natural gas in both retrofitted districts
- Rooftop photovoltaics cover up to 50% of post-retrofit electricity demand
- Deep district retrofit cuts life cycle carbon emissions by up to 58%
- Life cycle assessment reveals solar and heat pump production trade-offs

Journal Pre-proof

Cross-typology Positive Energy District pathways in Mediterranean Southern Italy: harmonised district energy modelling and urban-scale life cycle assessment

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ABSTRACT

Reducing carbon emissions is a central EU objective, and Positive Energy Districts (PEDs) are increasingly recognised as a practical pathway for urban decarbonisation. However, robust cross-typology evidence remains limited, particularly when operational performance is assessed alongside the life cycle implications of renovation measures. This study applies a harmonised PED-oriented workflow across two Mediterranean districts in Southern Italy undergoing deep energy renovation: the non-residential University Campus in Palermo and a mixed-use urban district in Bari. The framework combines consistent PED boundaries and indicators, district-scale energy modelling, rooftop photovoltaic (PV) potential assessment, and life cycle assessment of retrofit packages comprising envelope upgrades, heating, ventilation and air conditioning (HVAC) electrification, and rooftop PV deployment. Results highlight clear typology-dependent energy patterns. Both post-retrofit configurations achieve full electrification, completely phase out natural gas, and consequently shift final energy use towards electricity, partly compensated by rooftop PV generation. In Palermo, rooftop PV supplies 50% of annual post-retrofit electricity demand. In Bari, baseline active cooling was almost negligible and heating demand decreases by 75%. However, introducing electric cooling alongside full HVAC electrification further increases electricity demand, and PV covers 45% of annual post-retrofit electricity demand. Climate change impacts decrease by 59% in the Palermo Campus and 57% in the Bari district, while ozone depletion is reduced by 61% and 74%, respectively. In both case studies, photovoltaic systems are the main contributors to production-stage environmental burdens, while heat pumps are particularly relevant for ozone depletion. Overall, the findings support context-sensitive, life cycle-informed PED-oriented district renovation planning.

KEYWORDS: Positive Energy Districts; District energy modelling; Energy renovation; Rooftop photovoltaics; Urban areas; Life Cycle Assessment.

1. Introduction

Climate change mitigation has become a major global and European priority. Recent assessments show that 2024 was the warmest year on record, with global mean temperature reaching about 1.55°C above the 1850-1900 baseline [1], [2], while Europe is warming even faster, with land temperatures around +2.4°C and increasingly severe climate extremes [3]. In response, the European Union has set binding decarbonisation targets for 2030 and 2050 [4], [5], through the European Climate Law, which requires at least a 55% reduction in net greenhouse gas emissions by 2030 and climate neutrality by 2050 [6], [7].

This trajectory is framed by the European Green Deal and supported by the Fit-for-55 package [8], [9], alongside strengthened 2030 targets for renewable energy and energy efficiency [10], [11].

Within this policy context, the existing building stock remains a critical challenge [12], [13], particularly in Southern Europe [14], [15], where ageing and inefficient buildings are widespread and often concentrated in vulnerable urban areas [16], [17]. Since most buildings that will still be in use in 2050 already exist today, renovation is the primary lever for near- and mid-term decarbonisation. This is especially relevant in Mediterranean cities, where older districts account for a large share of final energy use and emissions, while compact urban form [18], [19], historic fabric and social complexity make large-scale retrofit more difficult to implement [20]. At EU level, buildings account for about 42% of final energy demand and 35% of greenhouse gas emissions [21] and similar patterns are observed in Mediterranean cities such as Athens and Barcelona, where buildings remain major contributors to urban energy use and emissions [22], [23]. Previous studies have shown both the potential and the complexity of district-scale retrofit in these contexts [24], [25], [26]. This urgency is reflected in recent EU initiatives, including the Renovation Wave and the 2024 recast of the EPBD, which reinforce the role of renovation as a central pathway towards a net-zero building stock by 2050 [4], [27].

Against this background, the Positive Energy District (PED) concept has emerged as a key district-scale paradigm for urban decarbonisation [28]. Building on earlier paradigms such as nearly/net/positive zero-energy buildings, PEDs extend the focus from the single-building scale to the district scale, where energy sharing, coordinated system management and broader urban integration become possible [28]. In dense urban contexts, isolated building-level interventions are often insufficient, whereas district-scale approaches are better suited to address the physical, functional and socio-economic complexity of urban decarbonisation [29]. In Europe, the concept has been mainly shaped within the SET-Plan Action 3.2 framework and related initiatives, which have progressively consolidated definitions, targets and implementation pathways [30], [31]. Recent mapping studies report up to 98 PED initiatives across Europe [32], confirming growing institutional uptake but also substantial heterogeneity in system boundaries, temporal scales, energy configurations and enabling conditions, which still limits cross-case comparability and replication [33], [34].

Current PED frameworks consistently describe these districts as highly efficient and flexible urban areas aiming to minimise annual energy imports, reduce emissions and maximise local renewable generation [31]. This implies that PED assessment cannot rely on a single target or indicator, but requires transparent accounting of energy balances, flexibility, system interactions and broader sustainability dimensions [35], [36]. At the same time, the literature still highlights major gaps in practice-oriented PED planning, integrated sustainability assessment and interoperable modelling tools able to support decision-making across scales and urban contexts [37], [38]. These limitations remain a major barrier to moving PEDs beyond pilot projects and towards wider and more replicable implementation [39], [40].

In parallel, PED deployment is increasingly linked to energy-community frameworks, which provide governance and market structures for collective self-consumption [41], [42], energy sharing and local benefit allocation [43], [44]. At EU level, this interface is formalised through Renewable Energy Communities under RED and Citizen Energy Communities under the Electricity Market Directive [45], [46] and has been progressively operationalised in Italy through Art. 42-bis of Decree-Law 162/2019 [47], Legislative Decree 199/2021 [48], the MASE CACER Decree [49] and the related GSE operating rules [50]. This direction is reinforced by the growing EU emphasis on renewable integration in buildings and districts [51], [52]. In this context, sustainability assessment must extend beyond operational energy alone, in line with the recognition that six of nine planetary boundaries [53], [54] have already been transgressed [55], [56], [57] and with the broader sustainability agenda [58], [59] reflected in the SDGs, especially SDG 7 [60], [61].

Recent literature increasingly highlights the need to account for wider environmental pressures (including material-related burdens and life cycle impacts not limited to carbon), in order to avoid burden shifting across impact categories and stages [55, 56]. This need is progressively recognised at policy level: the 2024 EPBD recast introduces Whole Life Carbon (WLC) requirements for new buildings and major renovations, making the climate impact of the full building life cycle a regulatory benchmark [62], [63]. Similarly, the Renovation Wave strategy and the Net-Zero Emission Buildings (NEB) framework reinforce the importance of addressing

environmental performance across the entire building life cycle, not only during the use phase [4], [27]. Nevertheless, the WLC metric introduced by the EPBD is limited to carbon-related impacts (GWP) alone and does not account for the full range of environmental burdens associated with retrofit strategies. Multi-indicator life cycle assessment, in turn, broadens this scope to resource use, water, toxicity and ozone depletion (among others), enabling a more comprehensive evaluation of burden shifting across impact categories and stages [64], [65], [66].

District-scale energy modelling has become an established tool for planning urban renovation. Automated workflows that generate and simulate building energy models from municipal geospatial data now enable energy conservation measures to be assessed across entire districts [67]. Related approaches have been applied to define shallow and deep retrofit packages combined with rooftop photovoltaic deployment in cities with different climates and construction practices [68]; to plan the large-scale renovation of residential building stocks towards nearly zero and positive district energy balances while assessing the resulting implications for distribution networks [69]; to support the electrification of residential neighbourhoods and quantify its effect on peak electricity demand [70]; and to integrate energy and carbon outcomes with investment indicators across entire urban building stocks [71]. Despite this broad scope, environmental performance is generally assessed only in operational terms, through energy savings and avoided use-phase emissions, whereas the embodied burdens associated with retrofit materials and technologies remain outside the system boundary.

In light of the above considerations, this work adopted a district-scale perspective to assess the interactions among buildings, energy systems and local actors that are often overlooked by sector-specific approaches. It addressed a recurring gap in the PED literature, where robust comparisons are still hindered by inconsistent system boundaries, not aligned indicators and the limited integration of operational performance with life cycle environmental impacts [72], [73]. To this end, a harmonised district-scale assessment framework was developed, linking building-level retrofit measures and rooftop PV integration with PED-oriented evaluation through a single transparent set of boundaries, modelling steps and indicators.

In this context, the term “harmonised” refers to the assessment workflow rather than to the underlying evidence base. Both districts are assessed using a common modelling platform, calibration protocol and acceptance criterion, retrofit pathway, life cycle assessment approach and district-scale energy balance formulation. The nature and completeness of the input data, by contrast, reflect the specific conditions and data availability of each case study.

The scale of application of the life cycle assessment also needs to be made explicit. Life cycle assessment was developed as a product-oriented method, in which the object of the analysis is a defined product system and the inventory is compiled from its bill of materials. Applying it to an urban system requires that object to be redefined: the assessed system is a district of heterogeneous buildings, the foreground inventory is derived from the district energy model rather than from a single product specification, and the reference flow is one year of district operation together with the annualised burdens of the measures applied to the stock. Recent work on circularity in the construction sector frames this transition explicitly, describing an integrated methodology in which life-cycle management addresses burden shifting at the product level, while product-level impacts are scaled up to project, sectoral and regional levels by coupling life cycle methods with material flow analysis within an overarching life cycle sustainability assessment framework [74].

The present study operates at the district scale of that progression. Its methodological contribution lies in deriving the material inventory and the operational demand from the same calibrated district model, so that both dimensions of the retrofit share one system boundary, one set of operating assumptions and one reference flow. The foreground inventory is therefore not compiled from a bill of materials and combined with separately assumed operating energy, as in product-oriented applications, but is generated together with the energy results for the same building stock. Two consequences follow and are examined in Section 4: the environmental comparison inherits the calibration evidence available for each district, and the annualised result can be resolved by building and by component, so that the distribution of burdens across a heterogeneous stock becomes part of the outcome rather than an aggregate.

The framework was applied on two Southern Italian case studies sharing a Mediterranean climate, but differing markedly in function, morphology and demand structure: the non-residential UNIPA Campus in Palermo (hereinafter, UNIPA Campus) - characterised by schedule-driven loads [75] - and a mixed-use district in Bari, characterised by a more heterogeneous demand profile. In the Bari case, the retrofit pathway also included the activation of space cooling services that were largely absent in the baseline, reflecting the growing relevance of cooling under rising temperatures and more frequent heat extremes. This is consistent with World Meteorological Organization (WMO) evidence, supported by Copernicus Climate Change Service (C3S) data,

identifying 2024 as the warmest year on record, as well as with IPCC AR6 projections indicating further growth in building cooling demand [76], [77]. By applying the same assessment logic and intervention categories in both districts, namely envelope measures, system upgrades and rooftop PV deployment, the analysis enabled controlled cross-context benchmarking of PED-oriented pathways under different boundary conditions.

The added value of the study lies in providing comparable and decision-relevant evidence on how district morphology and functional mix shape energy-demand reduction, electrification patterns, PV contribution (and load matching) and life-cycle environmental performance, also including the trade-offs between operational savings and embodied burdens. The proposed workflow contributes to strengthening the methodological basis for PED-oriented planning, performance accounting and replication, while helping close key gaps related to practice-oriented guidance [42], multi-dimensional indicator consistency [36] and interoperable multi-scale assessment methods [43].

2. Methodology

2.1 Assessment workflow, data collection and district-scale energy modelling

2.1.1 Overview of the assessment workflow

The adopted methodology includes the following steps:

- 1) Definition of the study areas and system boundaries (non-residential vs. mixed-use). The analysis considered the two Southern Italian urban areas introduced in Section 1: the non-residential Campus of the University of Palermo and a mixed-use district in Bari, the latter included to test the transferability of the workflow under different boundary conditions. District perimeters and building sets were identified through a structured mapping and verification process based on available cartographic layers, satellite views and on-site surveys, as illustrated in Fig. 1.



Fig. 1. Satellite view of the two case studies: UNIPA Campus (left) and Bari district (right).

- 2) Collection, mapping and pre-processing of measured energy data.

For the UNIPA Campus, electricity consumption and heating gas demand were compiled for a representative annual period and complemented with hourly electricity load profiles (2024). The datasets were spatially linked to the corresponding buildings and district boundaries, then quality-checked and processed to derive representative demand profiles. For the Bari reference district, the selected study area included 62 individual building units, most of which date back to the 1970s and 1980s, distributed

across 14 multi-unit building blocks. The stock is predominantly residential - including both linear blocks and tower-type buildings - and also includes one educational facility. No evidence of prior energy retrofits was identified, consistent with outdated envelope performance and inefficient heating systems. On this basis, the 14 building blocks were classified into four representative archetypes, defined using literature-based reference models and technical standards for the residential sector, including EN 16798-1:2019 (indoor environment and use parameters) [75], CEN/TR 15193-2:2017 (lighting energy calculation guidance) [78], TABULA [79], [80], EPISCOPE (reference archetypes and typology-based parameters for European building stocks, including the WebTool) [81], [82], UNI/TR 11552:2014 (thermophysical properties of typical Italian opaque envelope components and common construction assemblies) [83] and Italian representative building models [84]. The resulting classification comprised 5 building blocks in Archetype 1, 4 in Archetype 2, 4 in Archetype 3 and 1 in Archetype 4, ensuring a consistent benchmark for energy model set-up and district-scale alignment.

- 3) Development of district-level energy modelling inputs: geometry, envelope properties, use-related parameters and energy demand profiles. District-level inputs were organised within an integrated Urban Building Energy Modelling (UBEM) approach, which simulates the energy behaviour of the urban building stock as a whole and provides a consistent basis for the subsequent assessment from a life cycle perspective.

UBEM tools relying on resistance-capacitance (R-C) thermal network models have been widely adopted to simplify space energy-use calculations at the urban scale, with platforms such as CitySim [85], SimStadt [86] and City Energy Analyst (CEA) [87], developed to enable evaluation at the district and neighbourhood scale.

To ensure district-scale consistency and cross-case comparability, an integrated urban-scale, multi-building workflow was applied to both the Palermo case study and the Bari reference district. The resulting geospatial dataset was then used to develop the corresponding UBEM models - shown in Fig. 2 for the UNIPA Campus (left) and the Bari district (right) - with the analysed buildings highlighted in yellow.



Fig. 2. UBEM models of the UNIPA Campus (left) and Bari district (right). Analysed buildings in yellow.

For the Bari district, an additional visual detail is provided in Fig. 3. To improve visual clarity, the original CEA visualization was customised by highlighting the 14 analysed multi-unit building blocks in distinct colours.

[106] scripts built on the Hyperopt optimisation framework [107], [108], with an early-stopping criterion adopted to iteratively minimise the deviation between simulated results and the respective reference dataset.

5) Definition and simulation of retrofit scenarios across the different district typologies.

Building on the calibrated baseline, a set of retrofit scenarios was defined and tested to quantify the energy-performance improvement achievable through energy-efficiency measures and on-site photovoltaic deployment, consistently applied within the modelling framework.

6) Life cycle environmental assessment of renovation strategies.

For both case studies the associated environmental burdens were evaluated from a life cycle perspective in order to complete the energy-based assessment and avoid burden shifting, by accounting for the non-operational impacts linked to the selected renovation measures and, at the same time, for the impacts and benefits arising in the use phase as a consequence of the retrofit.

7) PED-oriented feasibility assessment.

Finally, the technical feasibility of reaching the PED targets was evaluated for the specific application context, consolidating district-scale results to verify effective progress toward the PED requirements.

2.1.2 Data collection, assumptions and modelling inputs

Building on the available information, the district-scale energy models were developed by combining the most relevant datasets with consistent assumptions for the building stock under analysis and, where feasible, supported by on-site inspections and field surveys.

Boundary conditions, core modelling assumptions and climate-related parameters were defined consistently and aligned with literature-based approaches [75], [78], [79], [109].

Weather data were derived from EnergyPlus EPW files representative of the local climate and directly imported into the UBEM platform as climatic boundary conditions. Operational schedules and usage profiles were defined by combining available local information with standard reference values. Internal gains were assigned using typical ranges for lighting and plug loads, tailored to use type and assigned archetype. Occupancy levels and infiltration rates were set within plausible bounds and, where needed, refined during model tuning and calibration processes to improve the robustness of the simulations.

- For the UNIPA Campus, the UBEM input dataset was defined by combining geometric and thermo-physical model inputs with evidence gathered through targeted technical surveys, on-site inspections and field checks, which supported the validation of key envelope and system characteristics. Energy-use patterns were derived from utility bills and metered data for a representative year (2024), considering both electricity demand and space-heating energy carriers. Weather data were taken from the EnergyPlus EPW file for Palermo-Punta Raisi Airport, while operational schedules and use profiles were derived from survey evidence and consolidated reference values. Where direct information was unavailable, assumptions were cross-checked against recognised standards and current regulations, including ASHRAE guidance [110], [111]. Internal gains, occupancy levels and infiltration rates were adjusted to reflect campus use patterns (primarily teaching spaces and offices).

The collected data also enabled the definition of representative recurrent construction and system features across the campus stock. Buildings were characterised by tuff-stone external walls, with a thermal transmittance $U = 1.4 \text{ W}/(\text{m}^2 \cdot \text{K})$, ground floors with grit-tile flooring ($U = 2.4 \text{ W}/(\text{m}^2 \cdot \text{K})$), reinforced-concrete beam-and-block horizontal elements ($U = 2.1 \text{ W}/(\text{m}^2 \cdot \text{K})$), flat concrete roofs ($U = 2.0 \text{ W}/(\text{m}^2 \cdot \text{K})$) and double clear glazing with aluminium frames without thermal break ($U = 4.0 \text{ W}/(\text{m}^2 \cdot \text{K})$). Surveys further showed that 10 of the 17 modelled campus buildings were served by a mixed HVAC configuration combining natural gas boilers for space heating, autonomous split units for cooling and, in some cases, rooftop reversible air-source heat pumps providing partial coverage, whereas the remaining buildings already operated with fully electric heating and cooling systems.

- For the Bari case study, model inputs were compiled from a combination of sources: where available, aggregated electricity billing data were used to inform archetype-specific calibration targets (Archetypes 1 and 2), while for building groups lacking metered evidence (Archetypes 3 and 4), inputs were derived from open datasets, GIS-based information, archetype libraries and literature-derived parameters to ensure district-scale internal coherence [109], [110], [111].

The resulting dataset enabled the definition of representative building archetypes across the district, including multi-storey residential buildings, mid-rise residential dwellings, high-rise tower blocks and non-residential school buildings. For these archetypes, envelope properties and system configurations were assigned through

standardised assumptions consistent with the available sources. Residential archetypes were generally characterised by external walls with a thermal transmittance of $1.20 \text{ W}/(\text{m}^2\cdot\text{K})$, roofs with a thermal transmittance of $0.80 \text{ W}/(\text{m}^2\cdot\text{K})$ and glazing with an average $U = 6.00 \text{ W}/(\text{m}^2\cdot\text{K})$. HVAC systems were assumed to rely on individual gas boilers for space heating, with no active cooling system assigned to thirteen of the fourteen building blocks; the remaining residential block, corresponding to about 12% of the district conditioned floor area, was modelled as already served by electrically driven equipment providing both space heating and space cooling.

2.2 Energy models evaluation: calibration and validation workflow

Across the different case studies, the building models were evaluated through a structured calibration-validation protocol, iteratively tuning uncertain inputs and adjustable parameters against measured data (when available) or, otherwise, against harmonised features of the adopted reference archetypes.

Calibration focused on adjusting key uncertain parameters (e.g., schedules, internal gains, ventilation/infiltration and system performance) within a $\pm 30\%$ variation range. The procedure was iterated until the deviation between simulated energy use (electricity and, where applicable, natural gas demand for heating) and the reference data - utility bills where available, otherwise benchmark values derived from the adopted reference archetypes - fell within $\pm 10\%$.

It should be noted that the two case studies rely on different levels of empirical evidence. The UNIPA Campus was calibrated against metered electricity and natural gas consumption for the year 2024, complemented by hourly load profiles, whereas the Bari district was calibrated on aggregated billing data for two of the four archetypes and, where metered evidence was unavailable, on archetype-specific reference values drawn from recognised sources. The same acceptance criterion was nevertheless applied to both districts, with model-to-data deviations required to remain within $\pm 10\%$ on an annual basis. This asymmetry in data availability is representative of the conditions typically encountered in district-scale assessment and is explicitly accounted for in the interpretation of the results.

More in details, model-to-data consistency was quantified as follows:

- For the UNIPA Campus, calibration and subsequent validation relied on annual electricity consumption and space-heating gas use for 2024, complemented by 2024 operational records. Although limited to a single year, this evidence base still allowed season-by-season consistency checks and helped limit overfitting (i.e., fitting to dataset-specific fluctuations rather than capturing the underlying energy behaviour). All datasets were mapped to the relevant building and district boundaries and quality-checked to derive representative demand profiles.
- For Bari, calibration and validation, where direct survey evidence and/or metered data were unavailable (including specific building groups such as tower buildings), occupancy and operating assumptions were derived from standard reference sources and regulatory/default profiles (such as EN 16798-1 [75], ASHRAE reference values [110] and other relevant guidelines [109], [111]) to ensure transparent and reproducible inputs. Archetype definitions were informed by the construction features summarised above and by benchmark parameter ranges; model reliability was assessed at the archetype level by comparing energy-use levels and seasonal demand patterns.

Indoor environmental conditions for the Bari district were assigned with reference to EN 16798-1:2019 [75], whose Table B.2 recommends, for residential spaces in Category II, a minimum operative temperature of 20.0°C during the heating season and a maximum of 26.0°C during the cooling season. The values adopted for the individual building blocks were adjusted within the calibration procedure described above and lie between 20.0 and 22.0°C for heating, with a mean of 20.7°C , and between 23.0 and 27.0°C for cooling, with a mean of 24.9°C ; setback temperatures were set at 18.0°C and 28.0°C respectively, and the cooling season was defined from 15 May to 15 September. The mean cooling setpoint is therefore 1.1 K below the Category II reference value, which corresponds to a precautionary estimate of cooling demand. Indoor comfort parameters, ventilation rates and the definition of the heating and cooling seasons were kept identical in the baseline and renovated configurations, so that the difference between the two scenarios reflects the change in envelope performance and in system configuration alone.

2.3 Tailored retrofit packages and technical feasibility across case studies

In this section, retrofit strategies are defined and described on a case-specific basis for the two case studies, with the extent and depth of the proposed interventions calibrated according to boundary conditions, technical feasibility and case-specific constraints.

2.3.1 UNIPA Campus: renovation pathway and rooftop photovoltaic potential

For the UNIPA Campus, an integrated retrofit package was implemented, combining envelope upgrades with system improvements that included full electrification (i.e., the replacement of gas boilers) and rooftop photovoltaic (PV) installation. This option was supported by the higher operational feasibility of coordinated interventions in a university campus, where actions can be planned and rolled out at both building and district scale within a centralised governance structure.

More specifically, the renovation pathway followed a three-step sequence:

- (i) reduce energy needs (through buildings performance improvements, namely envelope insulation and windows replacement);
- (ii) electrify end uses (by phasing out gas boilers and, where technically feasible, switching space heating, space cooling and DHW services to electric-powered systems);
- (iii) cover the residual demand through on-site renewable electricity generation (by installing rooftop PV panels).

These three key steps can be detailed as follows:

- (i) Energy needs were first lowered through envelope improvements. High-performance insulation materials were prioritised to support life cycle-oriented environmental objectives in line with Italian national requirements. Thermal transmittance targets were set according to the Minimum Requirements Decree [112], by climate zone;
- (ii) Heating and cooling systems were then converted to all-electric solutions by replacing fossil-based equipment with high-efficiency heat pumps, consistent with the EPBD [4], [5] trajectory toward the phase-out of fossil systems. Technology selection reflected district morphology and thermal plant configuration: centralised air-to-water units, producing hot and chilled water for distribution to the buildings, were adopted for the UNIPA Campus, and decentralised air-to-air units for the predominantly residential stock of the Bari district, the heat source being outdoor air in both cases;
- (iii) Lastly, on-site renewable generation was introduced through rooftop photovoltaic (PV) systems, considered the most deployable option under typical urban constraints. A conservative sizing approach was applied: only rooftops and viable flat surfaces were considered, while wind energy was excluded due to limited feasibility and higher regulatory barriers. This approach maximises the use of available surfaces while minimising interference with building functions, as well as constraints related to access, safety and operability. Overall, envelope upgrades, electrification and PV integration were treated as complementary actions to jointly reduce energy deficits and GHG emissions, while strengthening district autonomy. As shown in Fig. 4, the assessed rooftop PV potential across the campus corresponds to a total capacity of 2,381 kW.

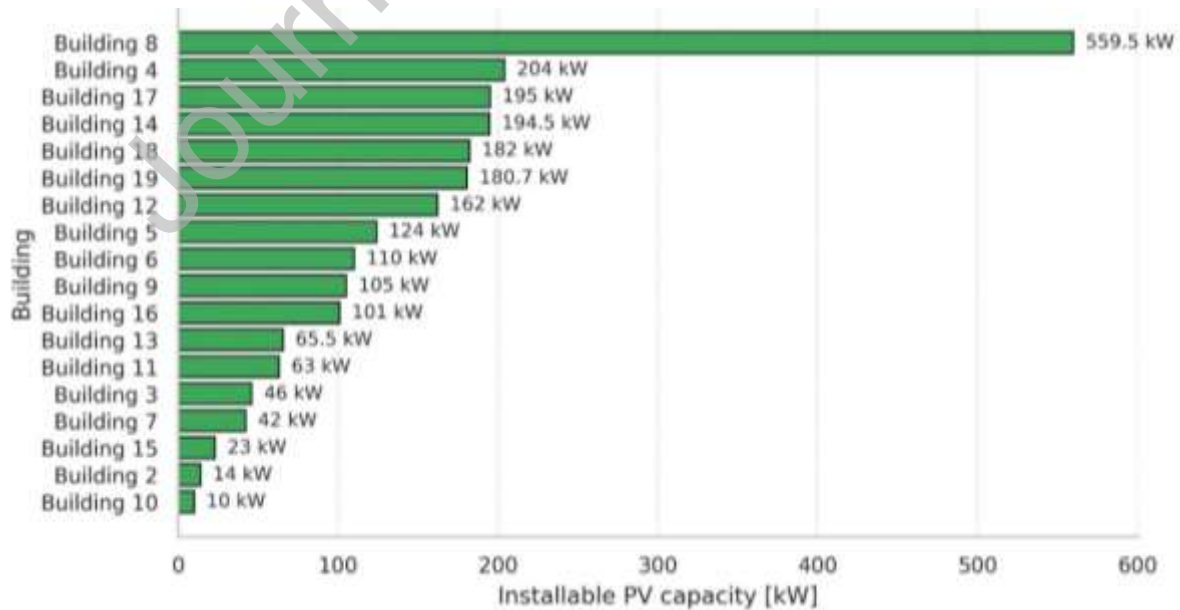


Fig. 4. UNIPA Campus: rooftop PV capacity potential by building (kW).

At building level, Fig. 4 reports the rooftop PV capacity potential across the UNIPA Campus: the mean value is about 132 kW, while results span a broad range (10.0-559.5 kW).

Capacity potential is unevenly distributed across the stock, with a small subset of buildings accounting for a large share of the total. Building 8 alone reaches 559.5 kW (23.5% of the total), while the five highest-potential buildings (Buildings 8, 4, 17, 14 and 18) sum to 1,335 kW (56.1%), rising to 63.7% when Building 19 is also included.

Conversely, six buildings with PV potential ≤ 70 kW (Buildings 10, 15, 7, 3, 11 and 13) amount to 263.5 kW in total (11.1%).

2.3.2 Estimation of photovoltaic generation

Annual electricity generation was estimated using the PVWatts online calculator (version 8), applied to the rooftop photovoltaic capacity resulting from the surface assessment described above.

Monofacial crystalline-silicon modules were assumed in both districts, with no rear-side contribution credited.

The PVWatts Standard module option was adopted, corresponding to a nominal module efficiency of approximately 19% and a temperature coefficient of power of $-0.37\%/^{\circ}\text{C}$. No manufacturer-specific module performance data were introduced, consistently with the district-scale screening level of the assessment.

PVWatts default values were retained for parameters that were not specifically modified for the two case studies. In both simulations, the DC-to-AC size ratio was 1.20, the nominal inverter efficiency was 96%, and the soiling loss was 2%.

For the UNIPA Campus, a fixed open-rack array with a tilt angle of 25° and a southward orientation (azimuth 180°) was assumed. Total system losses were 13.10%, corresponding to the PVWatts default loss configuration with the availability loss reduced from 3% to 1.9%.

For the Bari district, a fixed open-rack array with a tilt angle of 30° and the same southward orientation was assumed. The complete PVWatts default loss configuration was retained, resulting in total system losses of 14.08%.

The availability loss, which represents reduced system output associated with maintenance and outages, was set to 1.9% for the UNIPA Campus as a case-specific modelling assumption reflecting the centralised operation, continuous monitoring and coordinated maintenance of the university estate.

The default value of 3% was retained for the Bari district, for which no equivalent centralised operation and maintenance regime was assumed.

In both districts, shading was considered at two distinct stages of the assessment. First, roof portions affected by persistent shading, together with areas constrained by obstructions, insufficient continuous surface, setbacks, inter-row spacing and maintenance-access requirements, were excluded when determining the deployable photovoltaic capacity.

Second, a 3% shading loss was retained in the PVWatts simulations for the arrays installed on the roof areas considered suitable for PV deployment. This latter assumption accounts for residual shading-related losses during system operation and is included within the overall PVWatts system-loss calculation.

Under these assumptions the estimated specific yields are of about 1,449 kWh/kWp for the UNIPA Campus and 1,369 kWh/kWp for the Bari district.

2.3.3 Bari district: retrofit scenario and photovoltaic capacity

For the Bari case study, the retrofit scenario was defined by applying the three-step renovation pathway outlined above (reducing energy needs, electrifying end uses, integrating rooftop PV panels).

This configuration aligned with a mixed-use context, where lowering thermal loads and shifting end uses to electricity emerged as strategic levers to maximise the value of on-site PV generation, also reducing reliance on fossil-based energy carriers.

To distinguish the effect of the envelope renovation from those associated with HVAC electrification, a separate envelope-only control configuration was analysed. This configuration, hereafter referred to as the “Envelope-upgraded” configuration, was derived from the calibrated baseline by replacing only the thermal transmittances of the external walls, roofs and windows with their post-retrofit values. HVAC systems, operational schedules, indoor comfort parameters and heating- and cooling-service availability were retained unchanged.

2.3.4 Retrofit assumptions adopted for the two case studies

Table 1 summarises the retrofit packages adopted for the two case studies, including post-retrofit envelope performance targets, system efficiency upgrades, equipment replacement strategies and rooftop PV installation potential. Envelope targets were defined with reference to the Italian minimum energy performance requirements for building renovation and the related national regulatory framework [112], [113]. In both cases, these thresholds were treated as reference compliance values, rather than design targets. The retrofit packages therefore adopted more ambitious solutions, including high-performance external insulation systems and high-performance window replacements, resulting in post-retrofit U-values below the applicable regulatory limits.

This reflects a retrofit approach aimed at substantially reducing thermal loads and supporting service electrification, together with rooftop PV integration.

PV capacity potential was estimated through a practice-oriented assessment of suitable roof area, excluding portions constrained by shading, obstructions, insufficient continuous surface and standard layout requirements such as setbacks, inter-row spacing and maintenance access paths.

The packages described above should be regarded as feasible retrofit configurations rather than optimal solutions. They were defined on technical and contextual grounds, and the same three-step sequence was applied to both districts to ensure that the cross-typology comparison was based on a common set of measures rather than on two independently selected packages. No optimisation was performed across alternative combinations of retrofit measures; the optimisation procedure described in Section 2.2 concerns only the calibration of uncertain model inputs. Alternative combinations, including measures not included in the assessed packages, are discussed in Section 4.

Table 1. Retrofit assumptions for the UNIPA Campus and Bari district: envelope targets, system upgrades and rooftop PV potential.

Case study	Opaque envelope post-retrofit targets	Transparent envelope post-retrofit targets	System upgrades	Photovoltaic panels
UNIPA Campus Palermo	External walls: $U = 0.17 \text{ W/(m}^2\cdot\text{K)}$ Roofs: $U = 0.18 \text{ W/(m}^2\cdot\text{K)}$	High-performance glazing units with thermally broken frames and double glazing (4 mm glass/12 mm air gap/4 mm glass), low-emissivity coating, SHGC = 0.31, overall thermal transmittance (glass + frame) $U = 1.20 \text{ W/(m}^2\cdot\text{K)}$	Replacement of existing natural gas thermal plants with high-efficiency, electrically driven centralised air-to-water heat pumps, suitable for large-scale centralised applications; full electrification with gas boilers phased out; COP (heating) = 3.8; EER (cooling) = 3.5	Rooftop PV integration PV installation potential: 2,381 kW
Bari district	External walls: $U = 0.33 \text{ W/(m}^2\cdot\text{K)}$; Roofs: $U = 0.30 \text{ W/(m}^2\cdot\text{K)}$	High-performance glazing units with thermally broken frames and double glazing (4 mm glass/12 mm air gap/4 mm glass), low-emissivity coating, SHGC = 0.80, overall thermal transmittance (glass + frame) $U = 2.00 \text{ W/(m}^2\cdot\text{K)}$	Replacement of existing natural gas thermal plants with high-efficiency, electrically driven air-to-air heat pumps, considered more suitable for decentralised and residential contexts; full electrification with gas boilers phased out; COP (heating) = 4.0; EER (cooling) = 3.9	Rooftop PV integration PV installation potential: 830 kW

2.4 Environmental impact analysis based on Life Cycle Assessment

Alongside the energy-retrofit scenarios analysed in this study, an environmental analysis was performed to quantify life cycle burdens associated with the retrofit packages and the resulting energy use. The LCA was carried out in line with ISO 14040 [64] and ISO 14044 [65].

This coupling of dynamic building energy simulation and life cycle assessment follows an approach already applied at building scale, where the relative weight of non-operational impacts was shown to grow as operational energy demand is reduced [114].

2.4.1 Goal, scope and system boundary

A process-based LCA was carried out to quantify district-scale environmental impacts for the baseline and retrofit configurations. The system boundary covered production, use (operational energy) and end-of-life stages. Foreground modelling was coupled with background inventories from the Ecoinvent database v3.10 [115].

The assessment refers to each district as a whole. The reference unit is the set of buildings enclosed by the district perimeter defined in Section 2.1.1 and shown in Figs. 1-3, namely the 17 modelled campus buildings for the UNIPA Campus and the 14 multi-unit building blocks for the Bari district, taken over one year of operation.

The same perimeter delimits the three levels of the analysis: the buildings simulated in the energy model, the components and energy flows included in the life cycle inventory, and the generation and consumption terms of the district balance of Equation (6).

Within this perimeter the inventory covers the production and end-of-life stages of the retrofit components introduced by the renovation, together with the use phase of both configurations, expressed as the annual electricity and natural gas consumption returned by the district energy models.

Regarding system boundaries, the inventory and impact calculations adopted a cradle-to-grave scope for retrofit materials and technologies, covering production and end-of-life phases. These upstream stages were treated as major drivers to the overall environmental profile of renovation measures. Primary input data (e.g. quantities of insulation layers, window components, PV systems and HVAC upgrades) were derived from the retrofit design assumptions described in Section 2.3. Background datasets were taken from the Ecoinvent database (Ecoinvent 3.10 dataset) [115], [116], [117] and implemented in the SimaPro (PRé Sustainability) tool [118] to compute impact indicators - including carbon footprint - for the analysed retrofit materials and energy-system solutions. Service lives were assigned by component type based on database guidance and literature values, acknowledging that lifetime assumptions are a key determinant of long-term results [119], [120].

More specifically, the reference lifetime values adopted in this study were as follows:

- Photovoltaic systems: 30 years;
- Insulation materials: 30 years;
- Windows and fenestrations: 30 years;
- Heat pumps/HVAC upgrades: 20 years.

Since Equations (3) and (5) annualise the production and end-of-life burdens of each component over the service life of that component, and not over a common horizon, no shared replacement cycle is embedded in the results. A component assigned a 20-year service life carries an annual burden 50% higher than an otherwise identical component assigned 30 years, which over a thirty-year horizon corresponds to accounting for one replacement. Annualised production and end-of-life impacts are consequently inversely proportional to the assumed service life, so that any revision of these assumptions rescales the corresponding terms of the renovated configuration, leaving the use phase and the baseline configuration unaffected.

Two scenarios were compared:

- i) The baseline scenario, reflecting the current district condition and including only one year of environmental impacts associated with operational energy consumption during the use phase.
- ii) The renovated scenario, reflecting the post-retrofit condition and accounting for annualised impacts obtained by combining the annualised life cycle burdens of the implemented measures - insulation, window replacement, photovoltaic installation and HVAC electrification/system upgrades - with the impacts of operational energy use. In this case, the assessment included not only the use phase, but also the production and end-of-life stages of the retrofit solutions.

The comparison between the two scenarios is based on the difference between the pre- and post-retrofit conditions. The construction and end-of-life of the existing buildings are common to both conditions and

therefore entail the same impacts in both scenarios; these contributions do not affect the resulting difference and were consequently excluded from the system boundary of both configurations.

The production and end-of-life stages accounted for in the renovated scenario refer exclusively to the retrofit solutions introduced, which have no counterpart in the baseline condition. The use phase, by contrast, is included in both scenarios, with the operational energy consumption corresponding to each configuration.

The comparison is therefore symmetrical: the same life cycle stages are considered for both scenarios, and the production and end-of-life terms are non-zero only in the renovated configuration because the corresponding components exist there alone.

The difference between the two scenarios thus reflects the materials and technologies introduced by the retrofit together with the change in operational energy that they determine. This holds under the assumption that the renovation does not modify the remaining service life of the existing buildings, so that their construction and end-of-life burdens remain identical in the two scenarios.

Fig. 5 summarises the system boundary of the assessment, reporting for each configuration the life cycle stages and the components that were included and those that were left outside it.

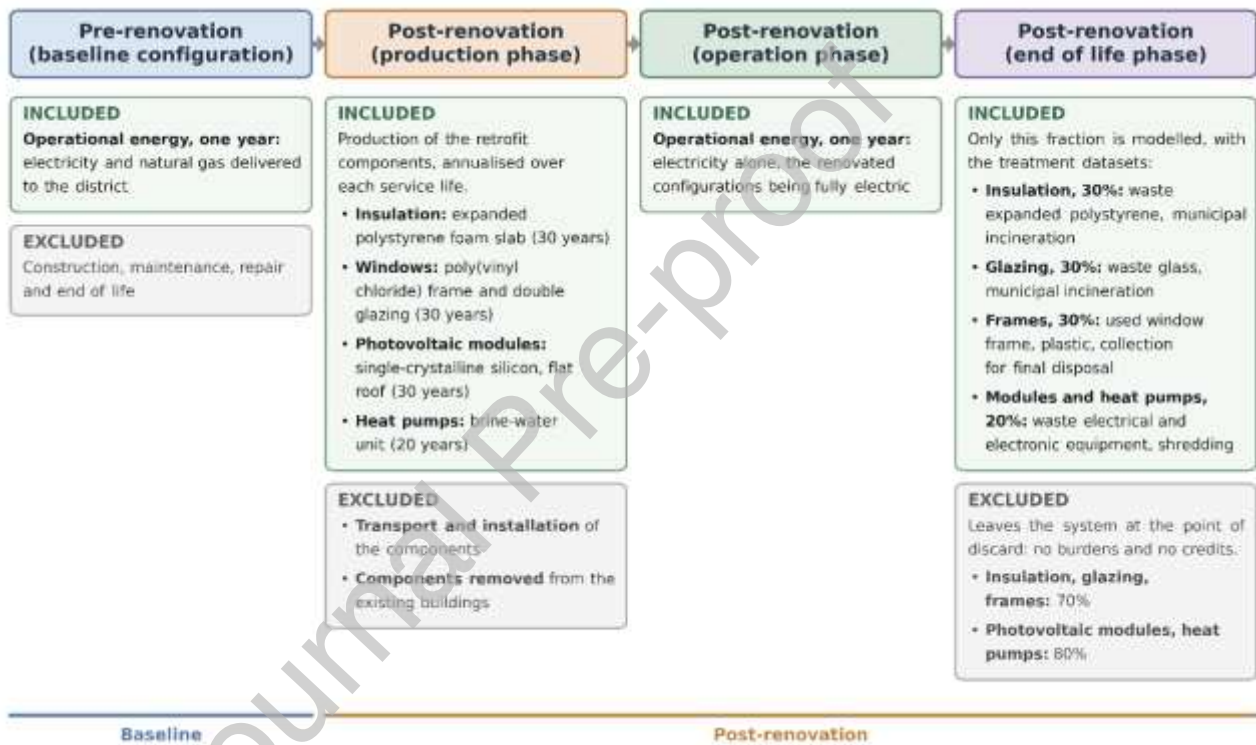


Fig. 5. System boundary of the life cycle assessment: life cycle stages and components included in and excluded from the pre-renovation baseline and the post-renovation configurations.

Production and end-of-life impacts of each retrofit component were annualised over its useful lifetime and then combined with the annual use-phase impacts, so as to refer both scenarios to a common annual basis. Post-renovation scenarios therefore combined:

- a) the annualised environmental burdens of implemented measures;
- b) one year of the resulting operational energy consumption;
- c) end-of-life impacts, that were modelled as described in Section 2.4.3.

2.4.2 Impact assessment and calculation of the annualised impacts

Environmental performance was assessed through the 16 midpoint impact indicators defined by EN 15804+A2 [121], complemented by Cumulative Energy Demand (CED) [117], for a total of 17 impact categories $j = 1, \dots, 17$ (acidification, climate change, freshwater ecotoxicity, particulate matter, marine eutrophication, freshwater eutrophication, terrestrial eutrophication, human toxicity-cancer, human toxicity-non-cancer, ionising radiation, land use, ozone depletion, photochemical ozone formation, resource use-fossils, resource use-minerals and metals, water use and cumulative energy demand).

On this basis, the key computational steps adopted to derive the annualised impacts for each category j and for each retrofit component i (insulation, windows, PV, heat pump/HVAC upgrade) are summarised in Equations (3)-(5), while Equation (6) refers to the annual PED electricity balance.

The annualised environmental impacts of the production phases (EI_p) were calculated as:

$$EI_p = \sum_i \frac{Q_i \times FC_{P,i}}{UL_i} \quad (3)$$

Where:

- Q_i : is the quantity of material or installed system capacity i (kg, m², kW, or kWh);
- $FC_{P,i}$ is the production characterisation factor for each component i (Indicator/unit);
- UL_i is the useful lifespan (expressed in years) of component i .

The environmental impacts related to energy consumption during the use phase (EI_U) were evaluated as:

$$EI_U = \sum_j E_j \times FC_{energy,j} \quad (4)$$

Where:

- E_j is the annual energy consumption for the j -th energy carrier (kWh);
- $FC_{energy,j}$ is the characterization factor for each energy carrier j (Indicator/kWh) derived from carrier-specific life cycle inventory data and emission factors.

The annualised environmental impacts of the end-of-life phase (EI_{EOL}) were assessed as follows:

$$EI_{EOL} = \sum_i \frac{Q_i \times FC_{EOL,i}}{UL_i} \quad (5)$$

Where:

- Q_i : is the quantity of material or installed system capacity i (kg, m², kW, or kWh);
- $FC_{EOL,i}$ is the end-of-life characterisation factor for component i (Indicator/unit);
- UL_i is the useful lifespan (expressed in years) of component i .

2.4.3 Life cycle inventory and background datasets

The datasets used to quantify the above-mentioned environmental impacts for both case studies are summarised below, distinguishing among the production, use and end-of-life phases.

Production phase:

- Insulation: Polystyrene foam slab {RER}| polystyrene foam slab production | Cut-off, U.
- Window frame: Window frame, poly vinyl chloride, U=1.6 W/m²K {RER}| window frame production, poly vinyl chloride, U=1.6 W/m²K | Cut-off, U.
- Window glass: Glazing, double, U<1.1 W/m²K {RER}| glazing production, double, U<1.1 W/m²K | Cut-off, U.
- Photovoltaic system: Photovoltaic flat-roof installation, 3kWp, single-Si, on roof {CH}| photovoltaic flat-roof installation, 3kWp, single-Si, on roof | Cut-off, U.
- Heat pump: Heat pump, brine-water, 10kW {CH}| heat pump production, brine-water, 10kW | Cut-off, U.

Use phase:

- Electricity Import: Electricity, low voltage {IT}| market for electricity, low voltage | Cut-off, U.
- Natural gas consumption: Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler modulating >100kW | Cut-off, U.

End-of-life phase:

- Insulation: Waste expanded polystyrene {CH}| treatment of waste expanded polystyrene, municipal incineration | Cut-off, U.
- Window frame: Used window frame, plastic {RoW}| treatment of used window frame, plastic, collection for final disposal | Cut-off, U.
- Window glass: Waste glass {RoW}| treatment of waste glass, municipal incineration | Cut-off, U.

- Photovoltaic system: Waste electric and electronic equipment {GLO}| treatment of waste electric and electronic equipment, shredding | Cut-off, U.
- Heat pump: Waste electric and electronic equipment {GLO}| treatment of waste electric and electronic equipment, shredding | Cut-off, U.

End-of-life was modelled as follows, component by component, according to the targets set by Directive 2008/98/EC for non-hazardous construction and demolition waste [122] and by Directive 2012/19/EU for the corresponding categories of waste electrical and electronic equipment [123]:

- Expanded polystyrene insulation and window glazing:
 - 70% of the material was assumed to be recycled;
 - 30% was treated in a municipal incinerator.
- Plastic window frames:
 - 70% of the material was assumed to be recycled;
 - 30% was collected for final disposal.
- Photovoltaic modules and heat pumps:
 - 80% of the material was assumed to be recycled;
 - 20% was modelled as waste electrical and electronic equipment, shredding.

The material sent to recycling leaves the assessed system at the point of discard: neither the burdens nor the benefits of the subsequent recycling operations are attributed to the renovation, and no recycling credit is accounted for.

The photovoltaic dataset refers to a nominal 3 kWp flat-roof installation and was used as a unit reference: the associated burdens, expressed per unit of installed capacity, were scaled to the capacity assessed in each district. Its single-crystalline silicon technology and flat-roof mounting correspond to those assumed in both case studies, so that the difference in installed capacity affects the scaling factor rather than the composition of the modelled system.

The heat pump dataset was applied to both case studies as a single unit reference for the heat generation equipment: it describes the production of an electrically driven unit with a nominal capacity of 10 kW, and the associated burdens, expressed per unit of installed capacity, were scaled to the heat pump capacity assessed in each district.

Adopting the same reference for both districts keeps the cross-case comparison independent of the choice of background data.

2.5 Positive Energy District-oriented assessment framework

The PED Reference Framework adopted here as the conceptual reference [28], [34] defines Positive Energy Districts through three functions, namely energy efficiency, energy flexibility and energy production, and leaves the specification of indicators, boundaries and targets to the national and project context.

It therefore provides a methodology and a transition pathway rather than a fixed set of metrics, and the criteria adopted in this study correspond to its functions as follows.

- The energy efficiency function is represented by the total final energy use of the baseline configurations and by the post-retrofit energy demand of each district, complemented at end-use level by the heating and cooling intensities per unit of conditioned floor area
- The energy production function is represented by rooftop photovoltaic generation and by the share of annual post-retrofit electricity demand that it covers.
- The energy flexibility function is not quantified: self-consumed, exported and imported electricity are reported as descriptors of the district-grid interaction under the assessed configurations, but no flexibility measure is modelled, consistently with the annual formulation adopted in Equation (6).

The net greenhouse gas emission requirement contained in the framework definition is addressed through the life cycle assessment described in Section 2.4, which evaluates both configurations across seventeen impact categories rather than through a single emission indicator.

All renovation scenarios were evaluated against the adopted PED targets through a district-scale PED-oriented assessment framework considering the following criteria:

- (i) the total final energy use in the baseline reference cases;

- (ii) the total grid-imported electricity in the post-retrofit configurations, i.e., the electricity required to cover the residual demand after PV self-consumption;
- (iii) the electricity exported to the grid, due to PV surplus not self-consumed.

Accordingly, the assessment considered annual district electricity demand and rooftop PV generation, as expressed in Equation (6).

$$B = \sum_{p=1}^q G_p - \sum_{p=1}^q C_p \quad (6)$$

Where:

- B denotes the annual district electricity balance, computed as the difference between annual PV electricity generation and annual district electricity consumption; in the absence of storage, Equation (6) is equivalent to the net annual grid exchange (exports minus imports) and therefore implicitly accounts for PV self-consumption.
- G_p represents the electricity generated by rooftop PV at hourly time step p (with $p=1, \dots, q$) and being $q=8,760$ (where 8,760 is the total number of hourly time steps considered over the year).
- C_p is the district electricity demand at the same time-step p .

Although PED balances are often expressed in primary energy terms, final energy is used here, since the renovated configurations are fully electrified. Both terms of Equation (6) therefore refer to the same energy carrier. Applying the same primary energy conversion factor to electricity generation and consumption would rescale both terms proportionally, leaving the sign of the balance unchanged.

Conversely, assigning different factors to on-site renewable generation and grid electricity would make the resulting balance dependent on the specific conversion convention adopted rather than on the underlying district energy performance.

Equation (6) is a particular case of the general district balance. Had natural gas consumption remained after retrofit, the assessment would instead have used a primary energy balance separating electricity generation, electricity consumption and natural gas consumption, with a specific conversion factor for each carrier:

$$B_P = f_{P,el} \sum_{p=1}^q G_p - [f_{P,el} \sum_{p=1}^q C_{el,p} + f_{P,gas} \sum_{p=1}^q C_{gas,p}] \quad (7)$$

Where:

- B_P is the annual district primary energy balance;
- G_p is the electricity generated by rooftop PV during hourly interval p ;
- $C_{el,p}$ and $C_{gas,p}$ are, respectively, district electricity and natural gas consumption during the same interval. All generation and consumption terms are expressed in energy units per interval, and $q = 8,760$ is the number of hourly intervals in the year.
- The factors $f_{P,el}$ and $f_{P,gas}$ convert electricity and natural gas, respectively, to primary energy on a consistent basis.

Additional energy carriers would be represented by analogous terms with their corresponding conversion factors.

All buildings are assumed to be electrically connected at district scale, so that PV surplus from one building can offset deficits in others, before any remaining excess is exported to the grid. When district generation is insufficient, residual demand is met through grid imports. Under these assumptions, the PED target is achieved when the annual electricity balance is positive ($B > 0$).

Since space heating and space cooling are supplied by electrically driven heat pumps in both post-retrofit configurations, their thermal demands are accounted for through the electricity required to meet them, together with appliances, lighting, domestic hot water and auxiliaries.

No district heating or cooling network is present, and no thermal energy crosses the district boundary; the electricity required for heating and cooling is therefore included directly in the demand term of Equation (6).

In addition, PED consistency is evaluated from an environmental perspective by applying the LCA framework and the annualisation procedure described in Equations (3) - (5) to both baseline and post-retrofit configurations, including production, use and end-of-life stages.

This makes it possible to complement the energy-balance criterion of Equation (6) with a category-by-category environmental assessment of baseline and post-retrofit configurations, in order to capture potential burden shifting associated with the retrofit measures.

3. Results

Results are presented in this section by first validating the baseline configurations for the two case studies and then assessing the effects of the renovation actions introduced in the previous sections.

Building energy performance was assessed through the UBEM workflow implemented in City Energy Analyst (CEA), ensuring consistency across buildings and at district scale.

Baseline model configurations were refined through the progressive adjustment of boundary conditions and key input parameters, including climate data, schedules, internal loads and operational assumptions, to better represent actual building characteristics and operating conditions.

3.1 Baseline assessment

As mentioned, the characterisation of the baseline scenarios was grounded on the analysis of historical energy bills over the adopted reference period.

Model reliability was confirmed through calibration against observed consumption, ensuring that the annual deviation between simulated and measured energy use remained below the predefined 10% threshold, thereby supporting robust scenario testing.

Calibration was implemented via in-house Python [105], [106] scripts built on the Hyperopt [107], [108] optimisation framework and including an early-stopping criterion. Boundary conditions and modelling inputs - such as climate data, schedules, internal loads and operational assumptions - were progressively and iteratively refined to reflect actual building characteristics and operating configurations.

Two dedicated calibration procedures were implemented:

- Thermal calibration: targeted annual sensible heating demand. The optimisation algorithm iteratively tuned key inputs - lighting and appliance power densities, heating and cooling setpoints and ventilation rates - over up to 300 iterations, aiming to reduce the annual percentage deviation between simulated outputs and reference consumption to below 10%. When the target was met earlier, the process was stopped to limit computational effort.
- Electricity calibration: followed an analogous optimisation pathway to match annual electricity use. The same parameter set and optimisation logic were adopted to minimise the deviation between simulated results and measured data.

Fig. 6 shows the percentage differences between measured and simulated electricity consumption (after calibration) for all the 17 modelled campus buildings. This comparison was used to assess the accuracy of the developed models and, consequently, to validate their reliability.

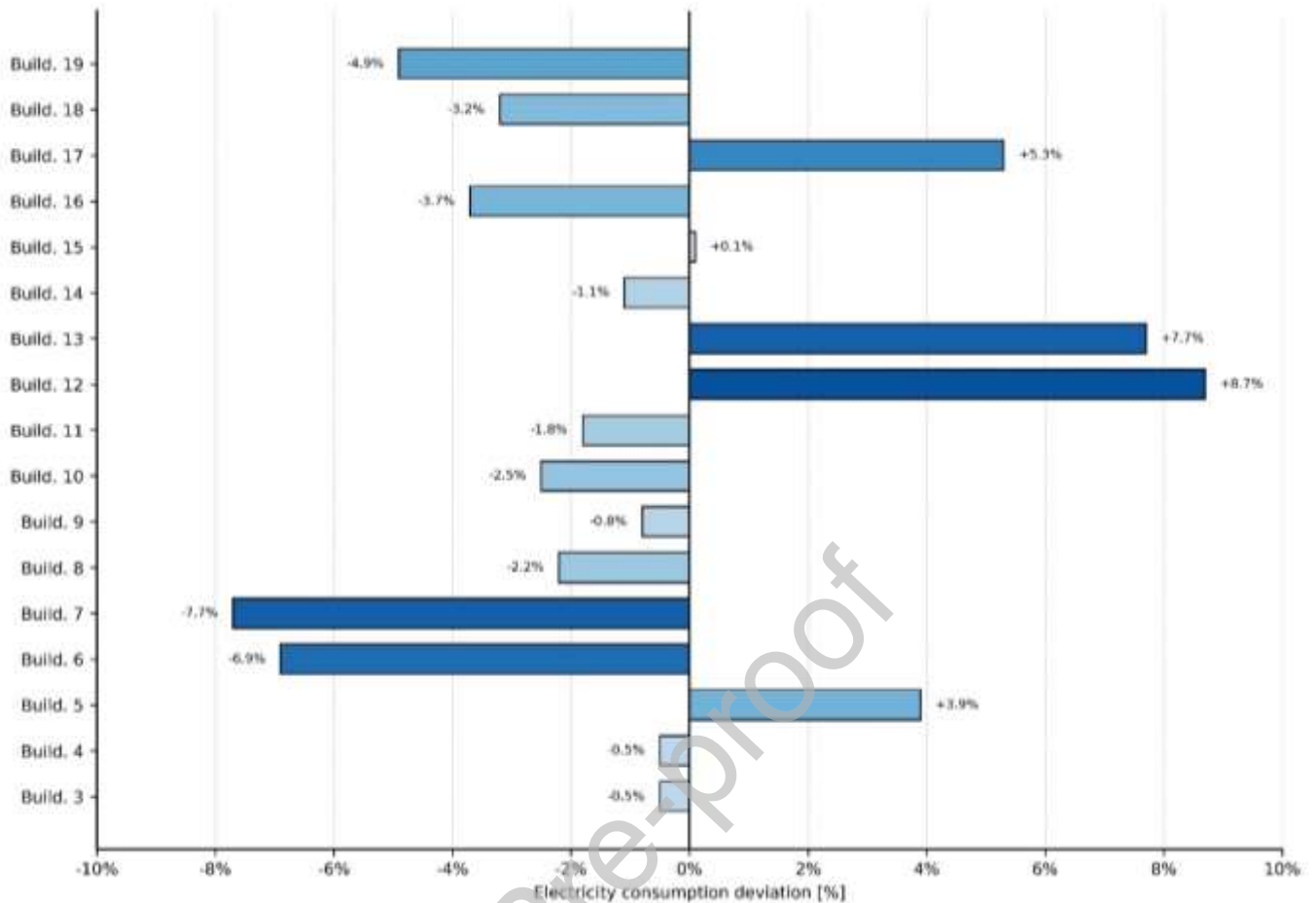


Fig. 6. UNIPA Campus: deviation between monitored and simulated electricity consumption by building.

As reported in Fig. 6, the deviation values range from approximately -7.7% to +8.7%, indicating consistency between the simulated models and the measured data.

Most buildings show absolute percentage deviations below 5.5%, confirming alignment between simulated and measured consumption profiles. Positive deviations denote an overestimation of consumption by the model, as for Building 12 (+8.7%), whereas negative deviations indicate an underestimation, as for Building 7 (-7.7%). Overall, the results remain within the $\pm 10\%$ tolerance adopted for calibration, consistent with the criteria commonly referenced in technical standards [75], [78] and ASHRAE guidelines [110].

Fig. 7 displays the deviations between measured and simulated natural gas consumption for buildings equipped with gas-fired heating systems.

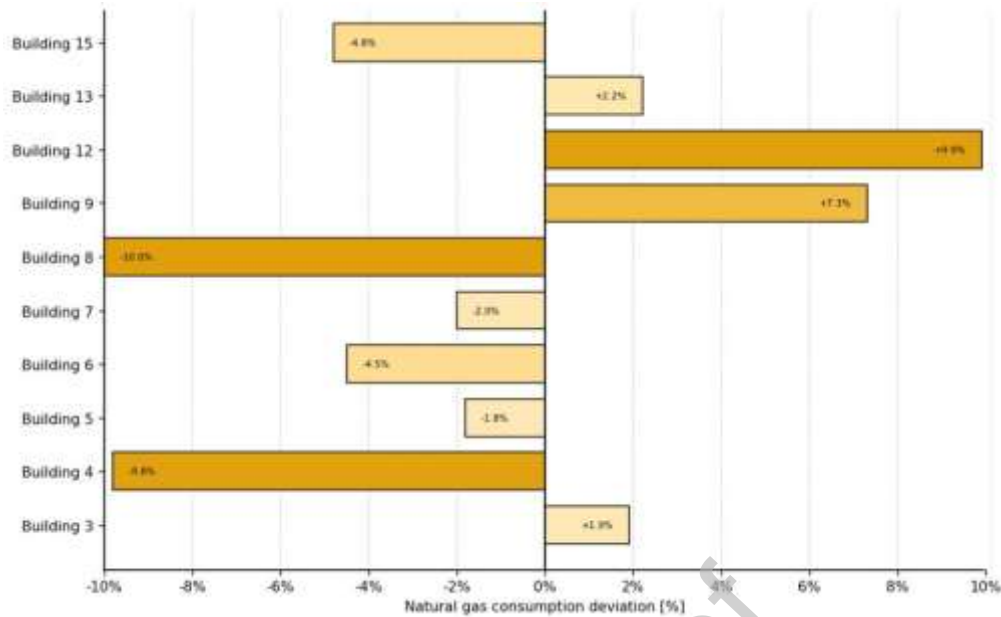


Fig. 7. UNIPA Campus: deviation between monitored and simulated natural gas consumption by building.

Also in this case, several buildings show deviations within a $\pm 5\%$ range, confirming consistency between simulated results and measured data. Building 12 presents a simulated overestimation of approximately $+9.9\%$, while Buildings 8 and 4 record the largest underestimations (-10% and -9.8% , respectively). Overall, these deviations are compatible with the calibration tolerance criteria adopted in this study and support moving forward with the analysis of annual energy flows. To provide a synoptic and comprehensive view of building-level energy use, Fig. 8 reports the annual electricity and natural gas consumption (MWh) for each modelled building as horizontal bars extending in opposite directions from the origin:

- electricity is shown in blue to the right;
- whereas natural gas is shown in orange to the left, thereby providing a single, clear overview of the two main energy carriers used across the university campus and enabling comparison of their relative contributions across buildings.

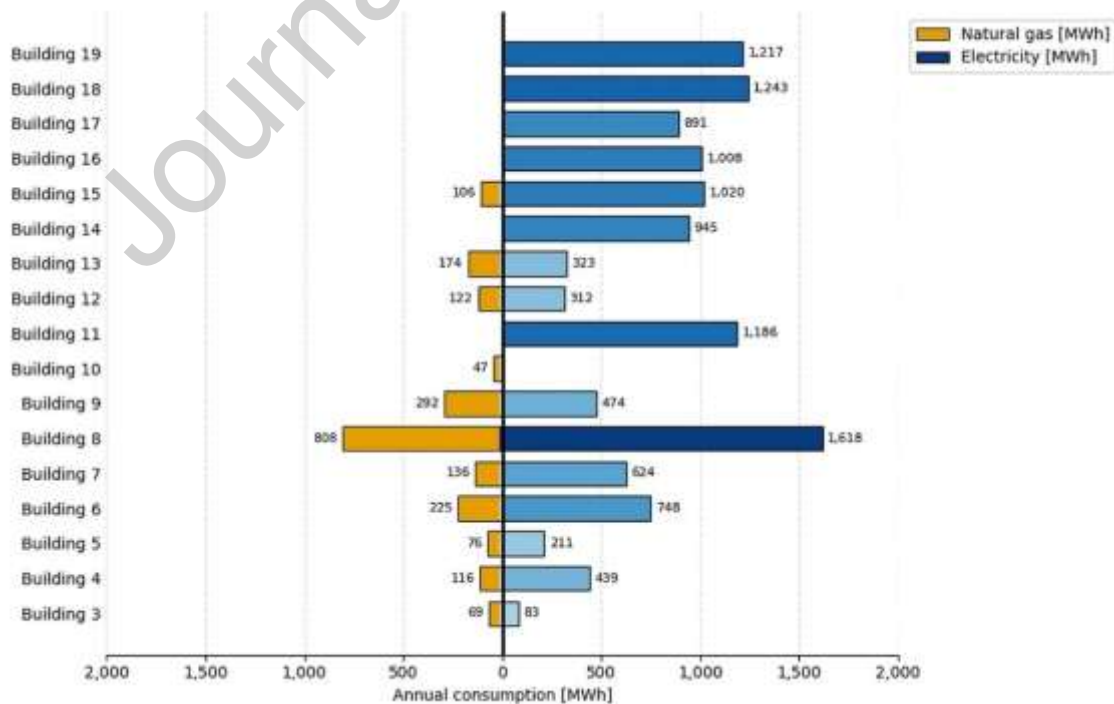


Fig. 8. UNIPA Campus: annual electricity (blue, right) and natural gas (orange, left) consumption per building.

The calibration outcomes for the four archetypes identified in the Bari district (7-storey residential buildings, 5-storey residential dwellings, residential towers and school) are reported to verify the correspondence between simulated energy demands and the selected reference values.

The iterative calibration runs ultimately converged to the validation outcomes discussed below.

1. Seven-storey residential archetype (Archetype 1): this group includes five buildings and was calibrated using annual electricity use derived from utility-bill analyses. The reference value adopted for calibration was 20.28 kWh/m²·year.
2. Five-storey residential archetype (Archetype 2): comprising four buildings, this archetype was calibrated against a benchmark annual electricity demand of 23.97 kWh/m²·year, also obtained from aggregated billing data.
3. Residential tower archetype (Archetype 3): this set consists of four high-rise buildings and was calibrated on space-heating demand. Given the lack of reliable electricity data for these buildings, the reference targets were taken from the TABULA database, assuming 68 kWh/m²·year for space heating.
4. School archetype (Archetype 4): it is represented by one single non-residential building; calibration relied on a national benchmark electricity demand of 22 kWh/m²·year, as reported in the RSE study [111].

Fig. 9 shows an overview of the calibration results across the four representative archetypes, based on the full set of screened multi-unit building blocks. Each subplot shows the blocks assigned to a given archetype, labelled with an archetype-specific progressive ID. This labelling is also consistently adopted in Table 2 to enable one-to-one cross-referencing between plots and tabulated values.

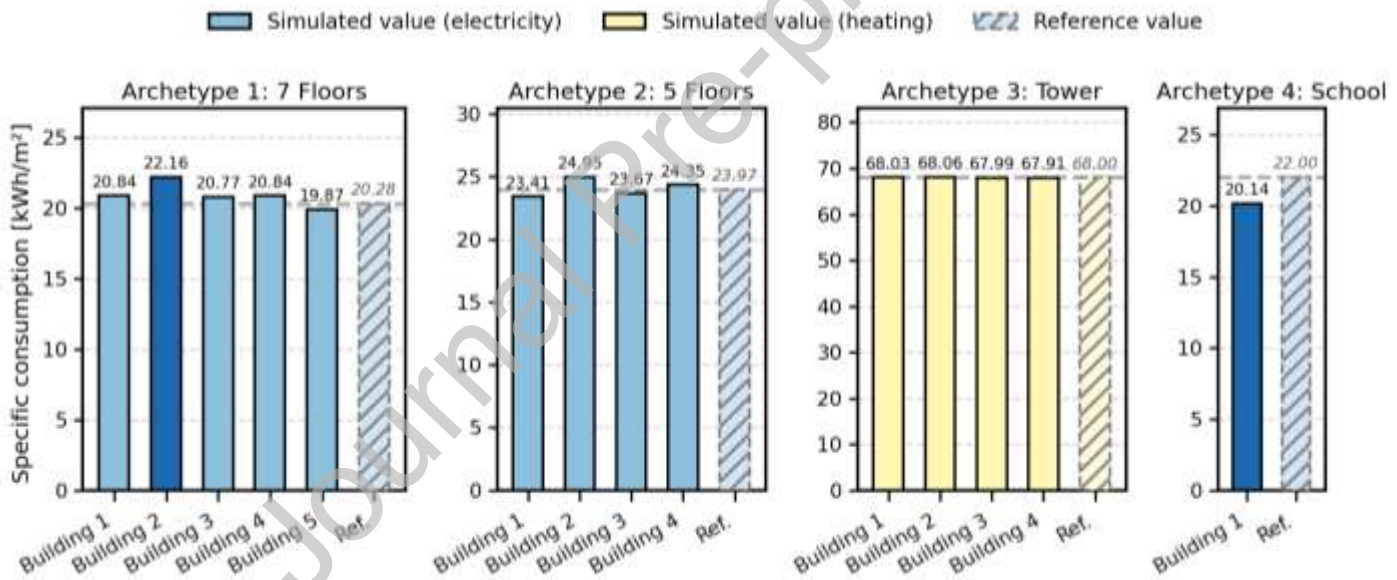


Fig. 9. Archetype-specific calibration results for the Bari district.

In more detail, Table 2 provides a building-level comparison for all simulated buildings in the Bari district, reporting the ID within each archetype, the assigned archetype, the corresponding reference value, the simulated annual demand (kWh/m²·year) and the resulting deviation.

Table 2. Building-level calibration performance - Bari district.

Building ID within each archetype	Archetype	Reference Source	Ref. Demand [kWh/m ² ·year]	Simulated Demand [kWh/m ² ·year]	Deviation [%]
1	Archetype 1	Energy-billing records	20.28	20.84	2.78%
2				22.16	9.28%
3				20.77	2.39%
4				20.84	2.78%
5				19.87	-2.02%
1	Archetype 2		23.97	23.41	-2.34%

2	Energy-billing records			24.95	4.09%
3				23.67	-1.26%
4				24.35	1.58%
1				68.03	0.04%
2	Archetype 3	TABULA	68.00	68.06	0.09%
3				67.99	-0.02%
4				67.91	-0.13%
1				20.14	-8.45%
1	Archetype 4	RSE study	22.00	20.14	-8.45%

As shown in Table 2, calibration results are consistent across all archetypes, with annual deviations remaining within the $\pm 10\%$ tolerance adopted in this study. More specifically, Archetype 1 shows deviations generally confined to a narrow range (-2.0% to $+2.78\%$), indicating close agreement between simulated and reference demands; only Building 2 reaches a higher deviation (9.28%), still within tolerance. Archetype 2 displays limited deviations (-1.26% to $+4.09\%$), suggesting stable performance across the buildings assigned to this archetype. Archetype 3 delivers the tightest match overall, with deviations near zero (within $\pm 0.13\%$), reflecting an almost one-to-one alignment with TABULA reference values. Finally, Archetype 4 shows a deviation of -8.45% . Although still within the adopted tolerance, this result suggests a systematic underestimation, possibly related to simplified operational assumptions or case-specific use patterns. Therefore, the calibration indicates that the UBEM model captures the buildings' energy behaviour with sufficient accuracy to support the subsequent comparative assessment and scenario analyses. Considered together, the calibration outcomes for both the UNIPA Campus and the Bari district confirm the robustness of the modelling framework. This cross-case consistency - achieved despite the different calibration datasets and strategies applied (metered utility data for UNIPA; archetype-based benchmarks for Bari) - supports the comparability of the two models and validates their use for the following assessment.

3.2 Post-renovation assessment

In this section, post-retrofit results are analysed for the two districts of interest to quantify the effectiveness of the renovation actions introduced in Section 2.3 ("Tailored retrofit packages and technical feasibility across case studies") in supporting the transition toward PED targets. As previously outlined, retrofit scenarios followed a consistent three-step pathway (energy demand reduction, end-use electrification and on-site renewable electricity generation). Outcomes are presented by case study and benchmarked against the corresponding baseline scenario; pre- and post-renovation comparisons are used to quantify percentage changes in energy needs and consumption trends and to appraise the role of the implemented retrofit measures. The following sub-sections provide a detailed, case-specific analysis along with the quantification of the achieved results.

Fig. 10 reports the electricity-consumption reductions achieved for UNIPA Campus Buildings 3-19 following the implementation of energy-efficiency retrofit measures, with reference to the 2024 typical year. Blue bars represent annual baseline electricity consumption (MWh), while light blue bars show post-retrofit consumption after the energy renovation interventions.

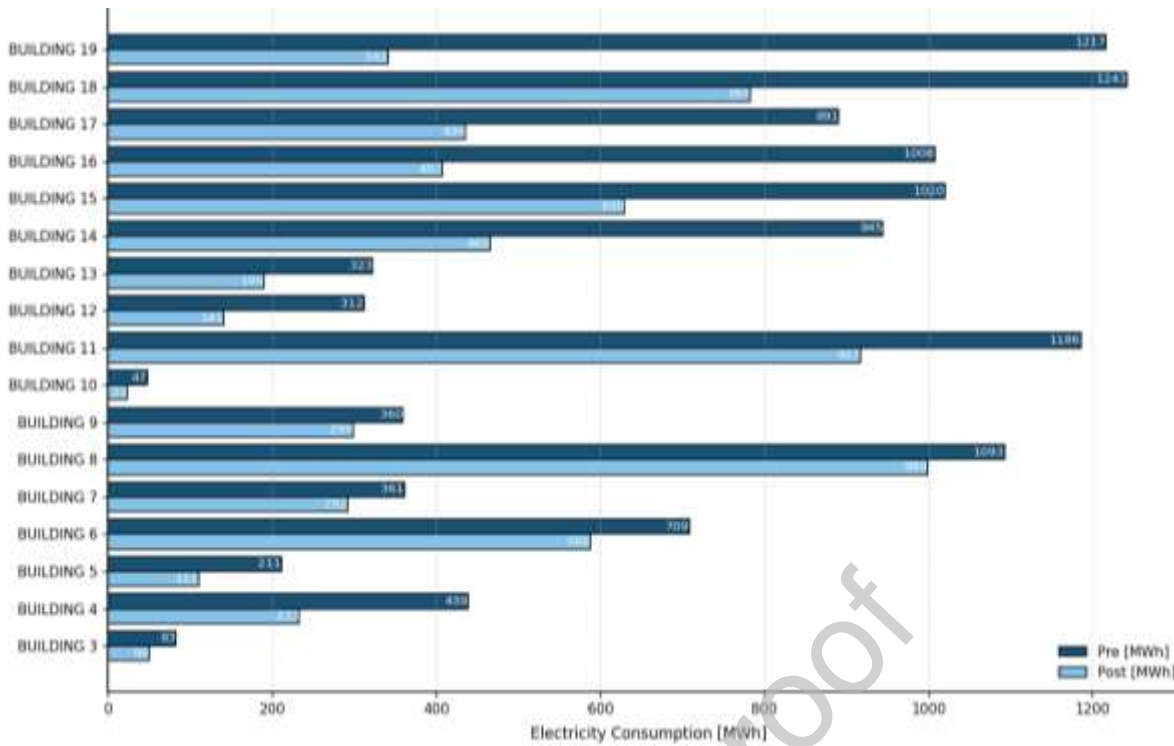


Fig. 10. UNIPA Campus: annual electricity consumption before and after retrofit.

The results of Fig. 10 also highlight a wide range of annual electricity savings across the analysed buildings, spanning from approximately -9% (Building 8) to -72% (Building 19).

In addition to Building 19, which shows the largest percentage reduction, notable decreases can be also observed for Building 16 (-60%), Building 12 (-55%), Building 10 (-51%), Buildings 14 and 17 (both -51%) and Buildings 4 and 5 (both -47%). These buildings therefore show high retrofit effectiveness in both relative and absolute terms.

In terms of absolute energy savings (MWh/year), the largest reductions are achieved by the following buildings:

- Building 19: from 1,217 MWh to 341 MWh (-876 MWh/year).
- Building 16: from 1,008 MWh to 407 MWh (-601 MWh/year).

Even after retrofit, some high-intensity buildings still show high electricity consumption, notably:

- Building 18: 783 MWh/year post-intervention.
- Building 15: 630 MWh/year.

These outcomes highlight structural residual loads, which can only be partially reduced through the implemented strategies.

Besides, it should be noted that for buildings characterised by low baseline consumption, reductions appear large in percentage terms, but remain limited in absolute terms, e.g.:

- Building 10: from 47 MWh to 23 MWh/year (-24 MWh/year; -51%).
- Building 3: from 83 MWh to 50 MWh/year (-33 MWh/year; -39%).

It is also worth observing that Building 8 shows the smallest relative improvement and still retains a high post-retrofit consumption (999 MWh/year), indicating scope for further intervention and optimisation in future work.

Fig. 11 overlays monthly photovoltaic generation and campus-level electricity consumption (shown as green and blue bars, respectively) with the electricity imported from the grid, exported to the grid and self-consumed (shown as dashed lines).

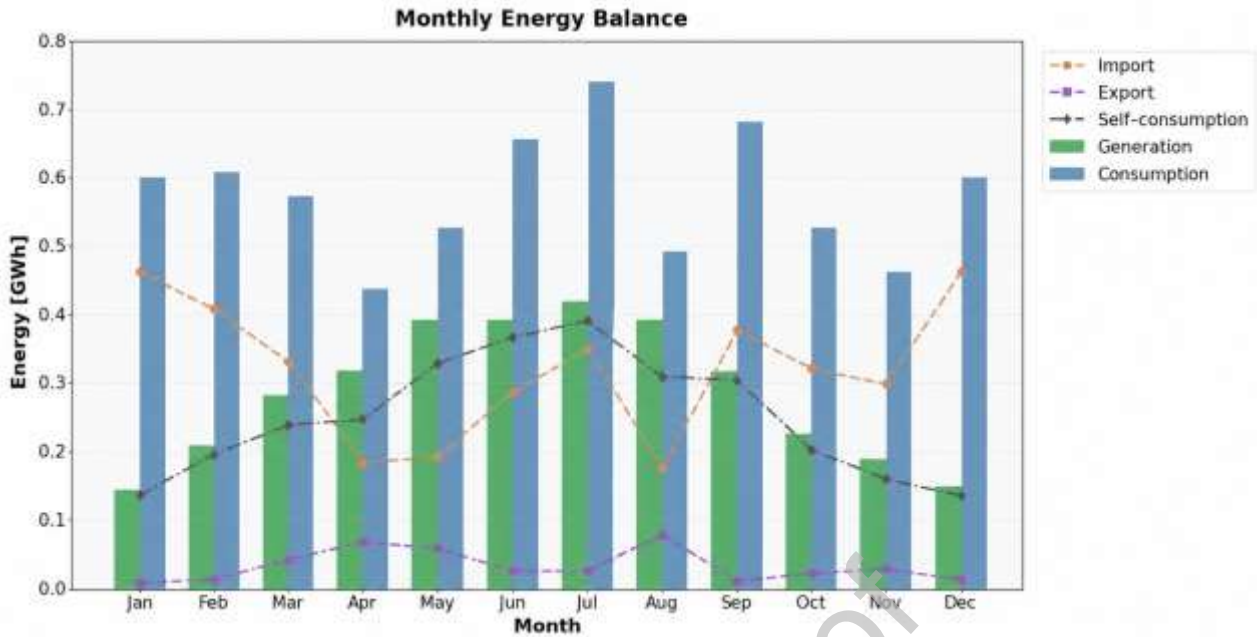


Fig. 11. UNIPA Campus: post-retrofit monthly electricity balance showing PV generation, consumption, imports, exports and self-consumption.

Based on Fig. 11, PV generation increases from winter towards spring and remains relatively high through summer, reaching about 0.4 GWh/month. District electricity demand also rises in summer and peaks in July at about 0.75 GWh/month, mainly due to space cooling and high internal loads. PV self-consumption improves during months with a better daytime alignment between generation and demand - particularly from spring to summer - whereas it is lower in winter as solar availability decreases. As a result, grid imports increase in the colder months, but remain significant in summer, especially in July, since peak cooling demand is not fully matched by PV output. Grid exports, by contrast, remain limited throughout the year and are confined to relatively small monthly surpluses. On an annual basis, approximately 3,038 MWh/year of the PV electricity generated is self-consumed within the Campus, while approximately 412 MWh/year is exported to the grid. Annual grid imports amount to approximately 3,869 MWh/year. Fig. 12 compares the annual photovoltaic (PV) electricity generation (green bars) with the annual electricity consumption of each building (blue bars) and reports both graphically and numerically the deviation between the two values.

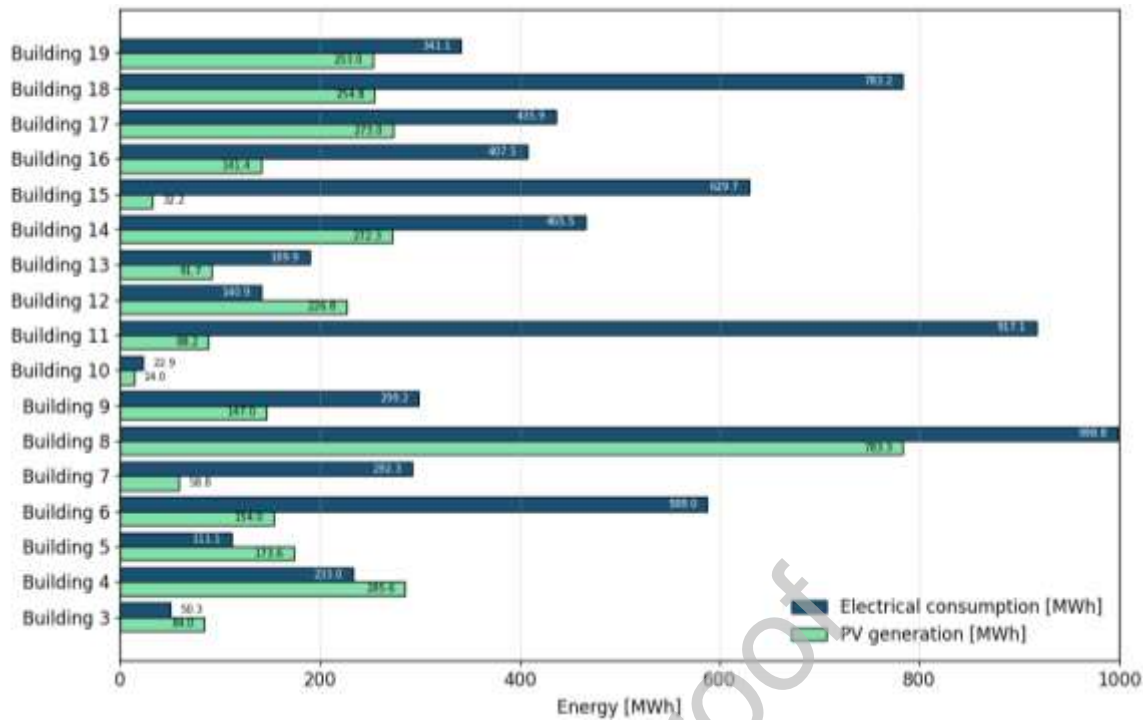


Fig. 12. UNIPA Campus: annual PV generation versus electricity consumption per building.

As shown in Fig. 12, only four buildings (3, 4, 5 and 12) achieve PV generation higher than their annual electricity demand, with energy surpluses of approximately +33.7 MWh, +52.6 MWh, +62.5 MWh and +85.9 MWh, respectively. All other buildings report PV production below the respective annual demand: in particular, Building 11 shows the largest negative gap (-829 MWh). These deficits quantify the electricity that must be imported from the grid to cover residual demand and help identify which buildings would benefit most from additional PV capacity or complementary measures aimed at reducing energy loads. Overall, the Campus shows an annual electricity demand of approximately 6,906 MWh, against an estimated PV potential of 3,450 MWh/year, corresponding to a coverage ratio close to 50%.

In absolute terms, this corresponds to a residual annual gap of approximately 3,456 MWh/year between post-retrofit electricity demand and rooftop PV generation, equal to 50.0% of the annual district demand, which would need to be covered through grid imports or offset by additional measures.

Although this share does not ensure self-sufficiency, it can substantially reduce reliance on grid electricity and provide a solid basis for progress toward Positive Energy District (PED) targets, especially when combined with demand-side flexibility strategies.

For the Bari district, the post-renovation compares the three configurations defined in Section 2.3.3: Baseline, Envelope-upgraded and Renovated.

Comparing Baseline with Envelope-upgraded isolates the effect of changing the thermal transmittances of the building envelope, while comparing Envelope-upgraded with Renovated quantifies the combined effects of HVAC electrification.

Table 3 reports a comparison of annual energy demand for all three configurations. Heating and cooling are reported as sensible space-heating and space-cooling demand, exclusive of emission and distribution losses, of generation efficiencies and of latent loads, whereas electricity is the annual final electrical energy of the district, which already includes the consumption of the systems meeting those demands; the quantities are therefore not additive.

Table 3. Bari district: annual energy demand by end use for the Baseline, Envelope-upgraded and Renovated configurations.

Energy demand	Baseline [MWh]	Envelope-upgraded [MWh]	Renovated [MWh]	Δ Envelope-upgraded – Baseline [MWh (%)]	Δ Renovated – Envelope-upgraded [MWh (%)]
Heating	3,906.88	1,124.73	974.94	-2,782.15 (-71.2%)	-149.79 (-13.3%)
Cooling	44.10	44.55	1,035.28	0.45	990.73
Electricity	1,739.75	1,646.30	2,508.16	-93.45 (-5.4%)	+861.86 (+52.4%)

Note: For cooling, the relative variation is not reported: the baseline value is close to zero, and the resulting percentage would not be informative. The absolute variation is given instead.

Under unchanged HVAC systems and service availability, the Envelope-upgraded configuration reduces annual sensible heating demand from 3,906.88 to 1,124.73 MWh/year (-2,782.15 MWh/year, -71.2%) and electricity consumption by 93.45 MWh/year (-5.4%), while cooling rises only from 44.10 to 44.55 MWh/year, the 0.45 MWh/year increase occurring in the only building block already provided with cooling.

Of the total heating-demand reduction of 2,931.94 MWh/year between the Baseline and Renovated configurations, 2,782.15 MWh/year (94.9%) is thus attributable to the envelope. The remaining 149.79 MWh/year, from 1,124.73 to 974.94 MWh/year, occurs at identical envelope thermal transmittances and is an HVAC-configuration effect: the hydronic terminals of the baseline systems are replaced by the air-based terminals of the air-to-air heat pumps, which modifies the ventilation and infiltration term of the sensible energy balance.

Cooling increases only in the transition from the Envelope-upgraded to the Renovated configuration, when active cooling is extended from one building block to all fourteen: demand rises by 990.73 to 1,035.28 MWh/year and district cooling intensity from about 0.6 to 13.6 kWh/(m²·year), at unchanged setpoints, ventilation rates and operating periods. The overall increase in electricity consumption of 768.41 MWh/year (+44.17%) therefore decomposes exactly into a reduction of 93.45 MWh/year from the envelope upgrade and an increase of 861.86 MWh/year from HVAC electrification and the extension of cooling service.

Fig. 13 compares monthly electricity demand before and after retrofit.

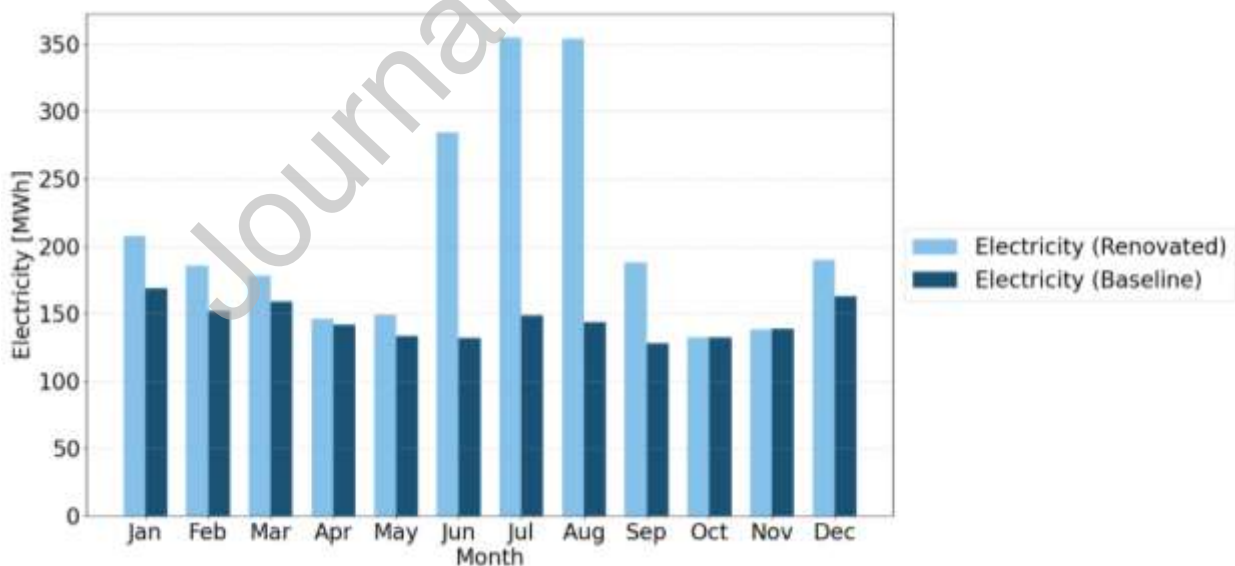


Fig. 13. Bari district: comparison between monthly electricity demand before and after retrofit.

Fig. 13 shows a marked summer increase in electricity use after retrofit, with demand rising from 148 to 355 MWh in July (+139.9%) and from 143 to 351 MWh in August (+145.5%).

This pattern contrasts with the corresponding trend observed for the UNIPA Campus, where post-retrofit electricity demand is governed primarily by schedule-dependent office and teaching loads, resulting in a more

stable monthly profile. In Bari, the sharp summer increase reflects the introduction of cooling services that were almost negligible in the baseline, making the monthly load curve markedly seasonal.

This structural difference has direct implications for the PED energy balance: while the UNIPA demand profile aligns relatively well with the PV generation curve throughout the year, the Bari district faces a seasonal mismatch in which peak PV generation coincides with peak cooling demand (thus partially improving summer self-consumption, but also significantly increasing total annual electricity consumption). This rise is mainly driven by cooling operation. In winter, electricity consumption increases more moderately - by approximately 20-25% compared to the baseline - due to the shift from gas-fired heating to electric heat pump operation.

To support the electrification of heating and cooling and limit reliance on grid electricity, the retrofit strategy adopted in this case study includes rooftop PV deployment, sized conservatively by assuming installation over 50% of the available roof area, corresponding to an overall capacity of 830 kW. Under this configuration, annual PV generation reaches 1,136.11 MWh, against a total district electricity demand of 2,508.16 MWh.

This means that PV covers approximately 45% of annual electricity demand. Of the electricity generated, 743.72 MWh is directly self-consumed on site, corresponding to about 65% of total PV output, while the remaining 392.38 MWh is exported to the grid. Despite this contribution, annual grid imports still amount to 1,764.44 MWh, indicating that the renovated configuration moves the district closer to PED-oriented targets but does not yet achieve a positive annual electricity balance.

In absolute terms, the residual annual gap amounts to 1,372.05 MWh/year, equal to 54.7% of the post-retrofit annual electricity demand of the district and corresponds to the net annual grid exchange resulting from 392.38 MWh of exports and 1,764.44 MWh of imports.

Monthly trends further show marked seasonal variations in generation, demand, self-consumption and grid exchange. Fig. 14 shows the post-renovation assessment for the Bari case study.



Fig. 14. Bari district: post-retrofit monthly electricity balance showing PV generation, consumption, imports, exports and self-consumption.

From Fig. 14, it can be observed that PV electricity generation reaches its maximum in summer, rising above 130 MWh/month. Over the same period, PV self-consumption rises to more than 100 MWh/month, supported by cooling-related electricity use during daylight hours; nevertheless, given the high summer load levels, a non-negligible share of electricity still needs to be imported from the grid.

By contrast, in winter (November-February), PV generation drops below 50 MWh/month, with a corresponding decrease in self-consumption and a marked increase in grid imports (above 160 MWh/month in December and January).

Alongside the seasonal mismatch, a structural constraint of the building typology applies: in a district of residential buildings of up to seven storeys the roof area available per unit of conditioned floor area is small relative to the electricity demand that floor area generates, so the limit lies in the density of demand rather than

in the photovoltaic technology. Closing the annual balance would therefore require additional generation capacity or a further reduction of demand, while complementary flexibility measures would improve the temporal matching between generation and demand.

The cross-case comparison highlights different PED-relevant constraints at district scale. The UNIPA Campus achieves a higher PV coverage ratio due to stronger daytime load alignment and more favourable rooftop availability. By contrast, the Bari district remains more dependent on grid imports because of higher post-retrofit electricity demand, driven by end-use electrification and the activation of cooling, together with lower roof-area-to-demand ratios. These patterns are also reflected in the monthly balances (Figs. 11 and 14), where summer demand peaks in Bari increase grid imports despite higher PV output.

3.3 Environmental assessment

This section presents the environmental results for the two analysed districts, namely the non-residential UNIPA Campus and the mixed-use Bari district.

The assessment compares baseline and post-renovation conditions in order to examine the environmental implications of the adopted retrofit strategies beyond energy performance alone. In the baseline configuration, impacts derive from operational energy use during the use phase. In the renovated case, use-phase impacts are first analysed for direct comparison with the baseline scenario and the assessment is then extended to the full life cycle, including production, use and end-of-life stages. In line with the methodological framework described in Section 2, production- and end-of-life-related impacts are annualised on the basis of the service lives assigned to the retrofit components.

Results are presented separately for each case study to highlight district-specific patterns and the main environmental effects and trade-offs associated with the transition towards more energy-efficient, PED-oriented district configurations.

To isolate the effect of the retrofit on operational energy use and the related use-phase environmental burdens, Table 4 reports the annual environmental profile of the UNIPA Campus under baseline and post-renovation conditions. The comparison is therefore limited to use-phase impacts, while the broader life cycle implications of the retrofit package are addressed in the subsequent sections.

Table 4. UNIPA Campus: annual use-phase environmental profile, baseline vs. post-renovation.

Impact Category	Indicator (unit)	Baseline	Renovated	Deviation
Acidification	mol H ⁺ eq	1.46E+04	6.29E+03	-57%
Climate change	kg CO ₂ eq	3.85E+06	1.59E+06	-59%
Ecotoxicity, freshwater	CTUe	9.98E+06	4.28E+06	-57%
Particulate matter	disease inc.	7.27E-02	3.12E-02	-57%
Eutrophication, marine	kg N eq	2.27E+03	9.64E+02	-57%
Eutrophication, freshwater	kg P eq	7.33E+02	3.16E+02	-57%
Eutrophication, terrestrial	mol N eq	2.59E+04	1.10E+04	-57%
Human toxicity, cancer	CTUh	1.46E-03	6.21E-04	-57%
Human toxicity, non-cancer	CTUh	4.93E-02	2.13E-02	-57%
Ionising radiation	kBq U-235 eq	4.33E+05	1.87E+05	-57%
Land use	Pt	1.67E+07	7.21E+06	-57%
Ozone depletion	kg CFC11 eq	8.83E-02	3.48E-02	-61%
Photochemical ozone formation	kg NMVOC eq	1.09E+04	4.60E+03	-58%
Resource use, fossils	MJ	5.52E+07	2.28E+07	-59%
Resource use, minerals, metals	kg Sb eq	3.89E+01	1.69E+01	-57%
Water use	m ³ depriv.	2.16E+06	9.36E+05	-57%
Cumulative energy demand	MJ	8.18E+07	3.41E+07	-58%

Table 4 shows that the UNIPA Campus achieves a uniformly improved use-phase environmental profile after renovation, with reductions across all the assessed impact categories.

The largest decrease is observed for ozone depletion (-61%). All the other indicators decrease within a relatively narrow range, generally between -57% and -59%, pointing to a highly consistent environmental

response across categories. This indicates that the post-retrofit changes in operational energy performance generate broadly aligned environmental benefits, with only limited variation in reduction magnitude among selected LCA indicators.

Table 5 reports the annual use-phase environmental impacts of the Bari district under baseline and post-renovation conditions.

Table 5. Bari district: annual use-phase environmental profile, baseline vs. post-renovation.

Impact Category	Indicator (unit)	Baseline	Renovated	Deviation
Acidification	mol H ⁺ eq	3.50E+03	2.86E+03	-18%
Climate change	kg CO ₂ eq	1.69E+06	7.24E+05	-57%
Ecotoxicity, freshwater	CTUe	2.54E+06	1.95E+06	-23%
Particulate matter	disease inc.	1.78E-02	1.42E-02	-20%
Eutrophication, marine	kg N eq	6.65E+02	4.39E+02	-34%
Eutrophication, freshwater	kg P eq	1.60E+02	1.44E+02	-10%
Eutrophication, terrestrial	mol N eq	7.47E+03	5.02E+03	-33%
Human toxicity, cancer	CTUh	4.22E-04	2.82E-04	-33%
Human toxicity, non-cancer	CTUh	1.07E-02	9.69E-03	-9%
Ionising radiation	kBq U-235 eq	9.02E+04	8.51E+04	-6%
Land use	Pt	3.44E+06	3.28E+06	-5%
Ozone depletion	kg CFC11 eq	5.99E-02	1.58E-02	-74%
Photochemical ozone formation	kg NMVOC eq	3.72E+03	2.09E+03	-44%
Resource use, fossils	MJ	2.43E+07	1.04E+07	-57%
Resource use, minerals, metals	kg Sb eq	7.84E+00	7.67E+00	-2%
Water use	m ³ depriv.	4.37E+05	4.26E+05	-3%
Cumulative energy demand	MJ	3.29E+07	1.55E+07	-53%

Table 5 shows that the renovated Bari district achieves lower use-phase impacts across all assessed categories, although with a markedly wider and more differentiated pattern of reductions than the UNIPA Campus. The largest decreases are observed for ozone depletion (-74%), climate change and fossil resource use (both -57%), and cumulative energy demand (-53%), whereas substantially smaller improvements are found for acidification (-18%), particulate matter (-20%), freshwater eutrophication (-10%) and only marginal reductions are observed for ionising radiation, land use, water use, resource use minerals and metals, and human toxicity non-cancer. This heterogeneous response is mainly explained by the full phase-out of natural gas in the renovated configuration, which drives the strongest reductions in categories most directly linked to fossil fuel use. At the same time, the Bari district presents a more articulated post-retrofit energy pattern than UNIPA.

Unlike the UNIPA Campus, where the pre-retrofit baseline was more clearly heating-dominated, the Bari baseline included virtually no active cooling, which was confined to a single building block; as a result, the renovated scenario introduces a new electricity-intensive cooling load that partly offsets the environmental gains from heating decarbonisation.

Consequently, the categories least sensitive to natural gas displacement and more strongly influenced by electricity supply, material flows, or indirect emissions, show the smallest reductions. These cross-case differences can therefore be attributed primarily to district morphology, functional mix and baseline energy conditions, rather than to the retrofit strategy itself. This interpretation is also consistent with the production-stage results: the UNIPA Campus, as a non-residential and more centralised district, presents a more concentrated embodied profile largely driven by PV systems and - for selected categories - by heat pumps; the Bari district - characterised by a predominantly residential stock articulated into multiple building blocks and typological configurations - shows a broader distribution of burdens across retrofit components, with windows contributing more markedly in several impact categories. Overall, despite the more differentiated post-retrofit energy balance observed in Bari, the operational environmental profile remains consistently improved across all indicators, confirming that the renovation delivers net environmental benefits in both case studies.

To move beyond the use-phase comparison and provide an integrated cross-case interpretation, the assessment was therefore extended to the full life cycle for both the UNIPA Campus and the Bari district, annualising production- and end-of-life burdens and combining them with the operational impacts of each renovated configuration. The next section further develops this perspective through dominance and hot-spot analyses, complemented by life cycle-based energy and environmental balances, to identify the main impact drivers and clarify how the adopted measures contribute to PED-oriented objectives. The following analyses jointly examine the contributions of life cycle stages and retrofit components across the 17 impact categories, enabling a direct comparison between the two districts. Fig. 15 reports the life cycle stage breakdown for the UNIPA Campus and Fig. 17 provides the corresponding breakdown for the Bari district; the two should be read in parallel to identify convergences and divergences in the embodied impact profiles of both case studies.

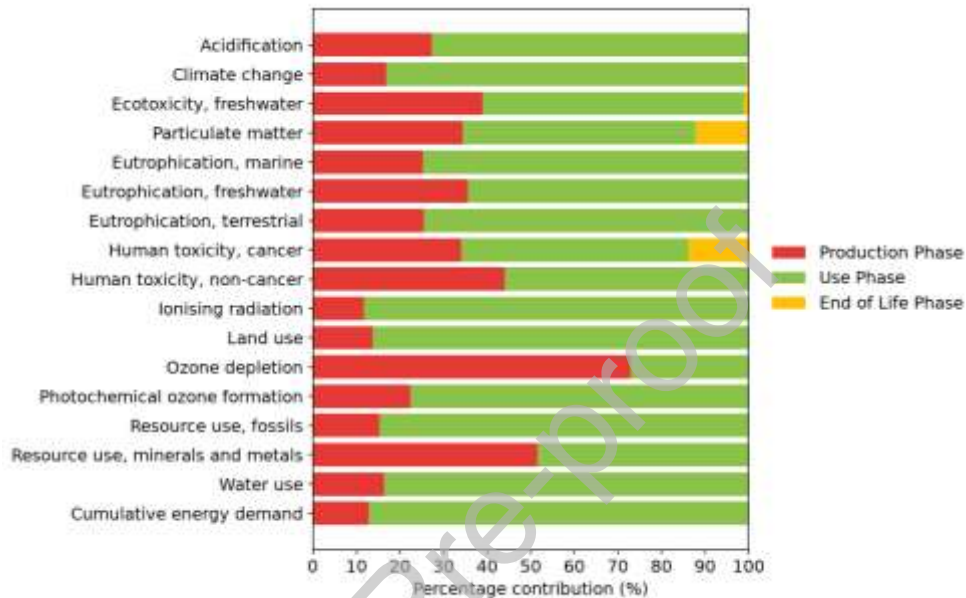


Fig. 15. UNIPA Campus: environmental impacts by life cycle phase.

The dominance analysis shows that the annualised environmental profile of the renovated UNIPA Campus is still largely governed by the use phase, which remains dominant in most impact categories, including ionising radiation (88.3%), land use (86.3%), cumulative energy demand (87.1%), fossil resource use (84.7%), water use (83.6%) and climate change (82.7%).

At the same time, the full life cycle perspective reveals relevant embodied trade-offs, with production becoming dominant for ozone depletion (73.0%) and contributing substantially to resource use, minerals and metals (51.5%), human toxicity, non-cancer (44.1%), freshwater ecotoxicity (39.0%) and freshwater eutrophication (35.5%). End-of-life effects remain generally limited, with the exception of particulate matter (12.2%) and human toxicity, cancer (13.9%). Overall, the operational profile improves across all impact categories, as reported in Table 4, while the annualised profile concentrates the embodied burdens in a limited set of categories; the results therefore confirm that a full life cycle perspective is necessary to capture burden shifting from operational energy to technology-related embodied impacts.

To further investigate the embodied hot spots emerging from the life cycle stage analysis, Fig. 16 focuses exclusively on the production stage and shows the contribution of each retrofit component across the considered environmental categories. Since each bar is normalised within the production phase, the figure highlights the relative role of insulation, windows, photovoltaics and heat pumps in shaping the embodied environmental profile of the renovated UNIPA Campus.

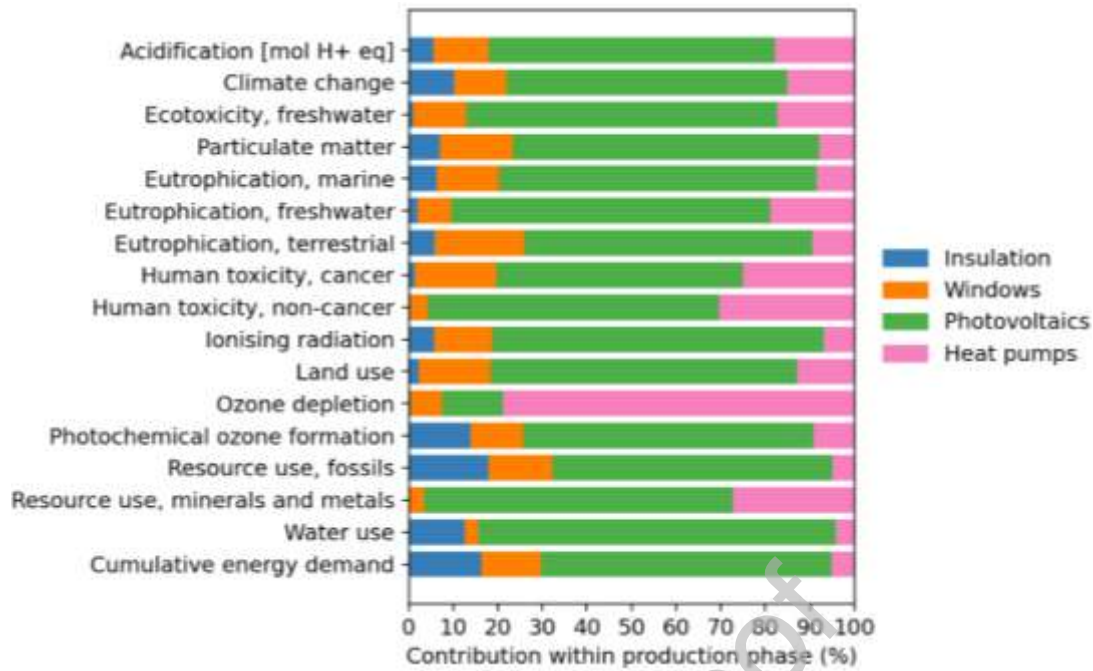


Fig. 16. UNIPA Campus: relative contribution of retrofit components to production-stage impacts.

Fig. 16 shows that, within the production stage, photovoltaics are the main contributor across most impact categories, confirming their central role in shaping the embodied environmental profile of the campus retrofit. Heat pumps emerge as the dominant component for ozone depletion and also provide relevant contributions in several toxicity- and resource-related categories. Windows play a secondary but non-negligible role in some impact categories, while insulation remains comparatively limited overall. The figure therefore refines the previous life cycle interpretation by showing that the main embodied trade-offs are concentrated primarily in PV systems and, for specific categories, in heat pumps.

Fig. 17 reports the results of the phase-based analysis for the Bari district, following the same approach adopted for the UNIPA Campus.

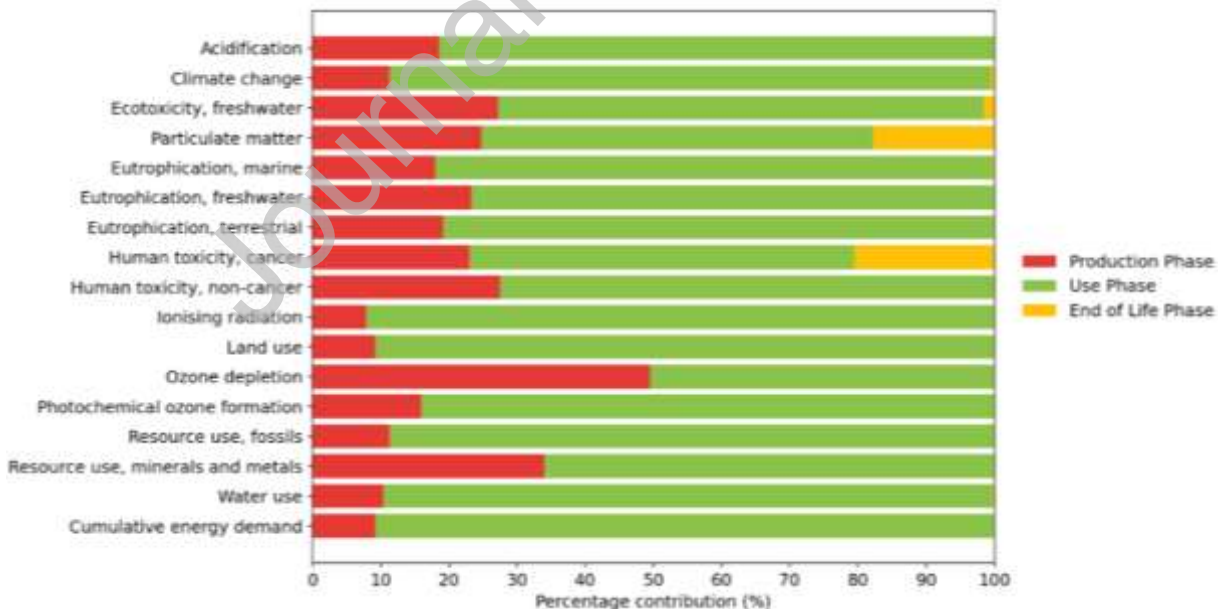


Fig. 17. Bari district: environmental impacts by life cycle phase.

This configuration remains mainly driven by the use phase, which exceeds 75% in several categories and reaches 89.14% for ionising radiation, 87.31% for land use and cumulative energy demand, 85.60% for water use, 84.58% for fossil resource use and 84.09% for climate change.

However, production-related burdens remain relevant for selected indicators, especially ozone depletion, which is clearly production-dominated (58.26%), as well as resource use, minerals and metals (42.32%), human toxicity, non-cancer (35.04%), freshwater ecotoxicity (34.58%), freshwater eutrophication (30.17%) and particulate matter (29.88%). End-of-life effects are generally limited, except for human toxicity, cancer (24.63%) and particulate matter (21.47%). Overall, the figure confirms that the annualised environmental profile of Bari is still largely shaped by operational impacts, while embodied burdens become relevant for selected categories. To further examine the embodied environmental profile of the Bari retrofit, Fig. 18 focuses on the production stage and shows the relative contribution of each retrofit component across the considered impact categories. When considered alongside the corresponding UNIPA results of Fig. 16, it also supports a cross-case interpretation of how production-stage burdens are distributed under similar retrofit strategies.

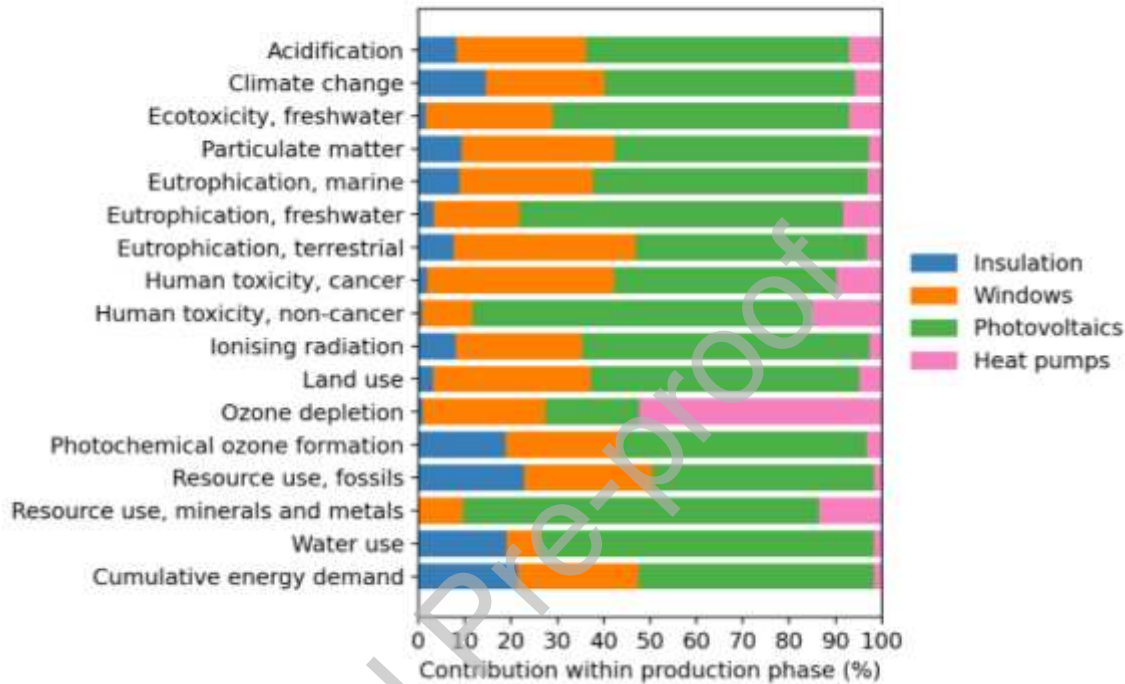


Fig. 18. Bari district: relative contribution of retrofit components to production-stage impacts.

Fig. 18 shows that, within the production stage, the embodied environmental profile of the Bari district is driven mainly by photovoltaics across most impact categories.

Heat pumps dominate ozone depletion and also contribute visibly to specific categories, while windows are particularly relevant for particulate matter, human toxicity, cancer and terrestrial eutrophication; they also remain non-negligible for marine eutrophication. Insulation generally plays a more limited role, although it becomes more visible in a few categories, such as photochemical ozone formation, resource use, fossils, water use and cumulative energy demand.

Overall, the figure refines the interpretation of production-stage burdens by identifying the main component-level contributions within the embodied environmental profile of the Bari retrofit.

Considered together, Figs. 16 and 18 show that the production-stage profile is more concentrated in the UNIPA Campus, largely dominated by PV systems and, for ozone depletion, by heat pumps. By contrast, the Bari district shows a more heterogeneous pattern of component-level contributions, with windows playing a more visible role across several impact categories, while insulation remains comparatively limited. This comparison confirms that, even under similar retrofit strategies, district morphology and building stock characteristics shape the distribution of production-stage impacts across components and indicators, further supporting the need for multi-category LCA in district-scale retrofit assessment.

4. Discussion

The comparative analysis of the non-residential UNIPA Campus and the mixed-use Bari district confirms that PED-oriented renovation strategies cannot be adequately assessed through either operational energy metrics or carbon-focused life cycle approaches alone. While the WLC framework established by the EPBD recast represents a significant policy step towards whole-life environmental accountability [4], [62], [63],

evidence from both case studies shows that a carbon-only approach would overlook relevant burdens in resource use, toxicity and ozone depletion categories, precisely those categories where embodied contributions become most visible once operational energy is reduced. An integrated framework combining district-scale energy modelling with multi-indicator life cycle assessment is therefore needed to support robust and informed PED-oriented renovation planning.

From the operational perspective, the renovated configurations improved the use-phase environmental profile of both districts, although with different response patterns. UNIPA showed a highly consistent improvement across all indicators, with ozone depletion decreasing by 61% and the remaining categories within a narrow range of -57% to -59%, including climate change, fossil resource use and cumulative energy demand. Bari also showed reductions across all assessed categories, but with a wider range of variation: from 74% for ozone depletion and 57% for both climate change and fossil resource use, to 3% for water use and 2% for resource use, minerals and metals. This indicates that the differentiated post-retrofit pattern observed for Bari is reflected not only in energy use by end use, but also in the operational environmental profile, which improves across all categories with markedly heterogeneous reduction levels.

A broader interpretation emerges from the full life cycle assessment. In both districts, the use phase remains dominant for the main energy-related indicators, confirming that operational energy still drives most annualised impacts after renovation. However, once operational burdens are reduced, embodied impacts become more visible and may alter the overall environmental profile. In the UNIPA case study, this is evident for ozone depletion, which is dominated by production-related impacts (73.0%) and for resource use, minerals and metals (51.5%), human toxicity, non-cancer (44.1%) and freshwater ecotoxicity (39.0%). Bari case study follows the same overall pattern, although with a more distributed embodied profile across technologies. In both districts, photovoltaics emerge as the main embodied hot spot, while heat pumps are particularly relevant for ozone depletion. By contrast, insulation remains comparatively marginal, whereas windows become relevant only in selected categories, mainly human toxicity, cancer and particulate matter.

Overall, the two case studies support a consistent interpretation: PED-oriented renovation can substantially improve district performance in terms of energy demand reduction, fossil-fuel displacement and on-site renewable integration, but retrofit effectiveness cannot be inferred from operational energy results alone. A robust assessment therefore requires a multi-indicator life cycle perspective able to capture both operational gains and technology-related burdens, especially those associated with PV systems, heat pumps and selected end-of-life processes.

A direct cross-typology comparison of the two districts further highlights the structural drivers behind the observed differences. The UNIPA Campus, as a compact non-residential district with centrally managed operations, achieves a relatively high PV coverage ratio (up to 50%), with a load profile that follows academic schedules and shows limited seasonal variation in electricity use. This makes the campus a favourable context for PED-oriented interventions: the coincidence between daytime PV generation and occupancy-driven demand supports high self-consumption rates, while centralised systems enable coordinated implementation of envelope upgrades, full electrification and PV deployment.

The Bari district, by contrast, represents a more challenging urban condition: a mixed-use residential area with decentralised ownership, heterogeneous building stock and limited prior retrofit history. Here, the activation of cooling services in the renovated configuration markedly reshapes the demand profile, introducing a strong summer peak that partially aligns with PV generation, but significantly increases total annual electricity demand.

The comparison with the envelope-upgraded configuration attributes this increase to the extension of the service and not to the envelope measure, which on its own reduces annual electricity use by 93.45 MWh/year.

Despite a PV coverage of 45%, the district does not achieve a positive annual electricity balance under the conservative sizing assumption adopted, indicating that meeting PED targets would require more ambitious future strategies, such as greater PV exploitation, further demand reduction and complementary flexibility measures.

The distance still separating the two districts from the PED target can be quantified. The residual annual gap amounts to approximately 3,456 MWh/year for the UNIPA Campus, equal to 50.0% of its post-retrofit annual electricity demand, and to 1,372.05 MWh/year for the Bari district, equal to 54.7% of its own. At the specific yields obtained, 1,449 and 1,369 kWh/kWp, closing the annual balance would require in the order of 2,385 kWp of additional photovoltaic capacity in the first case and 1,000 kWp in the second. For the UNIPA Campus this is of the same order as the entire assessed rooftop potential of 2,381 kW, already the maximum deployable once constrained surfaces are excluded; for the Bari district, where capacity was sized over 50% of the

available roof area, a less conservative use of the same surfaces would reduce the gap by an extent not quantified here.

Since the balance of Equation (6) is annual and no storage is considered, flexibility measures modify self-consumption, grid exchange and peak loads but leave the annual balance unchanged: the gap can be closed only through additional annual generation or a further reduction of demand. Three directions therefore appear worth exploring: deeper demand-side intervention on the buildings retaining the highest residual loads, still above 600 MWh/year for some UNIPA buildings; photovoltaic generation on district surfaces other than roofs, such as car-park canopies or façade-integrated systems; and the procurement of renewable electricity generated outside the district boundary, for instance through renewable energy communities, which would entail redefining the spatial boundary of the PED balance. The quantification reported here is a first-order screening of the effort required rather than a simulation-based assessment of these options. The first of these directions is supported at a different scale by stock-level evidence: for the Chinese residential sector, the most cost-effective demand-side package assessed within a life cycle framework is estimated to reduce cumulative emissions by 47% and the net present value of costs by 16% over the period to 2060 [124].

A further consideration concerns the interpretation of the cross-typology differences. Since the two districts were modelled under different levels of data availability, part of the observed variation in energy and environmental performance may reflect modelling uncertainty rather than district typology alone.

This is particularly relevant for the Bari district, where archetype-based assumptions were required for building groups lacking metered data.

The cross-case comparison therefore provides an indication of typology-related patterns rather than a precise quantification of differences driven by district typology alone. This aspect should be taken into account when interpreting the results.

The cooling electrification pathway adopted for Bari requires also specific attention in the context of climate change and PED concept implications. The activation of air-to-air heat pumps across a predominantly residential building stock (where space cooling was marginal in the baseline) reflects a transition that is already underway in Mediterranean cities and is expected to intensify under climate projections.

World Meteorological Organization (WMO) data and IPCC AR6 projections consistently show that building cooling demand in Southern Europe will grow significantly under future temperature trajectories, driven by more frequent and intense heat events and longer cooling seasons.

This means that the electricity demand increase observed in Bari after retrofit should not be interpreted only as a consequence of the chosen renovation strategy, but also as an anticipation of a structural trend: even without active cooling electrification, cooling demand would likely rise over the coming decades as the passive strategies already in place become insufficient. From a PED perspective, this implies that districts in Mediterranean climates must plan for higher future electricity loads in their energy-balance assessments, rather than sizing PV systems against current post-retrofit demand alone. The temporal dimension of the PED concept becomes particularly critical when the underlying demand is itself subject to significant climate-driven growth. Incorporating climate projections into the PED feasibility assessment therefore represents a necessary evolution of the methodology and the Bari case provides a concrete demonstration of why this matters for districts undergoing a transition towards space cooling.

A limitation of the modelling adopted here should be stated in the same context. Both districts were simulated with weather files representative of the regional climate, so that the local urban microclimate, and the urban heat island effect in particular, is not represented. Accounting for it would be expected to raise the cooling demand computed for both districts, and with it the electricity demand against which the district balance is assessed, while leaving the direction of the comparison between the baseline and renovated configurations unchanged, since the same climatic input is applied to both. Its explicit representation through microclimate-adjusted boundary conditions is identified as a further direction for future work.

Two implications follow for the design of PED-oriented renovation in this climate. The first concerns the retrofit package. The measures assessed here were limited to envelope upgrade, HVAC electrification and rooftop photovoltaics, applied in the same form to both districts in order to keep the cross-typology comparison consistent. Passive cooling, however, is not an unexploited option in the Bari district: in the baseline, thirteen of its fourteen building blocks have no cooling system, and the means by which summer conditions are moderated, namely openable windows operated for night ventilation and movable solar shading, are represented at the most effective settings available in the modelling library. The extension of active cooling is therefore assessed against a stock that already relies on such strategies, which cannot be strengthened further within the model.

The second implication concerns generation and flexibility. Where cooling is activated across a residential stock, the additional load is concentrated in the summer months and largely coincident with daylight hours, which improves self-consumption but also raises the annual demand against which the district balance is computed. Sizing rooftop photovoltaics on current post-retrofit demand therefore risks underestimating the capacity required over the lifetime of the intervention, while storage, which does not alter the annual balance as formulated in Equation (6), determines the share of the available generation that can be used within the district boundary.

From an environmental perspective, the cross-case analysis confirms that photovoltaics and heat pumps are the main contributors to material-related environmental burdens in PED-oriented renovation across both typologies.

This makes their embodied impact profile a key consideration in life cycle-based PED assessment: although PV and heat pump deployment can substantially reduce operational impacts, the related upstream burdens - particularly in resource use, minerals and metals, ozone depletion and toxicity-related categories - may become increasingly relevant as retrofit programmes expand in scale.

The results of both case studies consistently show that, once operational energy is reduced through electrification and efficient envelopes, these embodied burdens account for a non-negligible share of the annualised life cycle profile for several impact categories. This finding suggests that supply-chain decarbonisation and circular-economy strategies for PV modules and heat pump components should be considered as complementary actions within PED-oriented frameworks and that multi-indicator LCA should be treated as a standard - rather than optional - component of an integrated PED assessment. At European level the same argument is made for the building stock as a whole, where about 20-25% of life cycle emissions are embedded in construction materials and this share grows as operational energy use falls, so that circular renovation is identified as the point at which material and climate objectives meet [125].

The composition of the retrofit package also affects the environmental results: a configuration achieving a comparable demand reduction through greater reliance on envelope and other demand-side measures would alter the distribution of embodied impacts across components and impact categories rather than necessarily reduce them overall, as indicated by the component-level breakdowns in Figs. 16 and 18.

The assessment developed here is limited to energy and environmental performance, and the economic dimension of the retrofit packages was not quantified. The two dimensions do not necessarily move together. Scenario analysis of the Dutch residential stock indicates that façade refurbishment raises cumulative material use by 21-25% and costs by 2-6% while leaving life cycle emissions almost unchanged, that action on the heating system carries a greater carbon reduction potential, and that material circulation strategies can offset up to 89% of the material footprint and up to 23% of the emissions without removing the cost increase that renovation entails [126]. Read against the results obtained here, where the operational improvement is driven mainly by electrification and the residual production-stage burdens are concentrated in photovoltaic systems and heat pumps, this indicates that circular-economy strategies would act on precisely the components that dominate the embodied profile, and that their evaluation, together with life cycle costing, is the natural extension of the framework applied in this study.

The service lives assumed for the retrofit components directly affect the annualised results and therefore require explicit consideration. Under the adopted annualisation approach, the production and end-of-life burdens of each component are divided by its assumed service life; the effect of alternative assumptions can therefore be derived directly from the reported results without re-computing the inventory.

Assigning a 20- or 40-year service life to the photovoltaic system instead of 30 years would rescale its annualised production and end-of-life impacts by +50% and -25%, respectively, while values of 15 or 25 years for the heat pumps instead of 20 years would result in changes of +33% and -20%.

These variations affect only the renovated configuration, as production and end-of-life burdens are not included in the baseline.

Their influence is further limited to the impact categories substantially affected by the components under consideration.

Photovoltaic systems account for the largest share of production-stage burdens in both districts, making their assumed service life particularly influential, while heat pumps play a major role in ozone depletion. Earlier replacement of photovoltaic modules, for example due to performance degradation or damage, would therefore increase the annualised embodied burden mainly in the categories where retrofit-related non-operational impacts are concentrated. This interpretation, however, relies on two simplifying assumptions.

- First, each replacement is assumed to involve an equivalent component with the same background inventory data, so that possible changes in technology, manufacturing processes, or supply chains over time are not represented.
- Second, annualisation spreads production and end-of-life impacts uniformly over the assumed service life and therefore does not capture the actual timing of these burdens. The influence of component service lives and of end-of-life recycling assumptions is quantified below, while a parametric analysis based on explicit future electricity mixes remains a priority for further work.

The direction and magnitude of the two remaining assumptions can nevertheless be established from the reported results. End-of-life impacts are computed on the non-recycled fraction of each component alone, so that the assumed recycling shares act linearly on that term: raising the share assumed for insulation and windows from 70% to 80%, or lowering it to 60%, changes their end-of-life burden by -33% and $+33\%$ respectively, while a variation of ten percentage points around the 80% assumed for photovoltaic modules and heat pumps changes theirs by 50% in either direction. As with the service lives, these variations affect the renovated configuration alone, and their influence on the overall profile is confined to the categories in which the end-of-life stage carries appreciable weight, namely human toxicity, cancer and particulate matter, in which that stage accounts for 13.83% and 12.16% of the annualised impacts of the UNIPA Campus and for 24.63% and 21.47% of those of the Bari district.

The characterisation of the electricity supply acts instead on the use phase, which remains the dominant term of the annualised profile in both renovated configurations. A progressively decarbonised national mix would lower the use-phase contribution to climate change, and to most of the other impact categories. The two configurations are not equally exposed to this assumption: the renovated districts rely exclusively on electricity, whereas the baseline also draws on natural gas, so that a lower-carbon mix would act more strongly on the renovated case and widen the difference between the two in the categories governed by electricity supply.

These assumptions were tested systematically. Service lives were varied by ± 10 years for the components assigned a 30-year service life and by ± 5 years for the heat pumps, and end-of-life recycling shares by ± 10 percentage points, each parameter individually and then jointly in two bounding cases. Table 6 reports the resulting variation of the annualised profile of each renovated district across the seventeen impact categories. Service lives dominate: the bounding cases span $+5.7\%$ to $+26.9\%$ and -2.9% to -15.4% for the UNIPA Campus and $+5.4\%$ to $+25.7\%$ and -2.7% to -13.0% for the Bari district, with the largest values in ozone depletion, human toxicity, cancer, particulate matter and resource use, minerals and metals, and the smallest in the energy-related indicators. Recycling shares change the annualised profile by less than 1% in fifteen categories; the exceptions are particulate matter and human toxicity, cancer, which vary by $\pm 4.1\%$ and $\pm 4.6\%$ for the UNIPA Campus and by $\pm 7.2\%$ and $\pm 8.2\%$ for the Bari district. The categories governed by operational energy are therefore comparatively insensitive to both parameters, while those in which embodied burdens are concentrated respond most strongly; among the individual parameters, the service life of the photovoltaic system governs most categories and that of the heat pumps governs ozone depletion.

Table 6. Sensitivity of the annualised environmental profile of the renovated configurations to component service lives.
Base assumption: 30 years for insulation, windows and PV modules, 20 years for heat pumps.

Impact category	UNIPA Campus: 20-year envelope and PV, 15-year heat pumps [%]	UNIPA Campus: 40-year envelope and PV, 25-year heat pumps [%]	Bari district: 20-year envelope and PV, 15-year heat pumps [%]	Bari district: 40-year envelope and PV, 25-year heat pumps [%]
Acidification	+12.9	-6.6	+12.0	-6.1
Climate change	+8.2	-4.2	+7.8	-3.9
Ecotoxicity, freshwater	+18.9	-9.7	+17.9	-9.0
Particulate matter	+22.8	-11.5	+25.5	-12.8
Eutrophication, marine	+12.3	-6.2	+11.8	-5.9
Eutrophication, freshwater	+16.6	-8.5	+14.7	-7.4
Eutrophication, terrestrial	+12.4	-6.3	+12.6	-6.3
Human toxicity, cancer	+22.6	-11.6	+25.7	-12.9
Human toxicity, non-cancer	+19.8	-10.4	+16.7	-8.5
Ionising radiation	+5.7	-2.9	+5.4	-2.7
Land use	+6.6	-3.3	+6.2	-3.1
Ozone depletion	+26.9	-15.4	+24.1	-13.0
Photochemical ozone formation	+10.9	-5.5	+10.6	-5.3
Resource use, fossils	+7.5	-3.8	+7.7	-3.8
Resource use, minerals and metals	+23.4	-12.2	+20.2	-10.3
Water use	+8.1	-4.1	+7.2	-3.6
Cumulative energy demand	+6.3	-3.2	+6.3	-3.2

The two case studies also allow the implications of assessing life cycle performance at district scale to be stated more precisely.

- First, the object of the assessment is a portfolio of measures distributed over a heterogeneous stock, so that the same intervention yields different annualised impacts depending on the building to which it is applied: the aggregated district figure conceals a distribution, and the component-level breakdowns of Figs. 16 and 18 are part of the result rather than a supplementary detail.
- Second, the use phase is simulated rather than assumed, which makes the operational term of the inventory sensitive to the same modelling uncertainty that affects the energy results and ties the reliability of the environmental comparison to the calibration evidence available for each district.
- Third, the trade-off that becomes visible at this scale concerns not only life cycle stages and impact categories, but also the distribution of burdens across buildings, since rooftop photovoltaic capacity is unevenly distributed over the stock and five buildings alone account for 56.1% of the potential assessed in the UNIPA Campus. None of these features arises when the same technologies are assessed at the product level alone [74].

Taken together, the results of the two case studies support a more context-sensitive framing of the PED concept, rather than a simple energy-balance criterion.

Achieving a positive annual electricity balance is a necessary condition for PED classification, but it is not sufficient to guarantee that a district renovation strategy delivers optimal sustainability performance.

The evidence from the UNIPA Campus and Bari case studies shows that, under the assessed configurations, the PED target remains unmet in both districts, despite substantial improvements achieved through demand reduction, electrification and on-site PV generation.

These findings confirm that advancement towards PED goals depends not only on renewable energy integration, but also on district typology, retrofit scope and the balance between operational improvements and embodied burdens.

Accordingly, a robust PED assessment framework should integrate at least the following elements:

- a district-scale energy balance verified against realistic demand projections;
- a multi-indicator life cycle assessment of the adopted retrofit package;
- careful consideration of demand-side evolution, particularly the expected increase in cooling demand as temperatures rise in Mediterranean climates.

The harmonised workflow developed and tested in this study provides a replicable basis for implementing an integrated assessment approach across different urban typologies and climatic contexts. Its transferability is demonstrated at the level of the assessment procedure, which was applied without modification to two

districts differing in function, building stock and data availability, while the extension of the quantitative findings to other contexts calls for the same workflow to be applied to a broader set of districts and climates.

5. Conclusions

This work assessed the extent to which district-scale renovation strategies can support PED-oriented transitions in Mediterranean urban contexts by jointly evaluating post-retrofit energy performance and life cycle environmental impacts in two functionally different districts: the non-residential UNIPA Campus in Palermo and a mixed-use district in Bari. The comparison confirms the value of a harmonised district-scale framework capable of integrating energy modelling, rooftop PV assessment and multi-indicator life cycle evaluation across different urban conditions.

The results show that PED-oriented renovations can substantially improve district performance, although with typology-dependent outcomes. In Palermo, the post-retrofit configuration achieves a marked improvement in overall energy performance, with rooftop PV covering about 50% of post-retrofit electricity demand. In Bari, renovation strongly reshapes the final energy profile, with heating demand reduced by 75% and rooftop PV covering about 45% of annual electricity demand. These findings confirm that post-retrofit electricity trends cannot be interpreted in isolation, since part of the electricity demand reflects the electrification of formerly natural gas-based thermal uses and, in Bari, the activation of cooling services previously limited in the baseline condition.

In neither district, however, does the assessed configuration achieve a positive annual electricity balance. A residual annual gap of approximately 3,456 MWh/year remains for the UNIPA Campus, equal to 50.0% of its post-retrofit annual electricity demand, and of 1,372.05 MWh/year for the Bari district, equal to 54.7% of its own. The results therefore describe a quantified pathway towards PED conditions, rather than an accomplished Positive Energy District.

From the environmental perspective, renovation improves the use-phase profile in both districts: UNIPA shows a highly consistent reduction across all indicators, whereas Bari also exhibits reductions in all categories, although with more differentiated magnitudes.

However, the full life cycle assessment shows that operational improvements alone do not fully capture retrofit performance: in both districts, the use phase remains dominant for most energy-related indicators, but embodied impacts become more visible once operational burdens are reduced. This is especially evident in production-stage impacts associated with PV systems and, in some categories, with heat pumps and windows.

The two analysed case studies therefore support a consistent conclusion: energy savings, electrification and on-site renewable generation are necessary components of PED-oriented renovation, but they are not sufficient on their own to ensure overall effectiveness.

A robust evaluation requires a multi-indicator life cycle assessment able to capture both operational benefits and technology-related trade-offs. Accordingly, PED-oriented renovation should not be interpreted as the achievement of a single balance-based target, but as a district-scale transformation process requiring the joint evaluation of energy efficiency, fossil-fuel displacement, renewable integration and life cycle implications within the constraints of the built environment.

Overall, the study confirms that district renovation can effectively support the transition towards PED-oriented urban configurations when assessed through an integrated and context-sensitive framework.

Future research should extend this approach to a broader range of districts, test through dedicated simulations the additional generation and demand-side measures required to close the residual energy gap, and refine the environmental characterisation of retrofit technologies, in order to strengthen the transferability and decision-support value of PED-oriented assessment methods.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data supporting the findings of this study form an aggregated dataset comprising the district-level energy modelling outputs and the life cycle inventory and impact assessment results. The dataset is retained by the authors and is available from the date of publication and throughout the following ten years, enquiries being handled by the authors jointly. Data provided by third parties and used as model input remain subject to the authorisation of their owner.

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References

- [1] World Meteorological Organization (WMO), WMO confirms 2024 as warmest year on record at about 1.55°C above pre-industrial level, Press Release, 10 Jan. 2025. (Accessed: 09-February-2026).
- [2] Copernicus Climate Change Service (C3S), Copernicus: 2024 is the first year to exceed 1.5°C above pre-industrial level, 10 Jan. 2025. (Accessed: 09-February-2026).
- [3] Copernicus Climate Change Service (C3S), European State of the Climate 2024 - Trends in climate indicators (Europe: ~+2.4°C vs 1850-1900), 2025. (Accessed: 09-February-2026).
- [4] Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (EPBD recast). Available at: <https://eur-lex.europa.eu/eli/dir/2024/1275/oj/eng> (Accessed: 03-February-2026).
- [5] Questions and Answers on the revised Energy Performance of Buildings Directive (EPBD). It is available for download at: https://ec.europa.eu/commission/presscorner/api/files/document/print/en./qanda_24_1966/QANDA_24_1966_EN.pdf (Accessed: 03-February-2026).
- [6] Regulation (EU) 2021/1119 of the European Parliament and Council of the European Union of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (‘European Climate Law’). Available at: https://climate.ec.europa.eu/eu-action/european-climate-law_en (Accessed: 03-February-2026).
- [7] 2050 long-term strategy. Striving to become the world's first climate-neutral continent by 2050. Available at: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en (Accessed: 03-February-2026).
- [8] European Commission, The European Green Deal, 2019. Available at: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (Accessed: 09-February-2026).
- [9] Council of the European Union, Fit for 55, 2021. Available at <https://www.consilium.europa.eu/en/policies/fit-for-55/> (Accessed: 09-February-2026).
- [10] The European Green Deal - Striving to be the first climate-neutral continent. Available at: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (Accessed: 03-February-2026).

- [11] Directive (EU) 2023/2413 of the European Parliament and Council of the European Union, of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources (RED III), and repealing Council Directive (EU) 2015/652 - Official Journal of the European Union, OJ L, 2023/2413, 31 Oct. 2023. Available at: <https://eur-lex.europa.eu/eli/dir/2023/2413/oj/eng> (Accessed: 03-February-2026).
- [12] Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ%3AJOL_2023_231_R_0001&qid=1695186598766 (Accessed: 03-February-2026).
- [13] European Commission, “Renewable energy targets,” European Commission (DG ENER). Available at: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-targets_en (Accessed: 03-February-2026).
- [14] European Commission, “2030 energy efficiency target,” European Commission (DG ENER). Available at: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-targets_en (Accessed: 04-February-2026).
- [15] Economidou, M., Atanasiu, B., Despret, C., Maio, J., Nolte, I. and Rapf, O., 2011. Europe’s Buildings under the Microscope: A Country-by-Country Review of the Energy Performance of Buildings. Brussels: Buildings Performance Institute Europe (BPIE). ISBN 978-94-91143-01-4. Available at: https://www.bpie.eu/wp-content/uploads/2015/10/HR_EU_B_under_microscope_study.pdf (Accessed 4 Feb 2026).
- [16] ENTRANZE consortium, 2014. Laying Down the Pathways to Nearly Zero-Energy Buildings: A Toolkit for Policy Makers. Published November 2014 by the ENTRANZE consortium. Grant agreement n. IEE/11/922/SI2.615942 (Intelligent Energy Europe). Available at: <https://www.oeko.de/oekodoc/2203/2014-749-en.pdf> (Accessed: 04-February-2026).
- [17] Gevorgian, A., Pezzutto, S., Zambotti, S., Croce, S., Filippi Oberegger, U., Lollini, R., Kranzl, L. and Müller, A., 2021. European Building Stock Analysis: A country-by-country descriptive and comparative analysis of the energy performance of buildings. Bolzano, Italy: Eurac Research. ISBN 978-88-98857-68-5. Available at: https://webassets.eurac.edu/31538/1643788710-ebsa_web_2.pdf (Accessed: 04-February-2026).
- [18] Escandón, R., Suárez, R. and Sendra, J.J., 2019. Field assessment of thermal comfort conditions and energy performance of social housing: The case of hot summers in the Mediterranean climate. *Energy Policy*, 128, pp. 377-392. DOI: 10.1016/j.enpol.2019.01.009
- [19] Fernández-Agüera, J., Domínguez-Amarillo, S., Sendra, J.J., Suárez, R. and Oteiza, I., 2019. Social housing airtightness in Southern Europe. *Energy and Buildings*, 183, pp. 377-391. DOI: 10.1016/j.enbuild.2018.10.041.
- [20] Gangale, F. and Mengolini, A., 2019. Energy poverty through the lens of EU research and innovation projects. Luxembourg: Publications Office of the European Union. EUR 29785 EN; JRC113953. ISBN 978-92-76-08676-5. DOI 10.2760/972106. Available at: <https://publications.jrc.ec.europa.eu/repository/bitstream/JRC113953/kjna29785enn.pdf> (Accessed: 04-February-2026).
- [21] European Environment Agency (EEA), 2024. Buildings and construction - In-depth topics. Available at: <https://www.eea.europa.eu/en/topics/in-depth/buildings-and-construction> (Accessed: 04-February-2026).
- [22] Alexandri, E., 2022. From the Building to the Building Stock: Investigation of the Transformations of the Building Stock of the City of Athens for its Conversion into a Carbon Neutral City. *Green Energy and Sustainability*, 2(1), 0002. DOI: 10.47248/ges2202010002. Available at: <https://www.pivotscipub.com/ges/2/1/0002/html> (Accessed: 04-February-2026).
- [23] City of Barcelona, 2024. Climate City Contract - Baseline inventory & energy balance (2019). NetZeroCities platform. Available at:

https://netzerocities.app/_content/files/knowledge/4178/barcelona_nzc_ccc_ok.pdf (Accessed: 03-February-2026).

[24] Blázquez, T., Dalla Mora, T., Ferrari, S., Romagnoni, P., Teso, L. and Zagarella, F., 2022. Renovating Building Groups in the Mediterranean Climate: Cost-Effectiveness of Renewable-Based Heating Alternatives in the Italian Context. *Sustainability*, 14(19), 12303. DOI: 10.3390/su141912303. Available at: <https://www.mdpi.com/2071-1050/14/19/12303> (Accessed: 04-February-2026).

[25] Ulu, M. and Durmuş Arsan, Z., 2020. Retrofit Strategies for Energy Efficiency of Historic Urban Fabric in Mediterranean Climate. *Atmosphere*, 11(7), 742. DOI: 10.3390/atmos11070742. Available at: <https://www.mdpi.com/2073-4433/11/7/742> (Accessed: 04-February-2026).

[26] Citadini de Oliveira, C., Vaz, I.C.M. and Ghisi, E., 2024. Retrofit strategies to improve energy efficiency in buildings: An integrative review. *Energy and Buildings*, 321, 114624. DOI: 10.1016/j.enbuild.2024.114624. Available at: <https://www.sciencedirect.com/science/article/abs/pii/S0378778824007400> (Accessed: 04-February-2026).

[27] European Commission, 2020. A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives. COM (2020) 662 final. Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0662> (Accessed: 04-February-2026).

[28] JPI Urban Europe / SET-Plan Action 3.2, White Paper on PED Reference Framework (framework definition for Positive Energy Districts and Neighbourhoods), 2020. Available at: <https://jpi-urbaneurope.eu/wp-content/uploads/2020/04/White-Paper-PED-Framework-Definition-2020323-final.pdf> (Accessed: 04-February-2026).

[29] Kozłowska, A., et al., Positive Energy Districts: Fundamentals, Assessment Methodologies, Modeling and Research Gaps, *Energies*, vol. 17, no. 17, p. 4425, Sep. 2024, doi: 10.3390/en17174425.

[30] European Strategic Energy Technology Plan (SET-Plan), Action 3.2 (Smart Cities and Communities), Implementation Plan: Europe to become a global role model in integrated, innovative solutions for the planning, deployment and replication of Positive Energy Districts, June 2018. Available at: https://jpi-urbaneurope.eu/wp-content/uploads/2021/10/setplan_smartcities_implementationplan-2.pdf (Accessed: 04-February-2026).

[31] JPI Urban Europe, Europe towards Positive Energy Districts (PED Booklet - Update), 2020. Available at: https://jpi-urbaneurope.eu/wp-content/uploads/2020/06/PED-Booklet-Update-Feb-2020_2.pdf (Accessed: 04-February-2026).

[32] Bossi, S., Gollner, C., Theierling, S. Towards 100 Positive Energy Districts in Europe: Preliminary Data Analysis of 61 European Cases. *Energies* 2020, 13(22), 6083; <https://doi.org/10.3390/en13226083>

[33] Driving Urban Transitions Partnership & PED-EU-NET, PED-DB - Positive Energy Districts Database. Available at: <https://peddatabase.dutpartnership.eu/> (Accessed: 11-February-2026).

[34] JPI Urban Europe, Urban Europe - Positive Energy Districts (PED). Available: <https://jpi-urbaneurope.eu/ped/> (Accessed: 11-February-2026).

[35] S. Sareen et al., Ten questions concerning positive energy districts, *Building and Environment*, vol. 216, 109017, 2022. <https://doi.org/10.1016/j.buildenv.2022.109017>

[36] Guarino, F. et al., State of the Art on Sustainability Assessment of Positive Energy Districts: Methodologies, Indicators and Future Perspectives, in *Sustainability in Energy and Buildings* 2021, Springer, 2022. https://doi.org/10.1007/978-981-16-6269-0_40

[37] Shtjefni, D., Ulpiani, G., Uihlein, A., Bossi, S., Gollner, C., Koukoufikis, G., Bertoldi, P., Are positive energy districts more prevalent in wealthier European regions?, *Energy Research & Social Science*, vol. 133, 104603, 2026. <https://doi.org/10.1016/j.erss.2026.104603>

- [38] IEA EBC, Annex 83 website, Positive Energy Districts. Available at: <https://annex83.iea-ebc.org/> (Accessed: 04-February-2026).
- [39] Haase, M. et al., *Lessons learned from analysing PED case studies*, in 12th International Conference on Improving Energy Efficiency in Commercial Buildings and Smart Communities (IEECB&SC'24) and European ESCO Conference, Frankfurt, Germany, 6-7 Mar. 2024, pp. 118-132, E. Clementi and P. Bertoldi, Eds. Luxembourg: Publications Office of the European Union, 2024. ISBN: 978-92-68-14947-8. doi: 10.2760/716916.
- [40] Zhang, X. et al., Characterizing Positive Energy District (PED) through a Preliminary Review of 60 Existing Projects in Europe, *Buildings*, 11(8), 318, 2021.
- [41] Binda, T., Bottero, M., Bisello, A., *Evaluating Positive Energy Districts: A Literature Review*, in *New Metropolitan Perspectives*, Springer, 2022. doi: 10.1007/978-3-031-06825-6_170. Available at: file:///C:/Users/lorid/Desktop/EvaluatingPositiveEnergyDistricts_ALiteratureReview.pdf (Accessed: 05-February-2026).
- [42] Newman, H-M. et al. Qualitative Assessment Methodology for Positive Energy District Planning Guidelines, doi: 10.1007/978-981-16-6269-0_42, in book: *Sustainability in Energy and Buildings* 2021.
- [43] J. Natanian et al., Ten questions on tools and methods for positive energy districts, *Building and Environment*, 255, 111429, 2024.
- [44] Tuerk et al., Integrating Plus Energy Buildings and Districts with the EU Energy Community Framework: Regulatory Opportunities, Barriers and Technological Solutions, *Buildings* 11(10):468 (2021).
- [45] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). Available at: <https://eur-lex.europa.eu/eli/dir/2018/2001/oj/eng> (Accessed: 03-February-2026).
- [46] Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity. Available at: <https://eur-lex.europa.eu/eli/dir/2019/944/oj/eng> (Accessed: 03-February-2026).
- [47] Italian Republic, Decree-Law N. 162 of 30 December 2019, Art. 42-bis (renewable self-consumption and energy communities). *Gazzetta Ufficiale della Repubblica Italiana*. Available at: <https://www.gazzettaufficiale.it/eli/id/2019/12/31/19G00171/S> (Accessed: 03-February-2026).
- [48] Italian Republic, Legislative Decree No. 199 of 8 November 2021 (implementation of Directive (EU) 2018/2001; provisions on self-consumption configurations and renewable energy communities). *Gazzetta Ufficiale della Repubblica Italiana*, 30 Nov. 2021. Available at: <https://www.gazzettaufficiale.it/eli/id/2021/11/30/21G00214/> (Accessed: 03-February-2026).
- [49] Italian Ministry of Environment and Energy Security (MASE), Decree of 7 December 2023, No. 414 ("CACER Decree") on incentive tariff for RES plants within renewable energy communities and self-consumption configurations. *Gazzetta Ufficiale della Repubblica Italiana*, notice of publication, 7 Feb. 2024. Available at: <https://www.gazzettaufficiale.it/eli/id/2024/02/07/24A00671/> (Accessed: 03-February-2026).
- [50] Italian Gestore dei Servizi Energetici (GSE), Operating Rules for 'CACER' and distributed self-consumption configurations (Regole Operative CACER / autoconsumo diffuso), implementing MASE Decree No. 414/2023. Available at: https://www.gse.it/documenti_site/Documenti%20GSE/Servizi%20per%20te/AUTOCONSUMO/Gruppi%20di%20autoconsumatori%20e%20comunita%20di%20energia%20rinnovabile/Regole%20e%20procedure/ALLEGATO%201%20Regole%20Operative%20CACER.pdf (Accessed: 03-February-2026).
- [51] Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards

the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652. Available at: <https://eur-lex.europa.eu/eli/dir/2023/2413/oj/eng> (Accessed: 03-February-2026).

[52] Annex to the Commission Notice providing guidance on new or substantially modified provisions of the recast Energy Performance of Buildings Directive (EU) 2024/1275 - Solar energy in buildings (Article 10) Available at: https://energy.ec.europa.eu/document/download/fd6f89fe-711b-4025-bc37-76b99baaa3fe_en?filename=Solar%20energy%20in%20buildings%20%28Article%2010%29%20-%20annex%208.pdf (Accessed: 03-February-2026).

[53] Rockström, J., et al. A safe operating space for humanity. *Nature* 461, 472-475 (2009). <https://doi.org/10.1038/461472a>.

[54] Stockholm Resilience Centre, Planetary boundaries, *Stockholm Resilience Centre* (Stockholm University). Available at: <https://www.stockholmresilience.org/research/planetary-boundaries.html>. (Accessed: 05-February-2026).

[55] Richardson, K. et al., Earth beyond six of nine planetary boundaries, *Science Advances*, vol. 9, n. 37, 2023, doi: 10.1126/sciadv.adh2458.

[56] Steffen, W. et al., Planetary boundaries: Guiding human development on a changing planet, *Science*, vol. 347, n. 6223, 2015, doi: 10.1126/science.1259855.

[57] Wang-Erlandsson, L. et al., A planetary boundary for green water, *Nature Reviews Earth & Environment*, 2022, doi: 10.1038/s43017-022-00287-8.

[58] Sachs, J. D. et al., Sustainable Development Report 2025: Financing Sustainable Development to 2030 and Mid-Century, SDSN, 2025, doi: 10.25546/111909, available at: <https://sdgtransformationcenter.org/reports/sustainable-development-report-2025> (Accessed: 03-February-2026).

[59] Lella, L. et al, Pioneering a sustainable development goals monitoring framework for European regions, *Ecological Indicators* 166 (2024) 112248, doi: 10.1016/j.ecolind.2024.112248

[60] United Nations, Department of Economic and Social Affairs (UNDESA), THE 17 GOALS, Sustainable Development Goals. Available at: <https://sdgs.un.org/goals> (Accessed: 03-February-2026).

[61] United Nations General Assembly, Transforming our world: the 2030 Agenda for Sustainable Development, Resolution A/RES/70/1, 2015. Available at: https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf (Accessed: 03-February-2026).

[62] Fabbri, M., De Groote, M., and Rapf, O., *Building Renovation Passports: Customised roadmaps towards deep renovation and better homes*, 2nd ed. Brussels, Belgium: Buildings Performance Institute Europe (BPIE), Nov. 2016. ISBN: 9789491143175. Available at: https://bpie.eu/wp-content/uploads/2017/01/Building-Passport-Report_2nd-edition.pdf (Accessed: 09-February-2026).

[63] International Organization for Standardization, Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification, ISO 14067:2018. Geneva, Switzerland: ISO, 2018.

[64] International Organization for Standardization, Environmental management - Life cycle assessment - Principles and framework, ISO 14040:2021. Geneva, Switzerland: ISO, 2021.

[65] International Organization for Standardization, Environmental management - Life cycle assessment - Requirements and guidelines, ISO 14044:2021. Geneva, Switzerland: ISO, 2021.

[66] Zhang, W., Zhao, O., Xie, L., Li, Z., Wu X., Zhong J., Zou R., 2023. Factors influence analysis and life cycle assessment of innovative bifacial photovoltaic applied on building facade. *Energy*. 279, 128082. <https://doi.org/10.1016/j.energy.2023.128082>.

[67] Chen, Y., Hong, T., Piette, M.A., Automatic generation and simulation of urban building energy models based on city datasets for city-scale building retrofit analysis, *Applied Energy*, vol. 205, pp. 323-335, 2017, doi: 10.1016/j.apenergy.2017.07.128.

- [68] Ang, Y.Q., Berzolla, Z.M., Letellier-Duchesne, S., Reinhart, C.F., Carbon reduction technology pathways for existing buildings in eight cities, *Nature Communications*, vol. 14, art. no. 1689, 2023, doi: 10.1038/s41467-023-37131-6.
- [69] Johari, F., Lindberg, O., Ramadhani, U.H., Shadram, F., Munkhammar, J., Widén, J., Analysis of large-scale energy retrofit of residential buildings and their impact on the electricity grid using a validated UBEM, *Applied Energy*, vol. 361, art. no. 122937, 2024, doi: 10.1016/j.apenergy.2024.122937.
- [70] Hong, T., Lee, S.H., Zhang, W., Li, H., Sun, K., Kace, J., Informing electrification strategies of residential neighborhoods with urban building energy modeling, *Building Simulation*, vol. 18, no. 1, pp. 3-18, 2025, doi: 10.1007/s12273-024-1214-6.
- [71] Zhang, S., Chen, L., Huang, Q., Wang, X., Wang, Z., An integrated energy-carbon-economic assessment of building decarbonization at city scale, *Applied Energy*, vol. 424, art. no. 128406, 2026, doi: 10.1016/j.apenergy.2026.128406.
- [72] Chastas, P., Theodosiou, T., Bikas, D., Tsikaloudaki, K., 2020. Integrating embodied impact into the context of EPBD recast: an assessment on the cost-optimal levels of nZEBs. *Energy and Buildings*. 215, 109863. <https://doi.org/10.1016/j.enbuild.2020.109863>
- [73] Ongpeng, J.M.C., Rabe, B.I.B., Razon, L.F., Aviso, K.B., Tan, R.R., 2022. A multi-criterion decision analysis framework for sustainable energy retrofit in buildings. *Energy*. 239, 122315. <https://doi.org/10.1016/j.energy.2021.122315>
- [74] Zhang, C. et al., Enhancing the uptake of secondary raw materials in the construction sector through reuse and recycling, *Chem Circularity*, vol. 1, art. no. 100013, 2026, doi: 10.1016/j.checir.2026.100013.
- [75] UNI EN 16798-1:2019 Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6.
- [76] World Meteorological Organization (WMO). State of the Global Climate 2024. Geneva, Switzerland: WMO; 2025. WMO-No. 1368. Available at <https://wmo.int/publication-series/state-of-global-climate/state-of-global-climate-2024> (Accessed: 09-February-2026).
- [77] Cabeza, L.F.; Bai, Q.; Bertoldi, P.; Kihila, J.M.; Lucena, A.F.P.; Mata, É.; Mirasgedis, S.; Novikova, A.; Saheb, Y. 2022: Buildings. In: Shukla, P.R.; Skea, J.; Slade, R.; Al Khourdajie, A.; van Diemen, R.; McCollum, D.; Pathak, M.; Some, S.; Vyas, P.; Fradera, R.; Belkacemi, M.; Hasija, A.; Lisboa, G.; Luz, S.; Malley, J. (eds.), *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the IPCC*. Cambridge University Press, Cambridge, UK and New York, NY, USA. <https://doi.org/10.1017/9781009157926.011>
- [78] UNI CEN/TR 15193-2:2017, 2017 Energy performance of buildings - Energy requirements for lighting - Part 2: Explanation and justification of EN 15193-1, Module M9.
- [79] Diefenbach, N., Loga, T., et al., *Typology Approach for Building Stock Energy Assessment: Application of Building Typologies for Modelling the Energy Balance of the Residential Building Stock - TABULA Thematic Report No. 2 (Deliverable D8)*. Darmstadt, Germany: Institut Wohnen und Umwelt GmbH (IWU), Feb. 2012. ISBN: 978-3-941140-23-3.
- [80] Corrado, V., and Ballarini, I., *Energy Performance Indicator Tracking Schemes for the Continuous Optimisation of Refurbishment Processes in European Housing Stocks: Energy Refurbishment Progress of the Regional Housing Stock (Piedmont Region, IT), National report / Final version (Deliverable D3.2b)*, 2nd ed. Torino, Italy: Politecnico di Torino - Dipartimento Energia, Oct. 2015. ISBN: 978-88-8202-064-4.
- [81] Diefenbach, N., Loga, T., and Stein, B. (eds.), et al., *Application of Energy Performance Indicators for Residential Building Stocks: Experiences of the EPISCOPE Project (Deliverable D4.1b)*. EPISCOPE Project Team, Mar. 2016.

- [82] TABULA/EPISCOPE Consortium, TABULA/EPISCOPE WebTool (Building Typology WebTool). Available at: <https://webtool.building-typology.eu/#bm> (Accessed: 03-February-2026).
- [83] UNI/TR 11552:2014 - Technical Report - Abaco delle strutture costituenti l'involucro opaco degli edifici: parametri termofisici, Milano, Italy: UNI, 2014.
- [84] Carnieletto, L., Ferrando, M., Teso, L., Sun, K., Zhang, W., Causone, F., Romagnoni, P., Zarrella, A., & Hong, T. (2021). Italian prototype building models for urban scale building performance simulation. *Building and Environment*, 192, 107590. <https://doi.org/10.1016/j.buildenv.2021.107590>
- [85] CitySim Software. Available at: <https://www.epfl.ch/labs/leso/transfer/software/citysim/> (Accessed: 09-February-2026).
- [86] SimStadt Software. Available at: <https://immvis.github.io/projects/simstad/> (Accessed: 09-February-2026).
- [87] City Energy Analyst (CEA) Software. Available at: <https://cea.arch.ethz.ch/> (Accessed: 20-December-2025).
- [88] ISO 13790:2008 Energy performance of buildings - Calculation of energy use for space heating and cooling. International Organization for Standardization.
- [89] Wang, X., Tian, S., Ren, J., Jin, X., Zhou, X., & Shi, X. (2024). A novel resistance-capacitance model for evaluating urban building energy loads considering construction boundary heterogeneity. *Applied Energy*, 122896. <https://doi.org/10.1016/j.apenergy.2024.122896>
- [90] Corrado, V., Mechri, H. E., Fabrizio, E. (2007). Building energy performance assessment through simplified models: Application of the ISO 13790 quasi-steady state method. In *Proceedings of Building Simulation 2007*, Beijing, China, pp. 79-86.
- [91] Architecture and Building Systems. (2021). A Resistance Capacitance Model for an Energetic Simulation of a Building [Source code]. Available at: GitHub. <https://github.com/architecture-building-systems/> (Accessed: 09-February-2026).
- [92] City Energy Analyst. (2023). CEA Technical Documentation: Demand Calculation Module. Available at: <https://city-energy-analyst.readthedocs.io/en/latest/> (Accessed: 20-December-2025).
- [93] Fonseca, J. A., & Schlueter, A. (2015). Integrated model for characterization of spatiotemporal building energy consumption patterns in neighborhoods and city districts. *Applied Energy*, 142, 348-365. <https://doi.org/10.1016/j.apenergy.2014.12.068>
- [94] Ferrando, M., Causone, F., Hong, T., & Chen, Y. (2020). Urban building energy modeling (UBEM) tools: A state-of-the-art review of bottom-up physics-based approaches. *Sustainable Cities and Society*, 62, 102408. <https://doi.org/10.1016/j.scs.2020.102408>
- [95] SIA 2044:2011 Standard for simplified calculation of energy performance. Swiss Society of Engineers and Architects.
- [96] Kramer, R., van Schijndel, J., & Schellen, H. (2012). Simplified thermal and hygric building models: A literature review. *Frontiers of Architectural Research*, 1(4), 318-325. <https://doi.org/10.1016/j.foar.2012.09.001>
- [97] Crawley, D. B., et al. (2008). Contrasting the capabilities of building energy performance simulation programs. *Building and Environment*, 43(4), 661-673. <https://doi.org/10.1016/j.buildenv.2006.10.027>
- [98] Fonseca, J.A., Nguyen, T.-A., Schlueter, A., Maréchal, F. (2016). City Energy Analyst (CEA): Integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts. *Energy and Buildings*, 113, 202-226. <https://doi.org/10.1016/j.enbuild.2015.11.055>
- [99] Fonseca, J.A. (2016). Energy efficiency strategies in urban communities. Doctoral Thesis, ETH Zürich. <https://doi.org/10.3929/ethz-a-010639933>

- [100] Michalak, P. (2022). Thermal network model for an assessment of summer indoor comfort in a naturally ventilated residential building. *Energies*, 15(10), 3709. <https://doi.org/10.3390/en15103709>
- [101] Kokogiannakis, G., Strachan, P., Clarke, J. (2008). Comparison of the simplified methods of the ISO 13790 standard and detailed modelling programs in a regulatory context. *Journal of Building Performance Simulation*, 1(4), 209-219. <https://doi.org/10.1080/19401490802509388>
- [102] Ballarini, I., Corrado, V. (2012). Application of energy rating methods to the existing building stock: analysis of some residential buildings in Turin. *Energy and Buildings*, 49, 536-548. <https://doi.org/10.1016/j.enbuild.2009.02.009>
- [103] Reinhart, C.F., Davila, C.C. (2016). Urban building energy modeling — a review of a nascent field. *Building and Environment*, 97, 196-202. <https://doi.org/10.1016/j.buildenv.2015.12.001>
- [104] Dogan, T., Reinhart, C. (2017). Shoebox modeling: a method for the rapid generation of multi-zone urban building energy models. *Energy and Buildings*, 140, 230-240. <https://doi.org/10.1016/j.enbuild.2017.01.030>
- [105] Python Software Foundation, The Python Language Reference, version 3.14.3. Available at: <https://docs.python.org/3/reference/>
- [106] Python Software Foundation, Python 3.14.3 Documentation. Available at: <https://docs.python.org/3/>
- [107] Bergstra, J., Yamins, D., and Cox, D. D., Hyperopt: A Python Library for Optimizing the Hyperparameters of Machine Learning Algorithms, in *Proceedings of the 12th Python in Science Conference*, 2013, pp. 13-20, doi: 10.25080/Majora-8b375195-003. <https://doi.org/10.25080/Majora-8b375195-003>
- [108] Bergstra, J., Yamins, D., and Cox, D. D., Making a Science of Model Search: Hyperparameter Optimization in Hundreds of Dimensions for Vision Architectures, in *Proceedings of the 30th International Conference on Machine Learning*, vol. 28, pp. 115-123, 2013. Available at: https://hyperopt.github.io/hyperopt/?utm_source
- [109] ISO 18523-1:2016 - Energy performance of buildings - Schedule and condition of building, zone and space usage for energy calculation - Part 1: Non-residential buildings.
- [110] ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers Guideline 14-2014 - Measurement of Energy, Demand, and Water Saving.
- [111] Ricerca sul Sistema Energetico - RSE SpA, *I consumi della Pubblica Amministrazione. Soluzioni e impatti economici per edifici pubblici più efficienti*, Monografia RSEview, 2024. Available at <https://www.rse-web.it/wp-content/uploads/2025/01/2025-RSEview-PA.pdf> (Accessed: 19-February-2026).
- [112] Italian Republic, Decreto 28 October 2025: Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici, Official Gazette of the Italian Republic (Gazzetta Ufficiale), Serie Generale n. 283, 5 December 2025. Available at: <https://www.gazzettaufficiale.it/eli/id/2025/12/05/25A06487/SG> (Accessed: 01-July-2026).
- [113] Italian Republic, Presidential Decree No. 412/1993: Regulation defining building design, installation, operation and maintenance criteria for thermal systems and national climatic zoning, Official Gazette of the Italian Republic, 1993. Available at: <https://www.gazzettaufficiale.it/eli/id/1993/10/14/093G0451/sg> (Accessed: 19-February-2026).
- [114] Cusenza, M.A., Guarino, F., Longo, S., Cellura, M., 2022. An integrated energy simulation and life cycle assessment to measure the operational and embodied energy of a Mediterranean net zero energy building. *Energy and Buildings*. 254, 111558. <https://doi.org/10.1016/j.enbuild.2021.111558>.

- [115] Ecoinvent Association. Ecoinvent database, Version 3.10 (2023). <https://www.ecoinvent.org/>
- [116] Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. *International Journal of Life Cycle Assessment*. 21, 1218-1230. <https://doi.org/10.1007/s11367-016-1087-8>.
- [117] Frischknecht, R., Jungbluth, N., Althaus, H., Bauer, C., Doka, G., Dones, R., Hirschier, R., Hellweg, S., Köllner, T., Loerincik, Y., Margni, M., 2007. Implementation of Life Cycle Impact Assessment Methods. *American Midland Naturalist*. 150, 1-151. Available at: http://www.ecoinvent.org/fileadmin/documents/en/03_LCIAImplementation.pdf (Accessed: 19-February-2026).
- [118] PRé Sustainability B.V. SimaPro [software]. Amersfoort, The Netherlands: PRé Sustainability B.V.
- [119] European Commission – Joint Research Centre – Institute for Environment and Sustainability. (2010). *International Reference Life Cycle Data System (ILCD) Handbook: General guide for Life Cycle Assessment – Detailed guidance*. First edition. Luxembourg: Publications Office of the European Union. <https://doi.org/10.2788/38479>
- [120] Dodd, N., Donatello, S., and Cordella, M., Level(s) indicator 1.2: Life cycle Global Warming Potential (GWP): User manual - introductory briefing, instructions and guidance, ver. 1.1. Luxembourg: European Commission, Joint Research Centre, 2021. Available at: https://susproc.jrc.ec.europa.eu/product-bureau/sites/default/files/2021-01/UM3_Indicator_1.2_v1.1_37pp.pdf (Accessed: 19-February-2026).
- [121] CEN, EN 15804:2012+A2:2019 Sustainability of construction works—Environmental product declarations—Core rules for the product category of construction products. Brussels, Belgium: European Committee for Standardization, 2019
- [122] European Parliament and Council of the European Union, Directive 2008/98/EC of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance), *Official Journal of the European Union*, L 312, pp. 3-30, Nov. 22, 2008. Available at: <https://eur-lex.europa.eu/eli/dir/2008/98/oj> (Accessed: 19-February-2026).
- [123] European Parliament and the Council of the European Union, Directive 2012/19/EU of 4 July 2012 on waste electrical and electronic equipment (WEEE) (recast) (Text with EEA relevance), *Official Journal of the European Union*, L 197, pp. 38-71, Jul. 24, 2012. Available at: <https://eur-lex.europa.eu/eli/dir/2012/19/oj/eng> (Accessed: 19-February-2026).
- [124] You, K. et al., Mitigating emissions and costs through demand-side solutions in Chinese residential buildings, *Nature Communications*, vol. 16, art. no. 7358, 2025, doi: 10.1038/s41467-025-62675-0.
- [125] European Environment Agency (EEA), 2022. Building renovation: where circular economy and climate meet. Briefing no. 12/2022. Copenhagen: EEA. doi: 10.2800/895578. Available at: <https://www.eea.europa.eu/en/analysis/publications/building-renovation-where-circular-economy-and-climate-meet> (Accessed: 21-August-2026).
- [126] Zhang, C. et al., Revealing the interplay between decarbonisation, circularity, and cost-effectiveness in building energy renovation, *Nature Communications*, vol. 16, art. no. 7153, 2025, doi: 10.1038/s41467-025-62442-1.

Declaration of Interest Statement

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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