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Research Paper

Fostering the energy transition in a neighbourhood perspective: towards Positive Energy Districts' application for a university case study

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ABSTRACT

The European SET Plan Action 3.2 promotes the deployment and replication of 100 Positive Energy Neighbourhoods by 2025, disclosing the urgent need for adopting an integrated approach able to implement consistent actions aimed at sustainability. The aim of the paper is to investigate, in this framework, a mediterranean non-residential urban district: it analyses whether it could reach Positive Energy District (PED) targets by promoting energy efficiency actions, enhancing its environmental performances. This considering the environmental impact for a system of renovation actions and the goal of providing a benchmarking criterion for PED performances evaluation. Energy models were performed and simulated in non-steady state conditions for assessing their current energy performances; the validation process was followed by the assessment of selected retrofit scenarios and the implementation of Life Cycle Assessment studies. This to evaluate the feasibility of achieving PED level for a redesigned scenario. Results include the validation of the modelled district and an assessment of its renovation potentialities: they reveal that post-renovation configurations for on-site energy generation could provide up to 80 % of district's annual energy demand. Notwithstanding, the reduction in annual energy demand for the renovated configuration (assessed in the 40 %), is not sufficient to reach PED standards. The LCA approach highlighted that holistic solutions for PED design are required, even stressing that climate neutrality definition does not always imply energy neutrality (or positive energy) and vice versa: the renovated district allowed for a reduction of 63 % life cycle energy compared to only 34 % reduction of global warming potential.

1. Introduction

A growing interest on the European Strategic Energy Technology Plan (SET Plan) Action 3.2, through the programme "Positive Energy Districts and Neighbourhoods for Sustainable Urban Development", generated an articulated, international debate on the deployment and replication of 100 Positive Energy Neighbourhoods by 2025; this task, in connection with the work carried out by Urban Europe Joint Programming Initiative (JPI), triggered a multifaceted discussion, also fostering ideas' exchange and sharing of information among international think tanks, academic researchers, authorities and institutional bodies (JPI Urban Europe, European Strategic Energy Technology SET Plan Action 3.2, 2020). Indeed, there is an urgent need for providing a set of tools and guidelines aimed at the planning and the deployment of Positive Energy Districts (PEDs) across Europe. This calls for researchers, academics, scientists and decision-makers to establish and strengthen a proactive connection, by devising coherent, consistent, and reasonable policy proposals.

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The PED definition provided by JPI Urban Europe states that PEDs are "(…) energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility, and ICT systems, while securing the energy supply and a good life for all in line with social, economic and environmental sustainability" (JPI Urban Europe, White Paper on PED Reference Framework for Positive Energy Districts and Neighbourhoods, 2024). Also considering the Renewable Energy Directive III (Renewable Energy Directive III, 2023), released on 18/10/2023 and according to one of its most important articles (Art. 15a "Mainstreaming renewable energy in buildings"), "(…) Member States shall determine an indicative national share of renewable energy produced on-site or nearby, as well as renewable energy taken from the grid in final energy consumption in their building sector in 2030 that is consistent with an indicative target of at least a 49 % share of energy from renewable sources in the building sector in the Union's final energy consumption in buildings in 2030". The further, even more stringent and compelling prescriptions recently introduced (on 24 April 2024) by the Directive 2024/1275 of the European Parliament and of the Council on the Energy Performance of Buildings (Directive 2024/1275; The EPBD decrypted: a treasure chest of opportunities to accelerate building decarbonisation, 2024) call for significant actions, either in respect to the existing building assets (with a particular regard to the non-residential built heritage), either in terms of renewable energies' implementation (also through the optimization and the use of solar energy generation potential). The regulation introduces the buildings' renovation passport, which plays a crucial role in driving renovation policies for existing buildings by promoting the efficiency of technical building systems and the replacement of outdated ones. It also supports the adoption of adequate financing tools, support measures, and instruments capable of overcoming market barriers, elements that are essential to unlocking the necessary investments and assisting Member States in implementing their national renovation plans to achieve a zero-emission building stock by 2050. All recommended measures should incorporate life cycle Global Warming Potential (GWP) assessments, not only for new buildings (as specified in Article 7 and Annex III), but also in the refurbishment and retrofitting of existing ones. In addressing this urgent challenge, additional factors must be considered, including the growing energy demand (driven by urban expansion and the continuous operation of existing building communities) and the rigorous assessment of GHG emissions (with their contribution to climate change), integrated into the planning of renovation and redesign strategies. Such an approach could significantly contribute to mitigating environmental degradation.

Cities account for around 78 % of world's total energy consumption and are also responsible for up to 60 % of GHG emissions (Shu and Zhao 2023; United Nations Habitat – Generating power - Cities and Pollution, 2020). Even though urban areas globally cover less than 2 % of the whole earth's surface, their development and reshaping process towards higher energy efficiency scenarios and low-embodied carbon emissions configurations can undoubtedly contribute to resilient urban districts and national sustainable assets (Jin et al., 2005; UNPFA, 1999, Jin and Zhang, 2002).

Another factor that must be consciously addressed when considering medium-to-large scale buildings energy retrofit strategies is the relevant and mutual influence between building technologies - existing or to be settled from the outset - (Shu and Zhao 2023; Shu et al., 2024) occupants' behaviour, energy network allocation and buildings themselves (Jing et al., 2018; Shu et al., 2024).

1.1. Contribution of the research

The research is part of the Italian NRRP project GRINS - Growing Resilient, Inclusive, and Sustainable and examines possible energy retrofit approaches for the University of Palermo Campus buildings: as detailed in Paragraph 3.1, initial surveys gathered construction, energy systems and user data for representative buildings, leading to the creation and calibration of energy models using electricity and gas consumption data over four years (Paragraph 3.2). Various renovation solutions (described in Paragraph 3.3), including renewable energy integration, were evaluated in terms of their impact on energy consumption and environmental burdens (Paragraph 3.4). A central feature of this study is the holistic approach to the Positive Energy District framework, which takes into account both operational and life cycle impacts of renovation strategies (Paragraph 3.5). The research emphasizes the need to balance energy efficiency gains with the potential rise in embodied energy and related environmental impacts: through a case study tailored to the Mediterranean context, the study offers site-specific evidence and findings relevant to comparable urban districts, aiming to address gaps in current literature and support future PED-oriented policies. It provides valuable and innovative insights by integrating multiple dimensions of the low-carbon transition path within the PED framework (an aspect often overlooked in similar studies); unlike conventional approaches that primarily focus on operational energy efficiency, this study uniquely combines both use-stage and life cycle perspectives, ensuring that energy retrofitting strategies do not lead to unintended increases in embodied energy or environmental impacts. A distinctive feature is the adoption of a dynamic energy modelling approach that evaluates the combined impact of various renovation scenarios (including renewable energy integration) from a holistic, multi-scale perspective, addressing both individual buildings and the wider urban district. By applying this methodology to a Mediterranean-specific case study, the research provides localized, realistic insights that fill a critical gap in existing PED studies, which often lack context-specific applications. In addition, by mapping impact flows across life cycle and environmental indicators, this study introduces a comprehensive assessment framework that can guide future PED-related policies and decision-making, ensuring truly sustainable, resilient, and inclusive urban energy transitions.

The paper is organized as follows: Section 2 provides a comprehensive overview of the Positive Energy Districts (PEDs) concept, emphasizing its gradual conceptual evolution and recent practical developments. Section 3 outlines the methodology adopted in this research, detailing the case study under analysis, its key features, the modelling process, and the assessment metrics used to evaluate its energy performance. Section 4 presents and analyses the various scenarios considered in the study, systematically reporting and commenting on all the most relevant results and findings. Section 5 explores key issues and significant insights that emerged from the research, highlighting those that deserve further attention and merit careful consideration. Finally, Section 6 concludes the paper with a summary of its main findings and offers final remarks, drawing meaningful conclusions from the overall study.

2. State of the art

Starting from the analysis of a specific context of the Mediterranean area (and resting on distinctive boundary conditions for an urban non-residential pilot buildings' complex), this research addresses a tailored analysis of Positive Energy Districts. In this regard, taking into account the great challenge faced nowadays by policy makers when planning urban energy retrofit initiatives, and resting on a solid body of literature, this study aimed to connect and harmonize different approaches to energy efficiency. It was pursued by modulating multifaceted perspectives and being able to effectively tackle this subject beyond the simple post-renovation energy savings assessment.

As also highlighted in recent researches (Pierce et al., 2024; Shu and Zhao 2023), for a large-scale buildings' renovation strategy being effective and powerful (also disclosing its beneficial impact on the built heritage), different energy retrofit scenarios need to be considered, also assessing their real efficiency and feasibility through optimization models, as well as appraising their effect through data analytics and resting on other retrofit experiences gained from empirical projects.

On the other hand, the adoption of an energy retrofit decision-making process supported by a system integration-based approach - such as a GIS-based building stock modelling tool - (Buffat et al., 2017), or a platform able to support planners implementing informed energy efficient actions (Madrazo et al., 2018), can be useful for targeting effective strategies, especially when joined with investment costs' and upfront capitals' conscious allocation (Ascione et al., 2018).

Even though the above-mentioned elements undoubtedly play an important role into shaping effective energy retrofit policies and pro-active renovation strategies aimed at energy efficiency, another aspect (often overlooked, or however not effectively prioritized when dealing with this hard challenge) is related to a conscious quantitative environmental assessment able to wisely weight, calibrate and integrate the multiple aspects connected to efficient low carbon transition paths and energy efficient retrofit actions for non-residential urban assets. This when conceived in a Positive Energy District perspective.

By recognizing the significant role played by a mindful evaluation of the environmental costs associated with energy renovations in buildings (beyond merely energy-related aspects), this study also aimed to assess such aspects in a holistic perspective and to involve Life Cycle Assessment (LCA) related aspects: they are currently gaining increasing importance and significant relevance in the improvement plans and the reshaping process of complex urban areas. LCA is indeed becoming a critical factor for promoting sustainable design and facilitating the transition to energy-efficient built environments: nowadays it is therefore able to add distinctive features and discriminating relevance within buildings energy renovation decision-making processes.

In this regard, it is worth to mention the ISO 14040:2006 and the ISO 14044:2021 regulations (ISO 14040, 2006 Environmental management, Life cycle assessment, Principles and framework; ISO 14044, 2006 Environmental management, Life cycle assessment, Requirements and guidelines), as they serve as a key reference for evaluating, not only products' environmental footprint throughout their entire life cycle, but also to conduct in-depth evaluations during the testing phases of new systems (Zhang et al., 2023), to integrate environmental considerations into cost-optimization analyses (Chastas et al., 2020), as well, as in the case of the present study, to develop effective frameworks for comparing multiple energy retrofit measures (Ongpeng et al., 2022).

By reporting what stated by Oregi et al. (2015), three main LCA-related criteria can be identified when dealing with the analysis of environmental assessment of buildings refurbishments: while an all-involving LCA perspective can be undoubtedly considered as the most complete one (being able to involve all the renovation steps, from the manufacturing phase, to the product implementation stage, until the use and the end of life phase) (Blengini and Di Carlo, 2010), it can be quite difficult applying a similar strategy to a heterogeneous building stock, even more when the concurrent renovation goal is the achievement of a positive energy district target, and particularly if dealing with non-residential assets.

Besides, it is necessary to consider that, while on the one hand it is able to quantify the potential environmental impact throughout the entire products' life cycle (in terms of input and output of their whole lifetime and until their disposal), this approach does not take into account any geographical, climate-related aspect, nor the building users or occupation profiles effects.

An alternative to the above-mentioned approach consists in the application of a simplified methodology, as displayed by Hernandez and Kenny (2010), through an assessment primarily focused on the evaluation of building products' replacement and on their operational energy use in connection with the Zero Energy Building features. Also, Cellura et al., (2011) investigated the possibility to renovate and redesign existing buildings in a net zero energy perspective.

Another option, directly targeted to the usage phase assessment and to the evaluation of operation performances, is even more simple, although more affordable and of an easier implementation, and is also suitable to energy rating schemes clustering (Erlandsson and Levin, 2004; Zabalza et al., 2009).

Other researchers broadened lifecycle studies by concurrently considering multiple environmental impact factors (Österbring et al., 2019), and by also implementing building-specific GIS based models, but merely focused on the existing housing urban assets renovation scenarios: Mastrucci et al., (2020) adopted a spatio-temporal LCA framework by involving the implementation of a strategy able to integrate, on the one hand, the building stock's evolution, and on the other hand a time-adjusted carbon footprint estimation and a calibrated environmental assessment. A renovation stages' contribution, ranging between the 4 % and the 16 % for a single building's carbon footprint was quantified, with renovation impacts counteracting operational stage reductions up to 8 % - 9 %.

Almeida (Almeida et al., 2024; Szalay et al., 2022) also extended energy renovation assessment (dealing with energy efficiency projects limited to residential buildings) considering some of the non-operational phases mentioned in the ISO 14040:2006 four main stages LCA methodology.

By evaluating the embodied impacts connected to the case study retrofit (and resting both on specific Environmental Product Declarations - EPDs data (Bittencourt Morè et al., 2022), as well as on different other values provided by SimaPro software (Herrmann, Moltesen, 2015) and by the Ecoinvent Database (https://ecoinvent.org/database/), global warming potential (GWP) and non-renewable primary energy resources (PENRT) were quantified as primary environmental indicators for different building envelope's insulation scenarios. According to the obtained results (and keeping in mind that the 2023 Energy Performance of Building Directive stresses the whole lifecycle emissions consideration), decarbonization targets may be consistently affected and jeopardized whenever operational energy reductions are accompanied by high embodied energy values. In general, according to whole life cycle assessments, the burdens of renovation actions and their temporal distribution can be mostly overlooked, leading to potential overestimation of environmental benefits. Such a phenomenon could also affect existing building districts' renovation strategies.

It is therefore crucial to redefine and reshape the current national energy policies, for pursuing the following PEDs' distinguishing features:

- Energy production function: enabling appointed urban areas to rely on renewable energy only. This represents one of the main contributions towards the achievement of climate neutrality.
- Energy use prioritisation, by striving for energy efficiency: in order to maximise the potentialities of the available energy sources. This also passes through existing buildings' thoughtful retrofits and their energy grid embedding.
- Energy adaptability: by performing a careful and rational context's analysis, aimed at the implementation of reasonable energy strategies that consider background features and overall boundary conditions (e.g. territory's morphology and topography, population density, type and buildings' purposes, available local renewable energy resources and existing infrastructures).
- Life cycle assessment and environmental evaluation of different energy renovation strategies and scenarios.

What observed above, is also in line with one of the most relevant aspects prioritised by the SET-Plan ACTION n°3.2 Implementation Plan (JPI Urban Europe, European Strategic Energy Technology SET Plan Action 3.2, 2020).

Among the most relevant key-actions to be implemented for boosting "Europe to become a global role model in integrated, innovative solutions for the planning, deployment, and replication of Positive Energy Districts", it points out the importance of:

– Embedding PEDs in "an urban and regional energy system, preferably driven by renewable energy, in order to provide (…) flexibility of supply".
– Promoting high levels of energy efficiency, with the goal of keeping "(…) annual local energy consumption lower than the amount of locally produced renewable energy".
– Properly dealing with the existing regional energy system, in order to foster the "(…) use of renewable energy by offering optimised flexibility and (…) district-level self-consumption of electricity and thermal energy".
– Emphasising the distinctive PEDs' aim of joining "(…) built environment, sustainable production and consumption, and mobility to reduce energy use and greenhouse gas emissions and to create added value and incentives for the consumer (…)".
– Optimising the use of innovative and/or traditional materials, "(…) local RES and other low carbon energy sources, local storage, smart energy grids (…), cutting edge energy management (…) and ICT".

Directly linked to this last point and also broadening the evaluation of interoperability role in sustainability decisions, some useful reflections are reported by Elliot (Elliot, 2011), Ardente (Ardente et al., 2003), relevant aspects were investigated by Mora-Rodriguez and Preist (2016) and were applied to the use stage, as well as to the PED-targeted retrofit configuration for an existing non-residential district by Guarino (Guarino et al., 2020, 2023).

By applying a Life Cycle assessment perspective to the building sector - namely for a residential case study placed in southern Italy and primarily focusing on the analysis of construction materials and components for the usage stage – Cellura (Cellura et al., 2017a,b) calculated and highlighted the most relevant energy and environmental impact factors due to the construction phase, to the use and the building maintenance phase, as well as related to a demolition and end-of-life final scenario (through a Life Cycle Inventory data collection). Even more detailed lifecycle quantitative assessments were focused on the operational and embodied energy evaluated for a Mediterranean dwelling (targeted to reach the Net-Zero energy balance), by implementing inventory data, not only connected to the building envelope, but also integrating building technical systems' renovations (Cusenza et al., 2022; Ferrari et al., 2021).

The focus on a non-residential urban district - mainly focused on the quantitative assessment of low carbon transition strategies and also linked to the sustainable management of district's community areas, to urban mobility enhancement and respective avoided CO_2 emissions, energy savings and financial-related aspects - characterized the study conducted by Guerrieri et al. (2019).

In addition, by connecting the above-detailed framework to a literature review focused on the current pathway towards Positive Energy Districts' implementation, some of the most relevant key challenges and aspects that influence (hindering and/or delaying) their effective deployment, can be summarised as follows (Ala-Juusela et al., 2016; Vandevyvere et al., 2022; Zhang et al., 2021):

– Regulatory framework, certification, and standardisation system (JPI Urban Europe, European Strategic Energy Technology SET Plan Action 3.2, 2020; Zhang et al., 2021).
– New energy markets and sustainable business and funding models (JPI Urban Europe, European Strategic Energy Technology SET Plan Action 3.2, 2020).
– Societal innovation, social entrepreneurship, and citizen sensibilization/participation, as well as capacity-building, education, and training (JPI Urban Europe, European Strategic Energy Technology SET Plan Action 3.2, 2020; JPI Urban Europe, White Paper on PED Reference Framework for Positive Energy Districts and Neighbourhoods, 2024).
– Definition and tailoring of harmonised criteria and key performance indicators able to clearly define the "concept of an energy positive neighbourhood and the metrics and tools to measure the energy positivity level of an area" (Ala-Juusela et al., 2016).
– Development of innovative and integrated technologies, as "in many cases, the amount of renewable or sustainable energy needed for the district could possibly be produced in a cheaper and more efficient way outside the district or the city, but such a setup would at least partly go against the PED ambition" (Vandevyvere et al., 2022).
– Replication, upscaling and mainstreaming, also thanks to public sector innovation and procurement (JPI Urban Europe, European Strategic Energy Technology SET Plan Action 3.2, 2020; JPI Urban Europe, White Paper on PED Reference Framework for Positive Energy Districts and Neighbourhoods, 2024).
– Economic feasibility and cost efficiency, also considering that energy retrofitting of existing buildings remains costly and characterised by long payback periods (Vandevyvere et al., 2022).

Notwithstanding, the increasing and outspreading interest on PEDs and on how to reach these targets, can be related to the scale level they are characterised by. It transcends the individual building's context, also involving wider possibilities of innovative and advanced technologies' integration, as well as the engagement of a multifaceted audience of potential subjects, and ranging from economic investors, societal and institutional bodies, public institutions, private citizens etc. (Vandevyvere et al., 2022; PED-EU-NET - Cost Action CA19126). Being PEDs one of the most effective ways to involve such a new building paradigm within an advanced and interconnected energy network (thermal and electrical), they certainly promote - also thanks to the support of innovative IT infrastructures - a proactive shift from a "single building" energy approach to a more inclusive and interactive strategy.

Nevertheless, PEDs are not an entirely new concept and can be considered as an evolution of the concept of Net Zero Energy Districts (NZEDs), as well as Positive Energy Blocks (PEBs) can be seen as a wider and advanced concept of Nearly Zero Energy Buildings (NZEBs) (Magrini et al., 2020; Positive Energy Block definition by +CityxChange).

Since 2017, with the launch of the Positive Energy Districts and Neighbourhoods for Sustainable Urban Development programme (Positive Energy Districts Programme and Neighbourhoods definition and description), and within the larger JPI Urban Europe Initiative (JPI Urban Europe, European Strategic Energy Technology SET Plan Action 3.2, 2020; JPI Urban Europe, White Paper on PED Reference Framework for Positive Energy Districts and Neighbourhoods, 2024), the topic of "Policies and models for the energy transition: from barriers to breakthroughs" has been extensively studied (Magrini et al., 2020).

2.1. PED's application's gaps and aim of the paper

The state-of-the-art assessment revealed that, while PEBs request "at least three connected neighbouring buildings producing on a yearly basis more primary energy than what they use" (European Innovation Partnership on Smart Cities and Communities), the achievement of 100 Positive Energy Neighbourhoods by 2025 settled by European (EU) Member States, involves the more articulated concept of "(…) energy efficient districts that have net zero carbon dioxide emissions and work towards an annual local surplus production of renewable energy. Such districts help raise the quality of life in European cities, while reaching the COP 21 targets and making Europe a global role model. An open innovation framework with cities, industry, investors, research institutes and citizens' organisations all working together will help develop PEDs and the necessary R&I Activities. The approach integrates the technological, spatial, regulatory, financial, legal, environmental, social, and economic perspectives" (JPI Urban Europe, White Paper on PED Reference Framework for Positive Energy Districts and Neighbourhoods, 2024).

It is therefore evident that the emergence of a transition process from individual PEBs to interconnected positive energy blocks can trigger innovative actions for sustainable urban development; also, the Joint Programme on Smart Cities of the European Energy Research Alliance (EERA Joint Programme on Smart Cities) is lined up to these goals and highly interesting case studies. Similar new approaches to "Zero energy beyond single buildings" were discussed by Mavrigiannaki (Mavrigiannaki et al., 2021), Zhang (Zhang et al., 2021) within the "Creating Opportunities and Occasions to Promote a European Results-based Action for Training and Education" COOPERaTE, (2012)).

The following statement can be quoted for appraising the important paradigm shifts introduced: PEB/PED can be defined as "several buildings (new, retrofitted or a combination of both) that actively manage their energy consumption and the energy flow between them and the wider energy system. Positive Energy Blocks/Districts have an annual positive energy balance. They make optimal use of elements such as advanced materials (e.g., bio-based materials), local RES, local storage, smart energy grids, demand-response, cutting edge energy management (electricity, heating, and cooling), user interaction/involvement and ICT. Positive Energy Blocks/Districts are designed to be an integral part of the district/city energy system and have a positive impact on it (also from the circular economy point of view). Their design is intrinsically scalable, and they are well embedded in the spatial, economic, technical, environmental, and social context of the project site." (Alpagut, Gabaldòn, 2018).

In addition, a consistent literature review on how the wide, complex and multifaceted sustainability field has dealt in Europe with Positive Energy Districts implementation (Marotta et al., 2021; Europe towards Positive energy Districts booklet, 2020) highlighted significant aspects and displayed even more food for thought (Turci et al., 2022) but also challenges and critical points. The most peculiar elements and features that differentiate "Autonomous-PED", "Dynamic-PED", "Virtual-PED" and "Candidate-PED" were described (Leone et al., 2023; Lindholm et al., 2021), and the operating scheme of the first three of them were clarified and illustrated (Bossi et al., 2020).

Notwithstanding, most of the case-studies displayed and analysed considered suburban-residential areas, characterised by detached houses, low-rise dwellings, and residential neighbourhoods with limited building density areas.

Consequently, significant and complex challenges arise in the implementation of PEDs, particularly in mixed use neighbourhoods, high rise building districts and energy intensive constructions. As highlighted by Vandevyvere (Vandevyvere et al., 2022), achieving a PED target becomes even more demanding in the context of urban district renovation projects—especially those characterised by high building density or the presence of heritage and historical dwellings. For the above-mentioned cases, it can be also hard to deal with restrictive boundary conditions (e.g. onsite renewable energy generation, regulatory limits, historical ties, reliable energy audits), and to define a proper and integrated approach, suitable to wider, more articulated and varied contexts.

The aim of the paper is the assessment of the potential for verification of strict mathematical PED balance on a non-residential district, while investigating the corresponding environmental impacts generated in the process. As achieving a positive energy balance in the use stage does not guarantee an overall life-cycle reduction in the corresponding environmental impacts, the paper explores the implications of renovations and the implementation of on-site renewable energy solutions to reach PED on a wide range of concurring indicators.

3. Methodology

The adopted methodology includes the following steps:

1. The university buildings of interest (for this specific study the ones belonging to the Engineering Department, hereinafter respectively referred to as "Building 6", "Building 7", "Building 8" and "Building 9" presented in the Figs. 1 and 2 were modelled and simulated in non-steady state conditions in Energy Plus environment.
2. The electricity energy consumption and heating gas needs (monthly data collected over a four-year period), as well as electric load curves and energy loads (hourly data registered over a four-year period from 2019 to 2023) were collected, mapped, and analysed.
3. Buildings' opaque and transparent envelope details, buildings' occupancy rate, lighting and electric equipment devices were then implemented in the models.
4. The above task has been further adjusted and fine-tuned according to boundary condition settings, representative energy profiles, typical occupancy rate, internal loads and overall features' definition and customization.
5. A calibration procedure was therefore carried out, in order to align the energy performances of the modelled buildings to the existing case study.

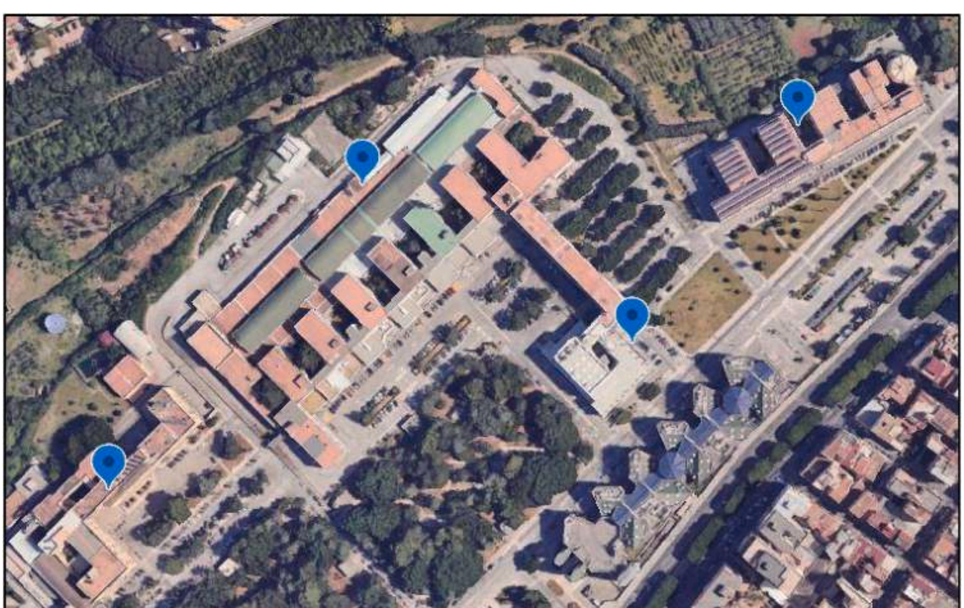


Fig. 1. A view of the University of Palermo Campus, with the four modelled buildings pinpointed.

Fig. 2. An aerial view of the University of Palermo Campus, with the four modelled buildings pinpointed.

6. Then, with reference to the calibrated models, different renovation solutions and renewable energy systems were assessed.
7. The environmental burdens associated to the different renovation strategies chosen were also assessed in a life cycle perspective.
8. Finally, the technical feasibility of a positive energy balance achievement for the specific application context was evaluated, with the final goal of assessing targeted PED requirements.

Taking into account all the information gathered, by implementing the most relevant available data and common details for the buildings of interest, the energy modelling was performed, finalised and assessed as per the following described methodology and operative steps.

3.1. On-site investigation, data acquisition and district's energy modelling

Several inspections and technical site visits were carried out on the buildings under study, also collecting the respective main data and detailed information. A historical consumption trend (based on the energy bills and on the utility company's collected meter readings) has been inferred by analysing a four-year timeframe. Since all the four analysed buildings are provided with a central heating system powered by a thermal gas station, the assessment included heating gas bills, in addition to the electricity bills. During the energy modelling process, including its calibration and validation steps, boundary conditions, key assumptions, and climate-related factors were carefully considered. Energy demand and climate uncertainties were based on Energy Plus weather data for Palermo. Key assumptions included schedules and usage profiles inferred from on-site surveys, electrical power consumption (with average lighting power density ranging from 3 to 12 W/m^2, depending on the thermal zone under analysis, and equipment variability ranging from 2 to 12 W/m^2). Additionally, the average number of occupants per building (ranging from 2 to over 100 per thermal zone, depending on usage and occupancy profiles) and variations in infiltration rates (ranging from 0.2 to 0.7 air changes per hour) were taken into account to fine-tune the dynamic models.

3.2. Energy models' assessment, calibration and validation process

The calibration process involved iteratively adjusting all variables and parameters of uncertainty within a range of $\pm$ 30 %, aiming for a maximum deviation of $\pm$ 10% from the collected utility bills. For completeness, it should also be noted that when real data from surveys were unavailable, comparisons were made with official sources such as ASHRAE or current regulations.

The above-mentioned steps have been performed taking into account the primary educational purpose of the interior spaces considered. However, during the customization and calibration process, the areas allocated for laboratories, technical areas, administrative offices, and services were not overlooked.

The following table summarizes all the main energy models' features and assumptions, also illustrating, for the baseline assessed scenario, the different envelope characteristics, the respective properties and the related thermophysical parameters.

The following Figs. 3 and 4 provide some views of two of the of the most representative buildings analysed and modelled (respectively Building 6 and Building 9).

3.3. Renovation and renewable energy systems scenarios

After having finalised all such steps, necessary to configure the

Table 1
Energy Models main settings and key-parameters.

BUILDING'S OPAQUE ENVELOPE		**TOTAL THICKNESS [m]**	**ESTIMATED U-VALUE [W/(m^2 K)]**
Exterior walls (from outside/exterior layer, up to inside/interior layer)	Tuff Stone (high density and porosity local stone, with a decent level of thermal and acoustic performances) Exterior cement plastering Internally plastered and finished by a cladding paint	0.36	1.4
Ground floors (from outside/exterior layer, up to inside/interior layer)	Top-finishing flooring in grit tiles Cement screed Stones/rock pebbles	0.27	2.4
Interior floors	Concrete and masonry slabs, plastered and with a top-finished flooring in grit tiles	0.34	2.1
Interior ceilings	Concrete and masonry slabs, plastered and finished by a cladding paint	0.34	2.1
Flat roof and exterior top-level characteristics	Concrete and masonry slabs, plastered and finished by a tiled floor	0.36	2.0
BUILDING'S TRANSPARENT ENVELOPE (GLAZING AND FRAMING FEATURES)		**LAYERS STRUCTURE [mm]**	
Exterior windows	Glazing: double pane, clear glass, air-filled. Frame and dividers: aluminium frame without thermal break	12–10–12	
THERMAL ZONES DEFINITION, FEATURES, AND USER'S PROFILE (with respective OCCUPANCY RATE, ENERGY LOADS, INTERNAL GAINS and ACTIVITY LEVELS estimated, settled and adjusted accordingly to People behaviours, Electric Equipment, Lighting and other Appliances user rates)		Approx. 100 Thermal Zones (distinguished and classified in Offices, Laboratories, Classrooms, Restrooms, Stairs and Elevators, Unconditioned Spaces and Other Zones)	

Fig. 3. Building 6 picture and, below, a view of the energy model created with SketchUp 3D Modelling Software (integrated by the Euclid-NREL Energy Plus Plugin).

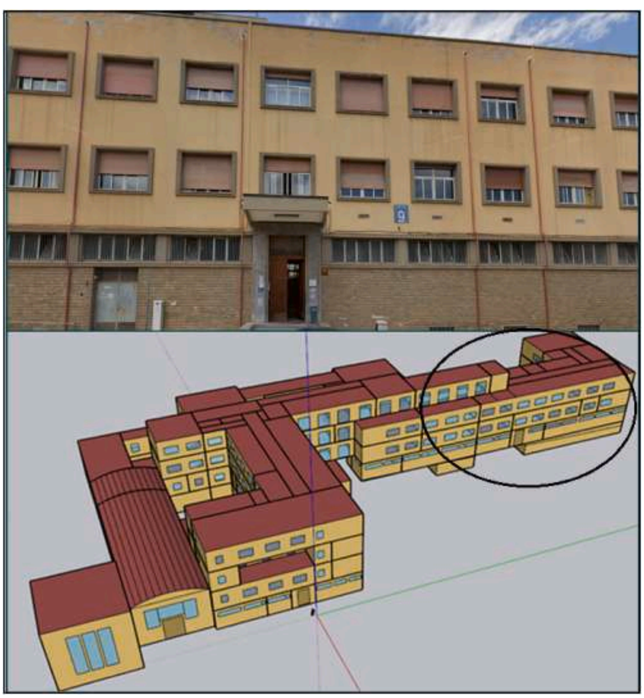


Fig. 4. Building 9 picture and, below, a view of the energy model created with SketchUp 3D Modelling Software (integrated by the Euclid-NREL Energy Plus Plugin).

effective state-of-the art of the district, and useful to define all the possible retrofit solutions for the case studies, several different renovation scenarios (also involving the renewable energy systems implementation) were defined, finalized and assessed.

The renovations introduced involved opaque and transparent building envelope enhancement, lighting systems' replacement with more efficient ones, heating and air conditioning systems thermostat settings' optimization, heating and cooling systems replacement and, finally, also the integration and implementation of renewable energy systems (namely roof-mounted photovoltaic panels).

Below are reported, for all the four buildings analysed, the above introduced detailed scenarios key-features:

- Scenario 1: thermal insulation of the building envelope with the application of an exterior layer of rock wool (and its respective anchoring substructure) for a total thickness of 0.180 m; below are specified the estimated U-values for the building envelope components (in the order exterior walls/roof):

- Building 6: 0.175/0.182 W/(m^2 K).
- Building 7: 0.172/0.188 W/(m^2 K).
- Building 8 and 9: 0.172/0.183 W/(m^2 K).

- Scenario 2: thermal insulation of the building envelope with the application of an exterior layer of cork (and its respective anchoring substructure), for a total thickness of 0.195 m; the U-values estimated for the Scenario 2 are as follows:

- Building 6: 0.175/0.182 W/(m^2 K).
- Building 7, 8 and 9: 0.172/0.183 (W/m^2 K).

- Scenario 3: existing windows replacement with new fenestration systems characterized by low-e selective double glazing, with air gap, along with thermal break aluminium frames. For Building 6, a window with a 3–13–3 mm glazing layers structure is proposed, characterized by an estimated U-value of 1.216 W/(m^2·K) and an SHGC (Solar Heat Gain Coefficient) of 0.315. Conversely, for Buildings 7, 8, and 9, the renovation suggested provided for windows with a 4–12–4 mm glazing layers structure, distinguished by an estimated U-value of 1.227 W/(m^2·K), and an SHGC of 0.314.

- Scenario 4: replacement of existing lights with high-efficiency LED lighting systems.

- Scenario 5: optimization of heating and air conditioning systems through thermostat settings pre-set at 20 °C and 26 °C for heating and cooling, respectively.

- **Scenario 6:** replacement and upgrade of the existing HVAC systems with more efficient solutions fully powered by electricity. In this regard, Table 2 provides a detailed overview of the proposed HVAC system upgrades for each building, allowing for a comparison, in terms of performance and efficiency, between the baseline scenario and scenario 6.

- **Scenario 7:** as a further solution for completing the retrofit actions to be involved in the district's renovation, a photovoltaic system's implementation has also been integrated for all the buildings of interest.

- **Scenario 8:** implementation and combination of the most effective energy renovation actions of above, after having tested ad assessed them separately.

According to the assessment of their energy generation potential (carried out through on-site surveys, climatic data and available buildings' roofing surface estimation, as well as through PV-systems simulations), the estimation following reported has been formulated.

Table 3 provides a view of the layout for roof-mounted PV-systems, as well as details about the assumed PV power potential.

3.4. Life cycle assessment and environmental study

With regard to the above-mentioned energy retrofit scenarios, Life Cycle Assessment evaluations were performed, also drawing respective environmental analysis considerations: indeed, all the energy retrofits introduced, modelled and analysed were also assessed in terms of environmental impact and ecological footprint.

The environmental assessment presented in this paper was developed in full accordance with the ISO 14040:2006 and ISO 14044:2021 standards, ensuring that the analysis is consistent with the best practices and internationally recognized methodologies for life cycle assessment.

In terms of system boundaries, the study applied a "from cradle to gate" approach considering the environmental impacts associated with

Table 2
Comparison between HVAC systems renovation proposals in Scenario 6 and in Baseline Scenario.

BUILDING	BASELINE SCENARIO					SCENARIO 6		
	Heating System	η	COP	Cooling System	EER	HVAC System	COP	EER
Building 6	Natural gas boilers with fan coils and radiators as terminal units	0.906	-	Autonomous split units	2.850	Reversible hydronic heat pumps	3.340	3.340
Building 7	Natural gas boilers with fan coils as terminal units	0.828	-	Hydronic chillers with fan coils as terminal units	5.050	Reversible hydronic heat pumps	3.280	3.260
	Autonomous split units	-	2.950	Autonomous split units	2.850	Unchanged		
Building 8	Natural gas boilers with radiators as terminal units	0.975	-	Autonomous split units	2.850	Reversible hydronic heat pumps	3.240	3.220
	Rooftop system powered by reversible heat pumps	-	2.850	Rooftop system powered by reversible heat pumps	2.750			
Building 9	Natural gas boilers with radiators as terminal units	0.918	-	Autonomous split units	2.850	Reversible hydronic heat pumps	3.280	3.260
						Variable Refrigerant Flow System	4.500	3.620

the earlier stages of the life cycle, including the extraction of raw materials, the production processes, and transportation.

These phases are, indeed, considered crucial for a comprehensive life cycle assessment, as they contribute to the overall environmental burden of the buildings' renovation process.

All the input data (primary data) were processed using dedicated spreadsheets, working documents, and specific assessments worked out through calculation tools: they were specifically designed to quantify the environmental impacts associated with the renovation materials used in the study (Cusenza et al., 2022).

Each material and component was modelled using environmental datasets (secondary data) extracted from the Ecoinvent Database (Ecoinvent 3.6 dataset; Frischknecht et al., 2007; Wernet et al., 2016). Subsequently, these were processed and evaluated using the SimaPro LCA software (SimaPro, PRé Sustainability).

In particular, the pollutants emissions – both direct and indirect – were calculated by applying a life cycle perspective to all the different renovation materials and renewable energy solutions incorporated into the buildings' retrofit project. The goal was to compute the respective carbon footprints and environmental impacts for each of these materials and energy systems.

This methodology ensures that the environmental assessment considers the entire life cycle of the products, from their production and transformation to their use and implementation in buildings.

To ensure a consistent and reliable evaluation, a series of assumptions was made regarding the useful life of the materials and systems. Specifically, a useful life of 10 years was assumed for the lighting systems, while the value of 30 years was assumed for photovoltaic panels and 15 years for insulation materials, heating and air conditioning system enhancements and fenestrations renovation (Guarino et al., 2020). These assumptions were supported by key values derived from the Ecoinvent 3.6 dataset (Frischknecht et al., 2007; Wernet et al., 2016), providing a solid foundation for the environmental analysis. The assumptions regarding the useful life of each material and system actually constitute a crucial aspect in evaluating their long-term environmental impacts (Cellura et al., 2017a,b).

In detail, the embodied energy and emissions (expressed in terms of environmental impacts) have been calculated as expressed by the following Eq. (1):

$$E_{i,j} = \quad q_i * EF_{i,j} \tag{1}$$

Where:

$E_{i,j}$ is the environmental impact of the i-esim renovation material/technology implemented (with -i that varies from 1 to m);

q_i is the quantity (mass, volume, area, lengths etc.) of the i-esim renovation material/technology implemented;

$EF_{i,j}$ is the specific environmental impact for the -jesim impact category (with -j that varies from 1 to n, being n the number of impact categories considered, and in this case n = 9, i.e. global warming potential, acidification, eutrophication, photochemical oxidation, abiotic depletion elements, abiotic depletion fossil fuels, water scarcity, ozone layer depletion and cumulative energy demand).

The data collection process was comprehensive, including all relevant environmental records and ecological burdens. These records cover a wide range of factors, such as raw material supply, transportation, production processes (for building materials and related components). Consequently, these environmental data are directly related to the renovation choices made, as they reflect the impacts of the specific materials and solutions adopted throughout the study.

3.5. Road to PED - PED assessment

As a consequence of the above-mentioned remarks, all the renovation scenarios analysed and assessed were evaluated in a Positive Energy District perspective, also discussing whether the achieved results are matching with PED targets or not.

In this regard, and in the light of the Positive Energy District key-definition and features adopted in the present study, the PED balance assessment was performed by considering all the energy uses that take place within the district's case study buildings and involving the energy exchanges through the grid due to the on-site generation.

For the current research's goals were therefore taken into account the on-site energy consumption and the energy produced by the buildings' rooftop integrated photovoltaic systems.

The assessment was performed on a yearly basis, according to the following Eq. (2):

$$B = \sum_{j=1}^{n} G_j - \quad \sum_{j=1}^{n} C_j \tag{2}$$

Where:

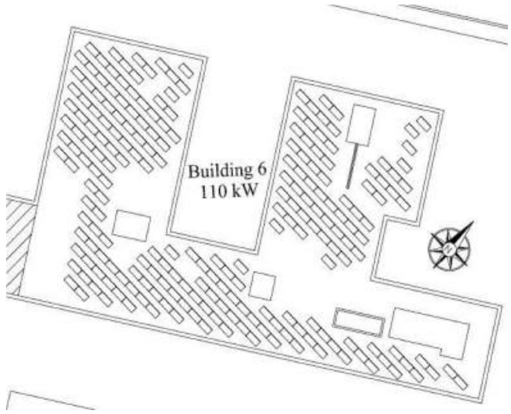
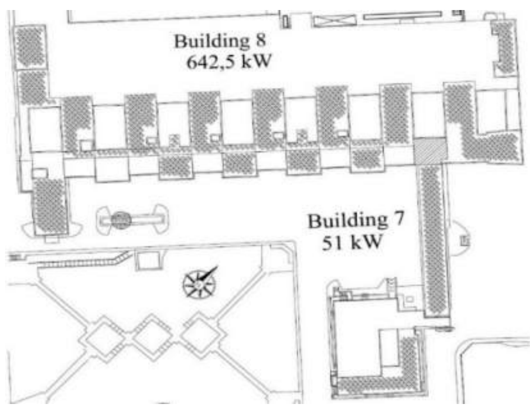
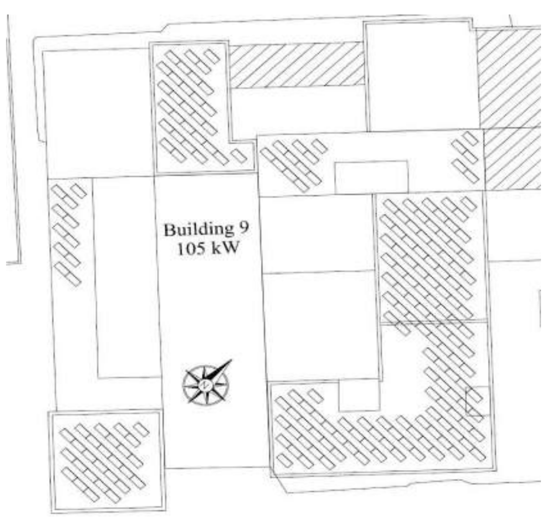
- B is the yearly district energy balance calculated as the difference between:

- G_j that is calculated as the annual energy generated by rooftop integrated photovoltaic panels, therefore with j ranging from 1 to 8.760 (this last number being the total number of hours accounted for a generic year). Although generally computed for primary energy, as the final renovated district is only using electricity as energy carrier this balance is presented as computed with final energy.

- C_j that is calculated as the annual energy consumed within the district (therefore with j ranging from 1 to 8.760).

It is noteworthy that the fundamental assumption here adopted is based on the energy connection among all the considered buildings: they are all conceived as connected to each other, involving their capability of exchanging energy flows (in terms of electricity) according to a peer-to-peer mutual linkage. All the potential energy generation surpluses produced by a single district's building are therefore firstly intended to cover other buildings' energy shortfalls, being finally transferred to the

Table 3
Scenario 7 - PV systems potential energy production for all the assessed buildings.

BUILDING	PV PANELS INSTALLATION TENTATIVE LAYOUT	INSTALLED PV POWER [kW_P]
BUILDING 6		110
BUILDING 7 **BUILDING 8**		51 642.50
BUILDING 9		105

grid only after the entire district's energy needs are satisfied.

The overall interactivity between generation and loads is characterized by the fact that all excess energy generated is sent to the power grid, while any required energy that is not covered by the generation potential of other district buildings is imported from the grid.

Considering the above remarks, the PED target can be reached as long as the final calculated balance is positive (i.e. if $B>0$).

For the goal of the present study, aimed at performing a concurrent PED assessment, not only based on the verification of the clause expressed by (3) - and therefore merely related to the comparison (on a yearly base) between the total primary energy consumed by the renovated district and the energy generated through roof-mounted photovoltaic panels – an additional evaluation criteria has been introduced (linked to an environmental assessment).

In this regard, an additional parameter has been included in the "road to PED assessment", by also computing the annualized embodied carbon contributions due to all the renovation actions implemented in the full renovated scenario (Scenario 8).

Thus, the PED reference criterion, expressed by Eq. (2) - has been linked to an extended verifying condition, formulated as follows:

$$B' = \sum_{j=1}^{n} EbI_j - \sum_{j=1,\ k=1}^{n,\ m} ErI_{j,k} \tag{3}$$

Actually, the Eq. (3) introduces a supplementary "PED-assessment-step" performed by calculating (and comparing) the annualized embodied impact for the baseline scenario and the one associated to the Scenario 8 (that combines and implements all the different renovation actions previously selected) and verifying that the embodied contribution due to the sum of all the retrofit actions does not exceed the one associated to the baseline scenario.

More in details, in Eq. (3):

- B' is the yearly district environmental balance yearly accounted within the district, calculated as the difference between:

- EbI_j is the annualized contribution due to the general environmental indicator related to the *baseline* scenario and calculated for all the environmental impact categories j (ranging from *1* to n, with n equal to 9, i.e. consisting in global warming potential, acidification, eutrophication, photochemical oxidation, abiotic depletion elements, abiotic depletion fossil fuels, water scarcity, ozone layer depletion and cumulative energy demand) correlated with energy use during the use stage.
- $ErI_{j,k}$ is the contribution due to the general environmental indicator related to the different renovation scenarios (thus with k ranging from *1* to m, being m equal to the total number of assessed retrofit scenarios) and calculated for all the environmental impact categories j (ranging from *1* to n, with n equal to 9, i.e. consisting in global warming potential, acidification, eutrophication, photochemical oxidation, abiotic depletion elements, abiotic depletion fossil fuels, water scarcity, ozone layer depletion and cumulative energy demand) caused by residual energy use during the use stage and the renovation actions (annualized).

In the light of the above remarks, the PED "extended target" can be reached as long as the final calculated balance is positive (i.e. if $B'>0$).

Consequently, the verification described by Eq. (3) can be expressed as follows:

$$\sum_{j=1}^{n} EbI_j - \sum_{j=1}^{n} ErI_j > 0 \quad (4)$$

The "road to PED assessment" here proposed therefore suggests not only to consider in the overall evaluation the PED requirement provided by (3), but also to verify that the balance expressed by (4) is positive.

4. Results

4.1. Existing buildings assessment

The assessment of the existing buildings was carried out through the analysis of the historical energy bills collected, referring to the four-year timeframe considered.

Based on such data, an annual trend was defined on a monthly basis, representative of their actual configuration's consumption: certain peculiarities emerged from the assessment, characterizing the district under examination (and discussed further in this article).

The reference trends of monthly energy consumption were traced back by using data directly retrieved from the energy bills (namely, natural gas – methane – and electricity). These generally show a slight degree of fluctuation, ascribable to the activities' distribution carried out within the buildings and influenced by their specific user profiles.

The registered patterns match with the typical university buildings' use, also being sensibly influenced by seasonal trends: a sensible electricity use increase during the summer season - driven by the rise of energy demand from cooling systems (all electrically powered) - is conversely followed - during the colder months - by a reasonable growth of methane consumption (that powers thermal plants in heating systems).

In this regard, the data related to the energy demand from natural gas were inferred from the analysis of methane gas bills: since they report all the consumption values in gas cubic meter units, it was necessary to perform an appropriate conversion by multiplying the aforementioned data by the lower heating value of methane gas (assumed as equal to 9.94 kWh/m^3).

As almost all the buildings meet their heating demand through systems powered by natural gas boilers (as stated above), the gas energy demand trend derived from methane invoices reflects the typical monthly pattern of space heating requirements for the various buildings.

The following tables (Table 4 and Table 5) detail the annual trend on a monthly basis for the data associated with all four analysed buildings, as well as for the district as a whole, also reflecting the higher cooling and heating demand of major buildings.

Obviously, the table associated to natural gas energy demand (Table 5) is only validated for the heating season (i.e., for the current case study, for the months of January, February, March, and December).

The following bar chart (of Fig. 5) reports, in a graphically aggregated way, all the data provided by the aforementioned tables, therefore allowing for a more consistent and impactful visualization of the overall district's consumption trends.

4.2. Model calibration and validation

The validation of all the performed energy models was carried out through a progressive calibration process aimed at satisfying the key-reference condition of the maximum deviation accounting in ±10% between the monthly data calculated from the models and those ones derived from the bills. All the assessed data obviously involve all the electricity demand and the thermal demand from methane.

The data from the energy models are obtained through dynamic simulations - hourly based - in Energy Plus environment; while the data related to electricity demand include, respectively, the demand for lighting, electrical equipment and air conditioning.

In particular, the electricity demand for air conditioning systems was calculated with reference to the ideal heating and cooling loads associated to the energy thermal zones served by electrically powered systems (also considering that, some thermal zones belonging to Building 7, are served by electrical heat pumps): appropriate evaluations were therefore performed also taking into account the efficiency indicators of all the different systems, in accordance with Table 2.

The monthly demand due to thermal energy from natural gas has been obtained by considering only the ideal heating loads for thermal zones equipped with systems powered by methane boilers.

The tables below (Tables 6, 7 and Table 8) report the calibration results for each single building - and for the district as a whole - also showing (for each month) the discrepancy between billing values and energy model data: they therefore allow for the verification of compliance with the maximum deviation value of ± 10 % between the monthly data inferred from the models and those derived from the bills.

As can be observed from the aforementioned tables, the minimum deviation value (in absolute terms, is associated to the data connected to the natural gas energy demand for the Building 8 (i.e. with an average deviation of 0.49 %), while the maximum one occurs for the energy demand from methane associated to Building 9 (with an average value of 8.52 %).

Consequently, all the other mean deviation values here assessed lie (as above shown) within the range defined by these two values.

The following figures (Fig. 6 and Fig. 7) display instead the calibration results for the entire district, also highlighting how, from an overall perspective, the monthly discrepancies here registered - compared to the ones derived from the individual buildings' validation assessment - are reduced.

4.3. District's renovation

The results obtained from the simulation of the district of interest and associated to all the different renovation actions here assumed are

Table 4
Monthly electricity demand from bills for the four buildings (considered separately) and for the district.

Electricity demand [kWh]					
Month	**BUILDING 6**	**BUILDING 7**	**BUILDING 8**	**BUILDING 9**	**DISTRICT**
January	57,876.00	38,128.25	86,626.00	44,308.03	226,938.28
February	50,508.00	40,964.00	83,514.45	39,998.88	214,985.33
March	37,946.00	38,310.75	78,728.75	39,873.41	194,858.91
April	28,404.00	30,314.25	58,100.25	31,835.09	148,653.59
May	33,200.00	35,628.75	60,278.33	35,572.36	164,679.44
June	38,300.00	46,213.33	95,529.33	47,115.26	227,157.92
July	51,234.00	57,373.06	101,706.47	37,612.04	247,925.57
August	37,738.00	37,439.27	65,060.51	33,856.02	174,093.80
September	52,594.00	44,626.75	78,744.58	43,119.14	219,084.47
October	46,210.00	43,081.49	81,455.04	40,532.84	211,279.37
November	42,945.00	36,551.85	73,994.57	36,612.00	190,103.42
December	44,885.00	36,854.81	79,589.13	39,575.88	200,904.82

Table 5
Monthly natural gas energy demand from bills for the four buildings (considered separately) and for the district.

Natural gas energy demand [kWh]					
Month	**BUILDING 6**	**BUILDING 7**	**BUILDING 8**	**BUILDING 9**	**DISTRICT**
January	76,389.84	52,791.82	203,260.51	96,382.52	428,824.69
February	93,440.25	35,082.82	208,293.10	102,800.65	439,616.83
March	103,663.65	30,265.51	143,787.69	69,347.79	347,064.65
December	67,502.15	25,222.78	140,718.60	57,714.45	291,157.98

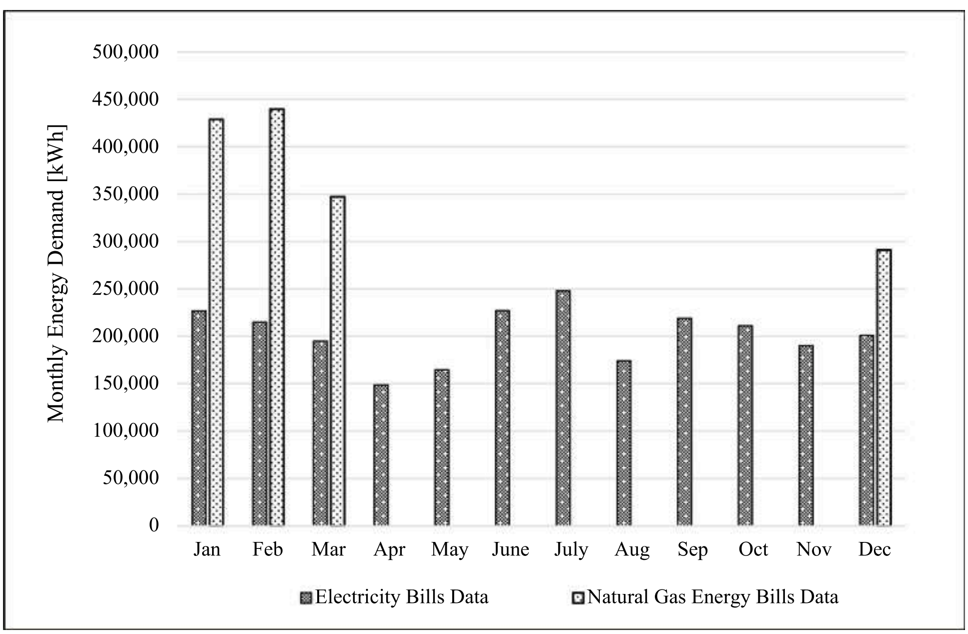


Fig. 5. Monthly electricity and natural gas energy demand from bills for the district.

summarized as follows, according to what introduced in paragraph *3.3 (Renovation and renewable energy systems scenarios)*.

The results derived from the analysis of any individual retrofit scenario are also compared, on a monthly basis, with the state-of-the-art reference values (i.e. to the baseline scenario) in order to appraise, in percentage terms, to what extent the effects of individual interventions are able to influence the base-case thermophysical performances, also impacting on potential energy consumption trends. The findings related to the Scenario 1 (presented in the Table 9 of below) show a reduction of the electricity demand, particularly during the summer season: it is associated to the improvement of buildings' envelope thermal performances, which actually allows for a cooling loads' decrease, thus leading to lower electrical energy values from cooling systems. The demand's reduction is even more significant when dealing with natural gas needs, reflecting the greater effects of the current renovation on the overall buildings' heating loads.

For the Scenario 2, as expected, the results show a reduction in energy demand quite close to the one obtained for the Scenario 1 (see the following Table 10). This is due to the fact that both the scenarios involve the same type of intervention (namely thermal insulation of external walls and roof, but with two different insulating materials) with resulting transmittance values very similar for Scenario 1 and Scenario 2.

Dealing with Scenario 3, the effects on the overall energy demand (summarized by Table 11) are less pronounced compared to the previous ones. A slight increase of the natural gas heating demand can be noted,

Table 6
Calibration results for electricity demand of energy models for the four buildings.

Electricity demand [kWh]												
MONTH	**BUILDING 6**			**BUILDING 7**			**BUILDING 8**			**BUILDING 9**		
	Energy Model	**Bills**	**Deviation**	**Energy Model**	**Bills**	**Deviation**	**Energy Model**	**Bills**	**Deviation**	**Energy Model**	**Bills**	**Deviation**
January	62,460.15	57,876	**7.92 %**	37,863.82	38,128.25	**−0.69 %**	82,041.86	86,626.00	**−5.29 %**	42,971.38	44,308.03	**−3.02 %**
February	54,240.20	50,508	**7.39 %**	37,230.42	40,964.00	**−9.11 %**	77,604.15	83,514.45	**−7.08 %**	42,321.35	39,998.88	**5.81 %**
March	36,582.15	37,946	**−3.59 %**	41,470.47	38,310.75	**8.25 %**	82,712.78	78,728.75	**5.06 %**	42,329.88	39,873.41	**6.16 %**
April	26,655.83	28,404	**−6.15 %**	31,638.17	30,314.25	**4.37 %**	52,562.40	58,100.25	**−9.53 %**	31,561.86	31,835.09	**−0.86 %**
May	33,206.92	33,200	**0.02 %**	37,995.21	35,628.75	**6.64 %**	61,614.70	60,278.33	**2.22 %**	36,563.57	35,572.36	**2.79 %**
June	35,521.03	38,300	**−7.26 %**	46,666.69	46,213.33	**0.98 %**	89,345.14	95,529.33	**−6.47 %**	51,619.85	47,115.26	**9.56 %**
July	47,677.38	51,234	**−6.94 %**	51,844.11	57,373.06	**−9.64 %**	101,016.14	101,706.47	**−0.68 %**	33,875.02	37,612.04	**−9.94 %**
August	34,718.12	37,738	**−8.00 %**	33,926.41	37,439.27	**−9.38 %**	66,474.62	65,060.51	**2.17 %**	34,345.65	33,856.02	**1.45 %**
September	55,623.54	52,594	**5.76 %**	41,263.34	44,626.75	**−7.54 %**	78,999.86	78,744.58	**0.32 %**	42,151.90	43,119.14	**−2.24 %**
October	48,051.76	46,210	**3.99 %**	39,529.20	43,081.49	**−8.25 %**	78,754.75	81,455.04	**−3.32 %**	40,236.35	40,532.84	**−0.73 %**
November	46,236.84	42,945	**7.67 %**	35,739.98	36,551.85	**−2.22 %**	76,974.55	73,994.57	**4.03 %**	39,444.77	36,612.00	**7.74 %**
December	45,828.44	44,885	**2.10 %**	35,928.25	36,854.81	**−2.51 %**	73,612.02	79,589.13	**−7.51 %**	41,158.54	39,575.88	**4.00 %**

Table 7
Calibration results for natural gas energy demand of energy models for the four buildings.

Natural Gas Energy demand [kWh]												
MONTH	**BUILDING 6**			**BUILDING 7**			**BUILDING 8**			**BUILDING 9**		
	Energy Model	**Bills**	**Deviation**	**Energy Model**	**Bills**	**Deviation**	**Energy Model**	**Bills**	**Deviation**	**Energy Model**	**Bills**	**Deviation**
January	75,498.53	76,389.84	**−1.17 %**	53,560.43	52,791.82	**1.46 %**	203,893.34	203,260.51	**0.31 %**	87,081.17	96,382.52	**−9.65 %**
February	98,002.74	93,440.25	**4.88 %**	36,771.32	35,082.82	**4.81 %**	209,663.18	208,293.10	**0.66 %**	92,686.19	102,800.65	**−9.84 %**
March	106,749.38	103,663.65	**2.98 %**	30,591.04	30,265.51	**1.08 %**	144,517.15	143,787.69	**0.51 %**	63,916.15	69,347.79	**−7.83 %**
December	68,277.57	67,502.15	**1.15 %**	23,683.12	25,222.78	**−6.10 %**	141,412.22	140,718.60	**0.49 %**	53,806.33	57,714.45	**−6.77 %**

Table 8
Calibration results for electricity and natural gas demand of energy models for the district.

DISTRICT	Electricity demand [kWh]			Natural gas energy demand [kWh]		
Month	**Energy model**	**Bills**	**Deviation [%]**	**Energy model**	**Bills**	**Deviation [%]**
January	225,337.21	226,938.28	**−0.71 %**	420,033.47	428,824.69	**−2.05 %**
February	211,396.13	214,985.33	**−1.67 %**	437,123.44	439,616.83	**−0.57 %**
March	203,095.28	194,858.91	**4.23 %**	345,773.72	347,064.65	**−0.37 %**
April	142,418.26	148,653.59	**−4.19 %**	-	-	-
May	169,380.39	164,679.44	**2.85 %**	-	-	-
June	223,152.72	227,157.92	**−1.76 %**	-	-	-
July	234,412.65	247,925.57	**−5.45 %**	-	-	-
August	169,464.81	174,093.80	**−2.66 %**	-	-	-
September	218,038.63	219,084.47	**−0.48 %**	-	-	-
October	206,572.05	211,279.37	**−2.23 %**	-	-	-
November	198,396.13	190,103.42	**4.36 %**	-	-	-
December	196,527.25	200,904.82	**−2.18 %**	287,179.24	291,157.98	**−1.37 %**

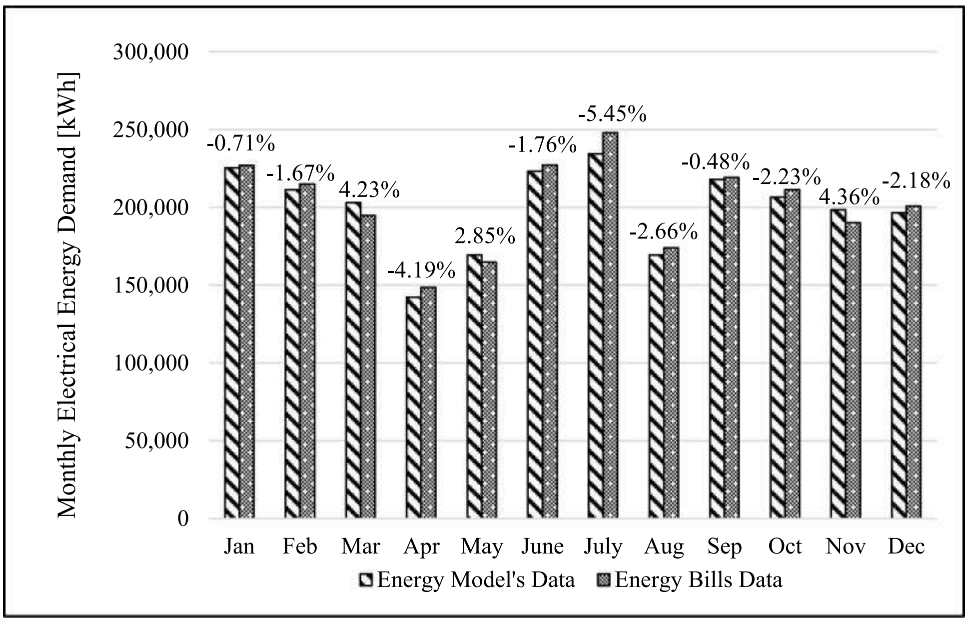


Fig. 6. Calibration results for electricity demand of the district.

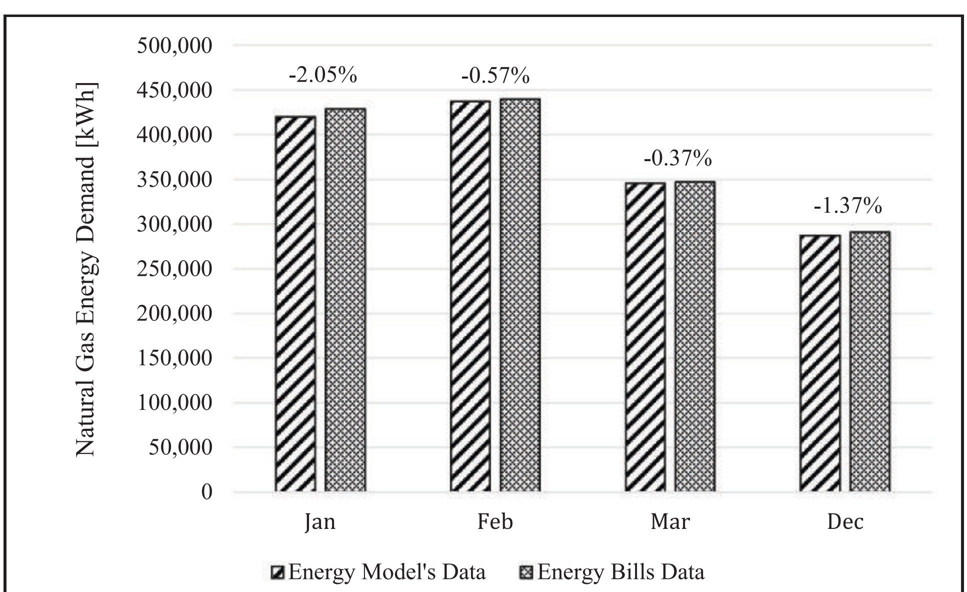


Fig. 7. Calibration results for natural gas energy demand of the district.

Table 9
Monthly electricity and natural gas energy demand for Scenario 1 compared to the Baseline Scenario.

Energy Demand [kWh]						
MONTH	**ELECTRICITY**			**NATURAL GAS**		
	Scenario 1	**Baseline**	**Deviation**	**Scenario 1**	**Baseline**	**Deviation**
January	225,126.93	225,337.73	**−0.09 %**	356,788.69	420,033.47	**−15.06 %**
February	211,165.98	211,396.88	**−0.11 %**	385,680.00	437,123.44	**−11.77 %**
March	202,956.08	203,090.09	**−0.07 %**	297,985.93	345,773.72	**−13.82 %**
April	142,424.79	142,424.79	**0 %**	0	0	**-**
May	168,741.86	169,389.78	**−0.38 %**	0	0	**-**
June	212,932.31	223,156.05	**−4.58 %**	0	0	**-**
July	217,668.64	234,400.77	**−7.14 %**	0	0	**-**
August	165,978.69	169,465.92	**−2.06 %**	0	0	**-**
September	215,238.84	218,035.42	**−1.28 %**	0	0	**-**
October	206,567.92	206,567.92	**0 %**	0	0	**-**
November	198,402.67	198,402.67	**0 %**	0	0	**-**
December	196,302.02	196,491.70	**−0.10 %**	236,953.47	287,179.24	**−17.49 %**
Total	**2363,506.71**	**2398,159.71**	**−1.44 %**	**1277,408.10**	**1490,109.87**	**−14.27 %**

Table 10
Monthly electricity and natural gas energy demand for the Scenario 2 compared to the Baseline Scenario.

Energy demand [kWh]						
MONTH	**ELECTRICITY**			**NATURAL GAS**		
	Scenario 2	**Baseline**	**Deviation**	**Scenario 2**	**Baseline**	**Deviation**
January	225,126.34	225,337.73	**−0.09 %**	356,086.24	420,033.47	**−15.22 %**
February	211,164.72	211,396.88	**−0.11 %**	384,602.61	437,123.44	**−12.02 %**
March	202,954.58	203,090.09	**−0.07 %**	296,259.33	345,773.72	**−14.32 %**
April	142,424.79	142,424.79	**0 %**	0	0	**-**
May	168,703.35	169,389.78	**−0.41 %**	0	0	**-**
June	212,763.45	223,156.05	**−4.66 %**	0	0	**-**
July	217,326.48	234,400.77	**−7.28 %**	0	0	**-**
August	165,936.24	169,465.92	**−2.08 %**	0	0	**-**
September	215,734.86	218,035.42	**−1.06 %**	0	0	**-**
October	206,567.92	206,567.92	**0 %**	0	0	**-**
November	198,402.67	198,402.67	**0 %**	0	0	**-**
December	196,300.74	196,491.70	**−0.10 %**	235,794.07	287,179.24	**−17.89 %**
Total	**2363,406.13**	**2398,159.71**	**−1.45 %**	**1272,742.26**	**1490,109.87**	**−14.59 %**

Table 11
Monthly electricity and natural gas energy demand for the Scenario 3 compared to the Baseline Scenario.

Energy demand [kWh]						
MONTH	**ELECTRICITY**			**NATURAL GAS**		
	Scenario 3	**Baseline**	**Deviation**	**Scenario 3**	**Baseline**	**Deviation**
January	225,371.27	225,337.73	**0.01 %**	424,169.88	420,033.47	**0.98 %**
February	211,448.06	211,396.88	**0.02 %**	444,048.24	437,123.44	**1.58 %**
March	203,128.51	203,090.09	**0.02 %**	356,762.34	345,773.72	**3.18 %**
April	146,331.43	142,424.79	**2.74 %**	0	0	**-**
May	171,403.61	169,389.78	**1.19 %**	0	0	**-**
June	215,228.04	223,156.05	**−3.55 %**	0	0	**-**
July	224,929.11	234,400.77	**−4.04 %**	0	0	**-**
August	166,787.81	169,465.92	**−1.58 %**	0	0	**-**
September	212,787.69	218,035.42	**−2.41 %**	0	0	**-**
October	203,496.30	206,567.92	**−1.49 %**	0	0	**-**
November	195,494.17	198,402.67	**−1.47 %**	0	0	**-**
December	192,837.16	196,491.70	**−1.86 %**	289,489.48	287,179.24	**0.80 %**
Total	**2369,243.16**	**2398,159.71**	**−1.21 %**	**1514,469.93**	**1490,109.87**	**1.63 %**

mainly due to a corresponding rise of heating loads derived from the adoption of windows with lower Solar Heat Gain Coefficient (SHGC) values. This aspect is thus able to counteract the beneficial effects connected to the new fenestration systems higher performances (namely consisting in lower U-values).

With reference to the Scenario 4, and by observing Table 12, it can be noted that the proposed lighting devices' replacement is able to produce significant results in terms of electricity demand reduction throughout the entire year. On the other side, it is responsible for an increase of natural gas demand, that is actually required for satisfying the higher heating loads due to the reduced lighting systems-related interior heat gains.

Scenario 5 leads to further significant results: as shown by the following Table 13, the optimization of systems' thermostat settings here proposed displays a sensible reduction of the electricity demand during the cooling period, accompanied by an even more marked decrease of natural gas demand during the heating season.

According to what proposed by Scenario 6, i.e. by switching the

Table 12
Monthly electricity and natural gas energy demand for the Scenario 4 compared to the Baseline Scenario.

Energy demand [kWh]						
MONTH	ELECTRICITY			NATURAL GAS		
	Scenario 4	Baseline	Deviation	Scenario 4	Baseline	Deviation
January	142,982.84	225,337.73	**−36.55 %**	449,124.37	420,033.47	**6.93 %**
February	135,717.68	211,396.88	**−35.80 %**	465,324.12	437,123.44	**6.45 %**
March	132,672.38	203,090.09	**−34.67 %**	372,834.70	345,773.72	**7.83 %**
April	95,611.92	142,424.79	**−32.87 %**	0	0	-
May	117,838.23	169,389.78	**−30.43 %**	0	0	-
June	156,971.11	223,156.05	**−29.66 %**	0	0	-
July	171,096.97	234,400.77	**−27.01 %**	0	0	-
August	113,796.74	169,465.92	**−32.85 %**	0	0	-
September	149,067.27	218,035.42	**−31.63 %**	0	0	-
October	131,271.40	206,567.92	**−36.45 %**	0	0	-
November	126,942.73	198,402.67	**−36.02 %**	0	0	-
December	123,564.33	196,491.70	**−37.11 %**	311,481.32	287,179.24	**8.46 %**
Total	**1597,533.59**	**2398,159.71**	**−33.39 %**	**1598,764.52**	**1490,109.87**	**7.29 %**

Table 13
Monthly electricity and natural gas energy demand for the Scenario 5 compared to the Baseline Scenario.

Energy demand [kWh]						
MONTH	ELECTRICITY			NATURAL GAS		
	Scenario 5	Baseline	Deviation	Scenario 5	Baseline	Deviation
January	225,026.96	225,337.73	**−0.14 %**	298,340.04	420,033.47	**−28.97 %**
February	211,096.58	211,396.88	**−0.14 %**	334,963.01	437,123.44	**−23.37 %**
March	202,930.73	203,090.09	**−0.08 %**	234,958.14	345,773.72	**−32.05 %**
April	142,424.79	142,424.79	**0 %**	0	0	-
May	160,571.86	169,389.78	**−5.21 %**	0	0	-
June	193,793.36	223,156.05	**−13.16 %**	0	0	-
July	203,535.95	234,400.77	**−13.17 %**	0	0	-
August	161,216.74	169,465.92	**−4.87 %**	0	0	-
September	192,636.07	218,035.42	**−11.65 %**	0	0	-
October	206,567.92	206,567.92	**0 %**	0	0	-
November	198,402.67	198,402.67	**0 %**	0	0	-
December	196,307.94	196,491.70	**−0.09 %**	192,374.11	287,179.24	**−33.01 %**
Total	**2294,511.56**	**2398,159.71**	**−4.32 %**	**1060,635.30**	**1490,109.87**	**−28.82 %**

existing heating and cooling systems to air conditioning systems exclusively electrically powered, an increase in the electricity demand during the winter months can be noted, with the concurrent elimination of natural gas energy loads (Table 14).

The integration of renewable energy systems at the district scale was also examined. Specifically, Scenario 7 proposed the implementation of roof-mounted photovoltaic panels on all available surfaces of the analysed buildings.

In this regard, Table 15 shows the trend of photovoltaic generation during the different months of the year, for all the single buildings and for the entire district, as well as the total yearly production.

In line with the objectives of this research, the investigation involves all the potential energy efficient improvements within the analysed district, also implementing a further "Full Renovation Scenario" (named as "Scenario 8"): it includes the integrated and combined solutions of building envelope insulation (from Scenario 2), the replacement of window elements (as outlined in the Scenario 3), the upgrading of lighting systems (Scenario 4), the optimization of thermostat management (as shown in the Scenario 5), and the complete electrification of heating and cooling systems (Scenario 6), in addition to the integration

Table 14
Monthly electricity and natural gas energy demand for the Scenario 6 compared to the Baseline Scenario.

Energy demand [kWh]						
MONTH	ELECTRICITY			NATURAL GAS		
	Scenario 6	Baseline	Deviation	Scenario 6	Baseline	Deviation
January	340,026.92	225,337.73	**50.90 %**	0	420,033.47	**−100.00 %**
February	330,738.42	211,396.88	**56.45 %**	0	437,123.44	**−100.00 %**
March	297,402.15	203,090.09	**46.44 %**	0	345,773.72	**−100.00 %**
April	142,496.91	142,424.79	**0.05 %**	0	0	-
May	169,742.87	169,389.78	**0.21 %**	0	0	-
June	221,285.45	223,156.05	**−0.84 %**	0	0	-
July	231,178.73	234,400.77	**−1.37 %**	0	0	-
August	169,472.92	169,465.92	**0.00 %**	0	0	-
September	215,836.77	218,035.42	**−1.01 %**	0	0	-
October	206,626.23	206,567.92	**0.03 %**	0	0	-
November	198,459.51	198,402.67	**0.03 %**	0	0	-
December	274,953.93	196,491.70	**39.93 %**	0	287,179.24	**−100.00 %**
Total	**2798,220.81**	**2398,159.71**	**16.68 %**	**0**	**1490,109.87**	**−100.00 %**

Table 15
Monthly and total annual generation from PV panels for individual buildings and for the entire district.

Scenario 7: PV Generation [kWh]					
MONTH	**BUILDING 6**	**BUILDING 7**	**BUILDING 8**	**BUILDING 9**	**DISTRICT**
January	7266.20	3368.87	42,441.21	6935.92	60,012.20
February	8874.45	4114.52	51,834.84	8471.06	73,294.87
March	13,577.79	6295.16	79,306.62	12,960.61	112,140.18
April	16,294.05	7554.51	95,172.07	15,553.41	134,574.04
May	19,173.78	8889.66	111,992.29	18,302.24	158,357.97
June	19,026.31	8821.29	111,130.95	18,161.48	157,140.03
July	20,047.57	9294.78	117,096.02	19,136.31	165,574.69
August	18,950.18	8785.99	110,686.27	18,088.81	156,511.24
September	15,041.04	6973.57	87,853.33	14,357.35	124,225.30
October	11,737.28	5441.83	68,556.37	11,203.76	96,939.24
November	8063.76	3738.65	47,099.67	7697.22	66,599.30
December	6348.52	2943.41	37,081.15	6059.95	52,433.03
Total	**164,400.91**	**76,222.24**	**960,250.78**	**156,928.14**	**1357,802.08**

of photovoltaic panels installed on building rooftops (renewable energy integration scenario).

The choice of adopting the Scenario 2 building envelope insulation solution (cork insulation) instead of the Scenario 1 (rock wool insulation) is connected to the aim of performing a study able to privilege the use of natural-based materials, also maximizing environmental sustainability and energy performances.

Table 16 illustrates how the expected energy overall consumption (still based on the dynamic simulation of the energy models), varies between the Scenario 8 and the baseline scenario. The results highlight a significant reduction in the electricity demand during the summer months, with a percentage decrease up to 48.50 % in June. Similarly, a global reduction in electricity demand is observed during the winter period, although it is less pronounced due to the electrification of the district's heating systems. Concurrently, the natural gas demand is entirely eliminated.

It is noteworthy that the monthly trend of electricity demand for the Scenario 8 in some cases is lower than total photovoltaic production (as per the outcomes ascribable to renewable generation systems integration). Indeed, from Fig. 8, it is possible to infer that photovoltaic generation is sometimes able to balance (in some cases also exceeding), the district's electricity demand, namely from April to September. Beside this aspect, the study also investigates the hourly coupling between generation and load.

Fig. 9 illustrates the district's electricity import and export patterns, highlighting the significant contrast between the autumn/winter and spring/summer periods.

4.4. *Life cycle assessment and environmental study*

As mentioned in paragraph *3.4 Life Cycle Assessment and environmental study*, the present research also involved the analysis, in a Life Cycle Assessment (LCA) perspective, of all the renovation solutions adopted: this in order to investigate the several retrofit actions here implemented, not only in terms of their energy performances, but also under an environmental and ecological perspective throughout the whole life cycle of the newly introduced products and services.

The analysis of the energy renovations environmental impact and their respective Life Cycle Assessment displays all the different environmental impact indicators comparison for all the discussed scenarios, by prioritizing the Scenario 8 outcomes and highlighting a relevant decrease for the Global Warming Potential contribution (almost halved compared to the Baseline Scenario), a slight difference (respectively a growth and a reduction) of the Acidification and of the Photochemical Oxidation impacts, while a consistent increase of Eutrophication effects is registered (as reported by Fig. 10).

All the environmental assessment results (also considering the other impacts illustrated in Fig. 11 and except the Ozone Layer Depletion impact) are primarily influenced by the adoption of the exterior cork insulation layer, while instead the most consistent contribution to the Ozone Layer Depletion can be ascribed to the thermal plants' replacement.

Notwithstanding, as demonstrated by Fig. 12, the Cumulative Energy Demand for the Scenario 8 has been reduced by more than half, also revealing significant results in terms of the amount of primary energy consumed during the entire life cycle of the retrofitted system boundaries.

The following Table 17 is able to summarize all the aforementioned

Table 16
Monthly electricity and natural gas energy demand for Scenario 8 compared to the baseline Scenario.

Energy demand [kWh]						
MONTH	**ELECTRICITY**			**NATURAL GAS**		
	Scenario 8	**Baseline**	**Deviation**	**Scenario 8**	**Baseline**	**Deviation**
January	221,005.73	225,337.73	**−1.92 %**	0	420,033.47	**−100.00 %**
February	227,119.43	211,396.88	**7.44 %**	0	437,123.44	**−100.00 %**
March	198,617.25	203,090.09	**−2.20 %**	0	345,773.72	**−100.00 %**
April	96,090.08	142,424.79	**−32.53 %**	0	0	-
May	107,517.20	169,389.78	**−36.53 %**	0	0	-
June	114,917.12	223,156.05	**−48.50 %**	0	0	-
July	127,791.46	234,400.77	**−45.48 %**	0	0	-
August	102,417.54	169,465.92	**−39.56 %**	0	0	-
September	123,121.93	218,035.42	**−43.53 %**	0	0	-
October	132,720.26	206,567.92	**−35.75 %**	0	0	-
November	128,317.50	198,402.67	**−35.32 %**	0	0	-
December	173,673.27	196,491.70	**−11.61 %**	0	287,179.24	**−100.00 %**
Total	**1753,308.77**	**2398,159.71**	**−26.89 %**	**0**	**1490,109.87**	**−100.00 %**

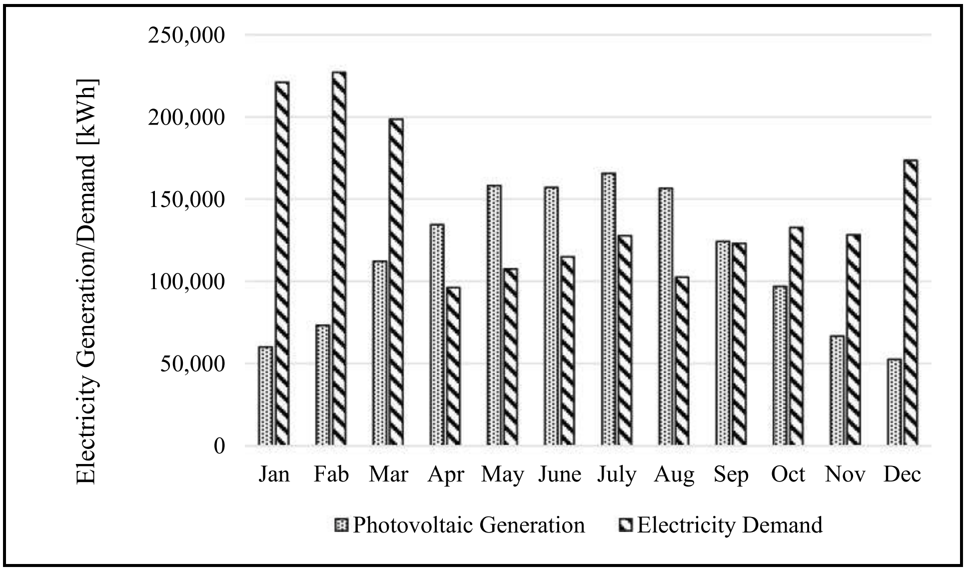


Fig. 8. Monthly photovoltaic generation, and electricity demand for the Scenario 8.

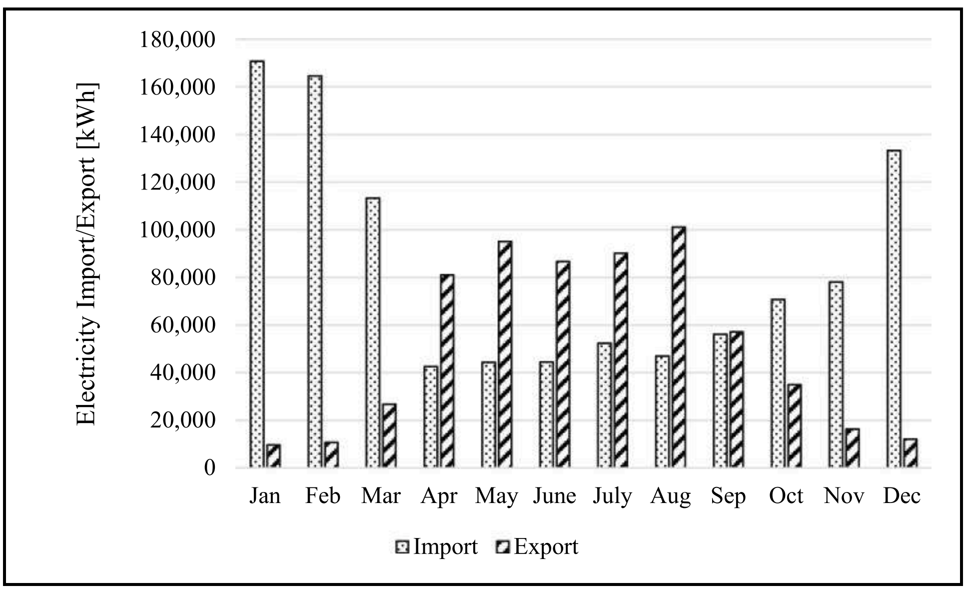


Fig. 9. Monthly electricity import, and export for the Scenario 8.

environmental performances associated to the different renovation scenarios analysed (also involving the outcomes due to the renewable energy generation framework, as well as considering the combined renovations scenario). This synoptical assessment actually provides a complete environmental results' overview, therefore enabling the formulation of consequent discussions.

4.5. Positive energy district balance and respective targets' achievement road to PED assessment

Through the Positive Energy District assessment and by evaluating whether the PED targets can be achieved or not by the Scenario 8, it is possible to infer (also looking at the Fig. 13b) that PED

standard requirements can be in some cases met with the reduction in cumulative energy demand combined with the use of renewable energy generation systems (namely photovoltaic panels).

However, from an environmental perspective, interesting outcomes are disclosed by assessing (on an annual basis and considered individually) all the environmental indicators, for any single energy renovation adopted (Fig. 14): in this regard, it is noteworthy the relevant Electricity import impact for all the different nine environmental factors here assessed, while instead – as previously anticipated – thermal plants renovation effects in regard to the Ozone layer depletion reveal their primary impact.

From the results shown by Fig. 15, that reports all the different environmental indicators, annualized and calculated on a percentage basis for the entirely renovated district - in a PED perspective as well and according to the Eq. (4) - a non-homogeneous variation and an un even fluctuation trend can be highlighted: in particular, with regards to the consistent Eutrophication impact, to the Abiotic depletion elements and with respect to the Ozone layer depletion, impact values more than doubled must be noted, while on the other side, the cumulative energy demand has been more than halved for the overall retrofitted configuration (and significant percentage reductions can be reported for the Global Warming Potential and the Abiotic depletion due to fossil fuels as well).

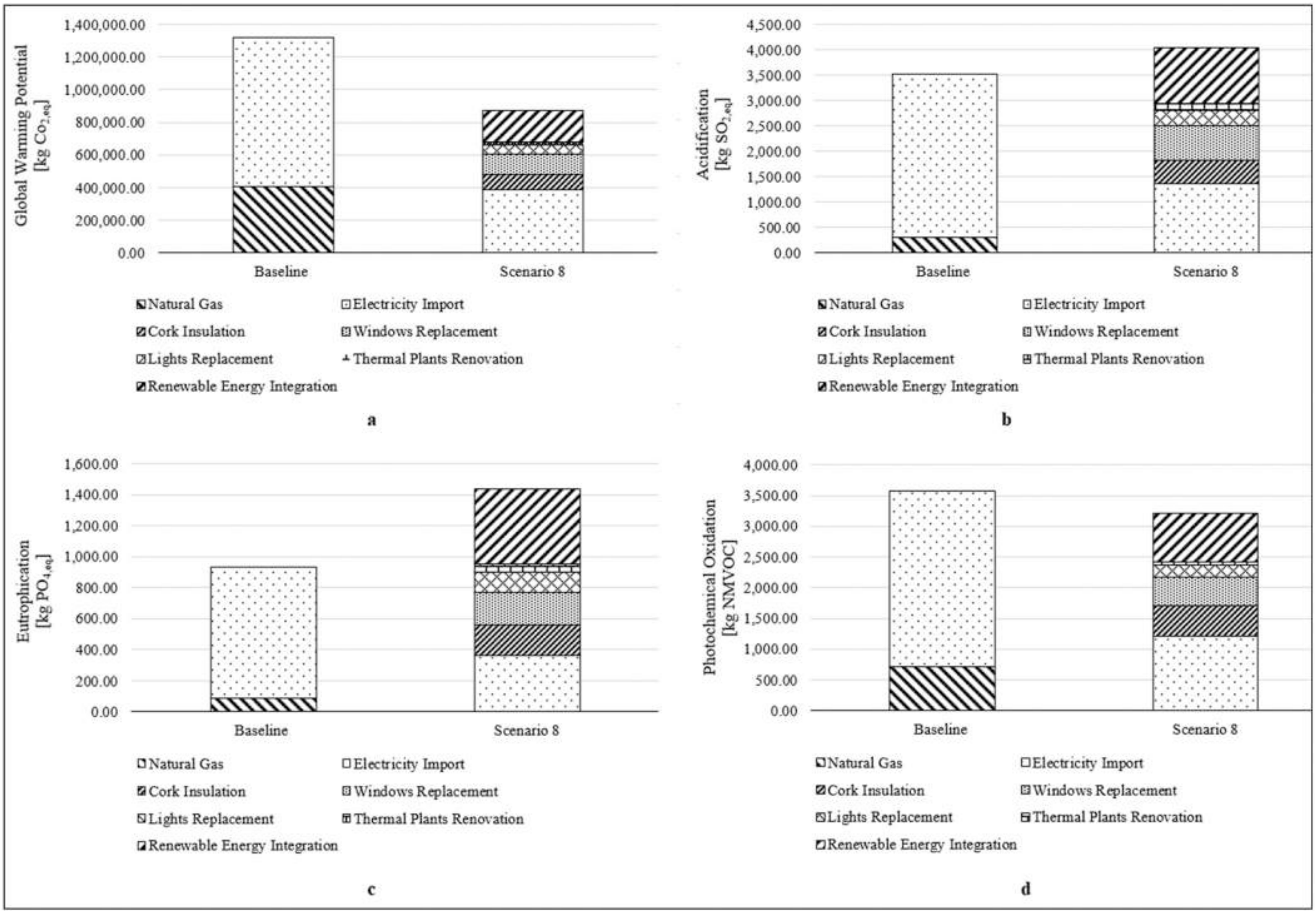


Fig. 10. Life Cycle Assessment. a Global Warming Potential: Baseline vs. Scenario 8 scenario. b Acidification: Baseline vs. Scenario 8. c Eutrophication: Baseline vs. Scenario 8. d Photochemical Oxidation: Baseline vs. Scenario 8.

4.6. Life cycle assessment and environmental study sensitivity analysis

An advanced evaluation has been introduced for the final Scenario 8, already assessed, by considering the hypothesis of slightly varying the useful lifetime and maintenance schedules of all the renovation actions. For this purpose, a sensitivity analysis has been performed to evaluate how the most significant environmental impacts change when different lifespans are assigned to the retrofit actions. More specifically, this variation has been applied by varying their useful life by $\pm$ 5 % and further extending the time window to a $\pm$ 50 % variation. The results of this analysis are illustrated in Figs. 16 and 17.

As it is possible to note by observing Figs. 16 and 17, an increase or decrease in the average lifetime assigned to all materials and systems life span (mentioned in paragraph 3.1.4), leads to a corresponding decrease or increase, respectively, in the associated environmental impacts. The differences in component durability can lead to significant variations in the results, potentially reducing annual impacts considerably. In some cases (e.g. water scarcity), this may even result in renovation performing better than the original baseline scenario, namely in the + 50 % case.

5. Discussion

In the light of all the results achieved for the case study of interest and focusing on the combined PED targets analysis and environmental LCA evaluation for a non-residential district considered as a representative for a southern Mediterranean university campus, the following remarks can be formulated.

With regards to the existing buildings assessment, its energy modelling and respective calibration and validation have been performed: a data collection (based on the historical energy bills ranging from year 2017 to 2023) highlighted a general periodical oscillation mainly due to the different buildings' energy profiles combined with a relevant natural gas demand for the colder months (namely in February) and electricity demand during the summer season (except August), ascribable to the intensive use, respectively, of heating and cooling systems. All the energy models performed for the analysed buildings were progressively calibrated and arranged in order to fall within the maximum deviation of $\pm$10% between the monthly data calculated for the models and those ones inferred from the energy bills.

The introduction and the assessment of all the different renovation scenarios were carried out in order to turn the existing district renovation into a higher energy performance levels configuration; in particular, by analysing the targeted changes assumed for each specific scenario, it is possible to infer the following considerations:

- For the first two scenarios (namely Scenario 1 and Scenario 2, whose main characteristics were, respectively the application of an external insulation layer of rock wool and cork) analogous results were achieved (resulting in a natural gas energy demand reduction, compared to the Baseline Scenario, during the colder season ranging between the 11.77 % for the month of February and for the Scenario 1 and the value of 17.89 % in December for the Scenario 2).
- Dealing with the third Scenario (associated to existing windows replacement with more efficient ones), less relevant results in terms of the overall energy demands reduction have been

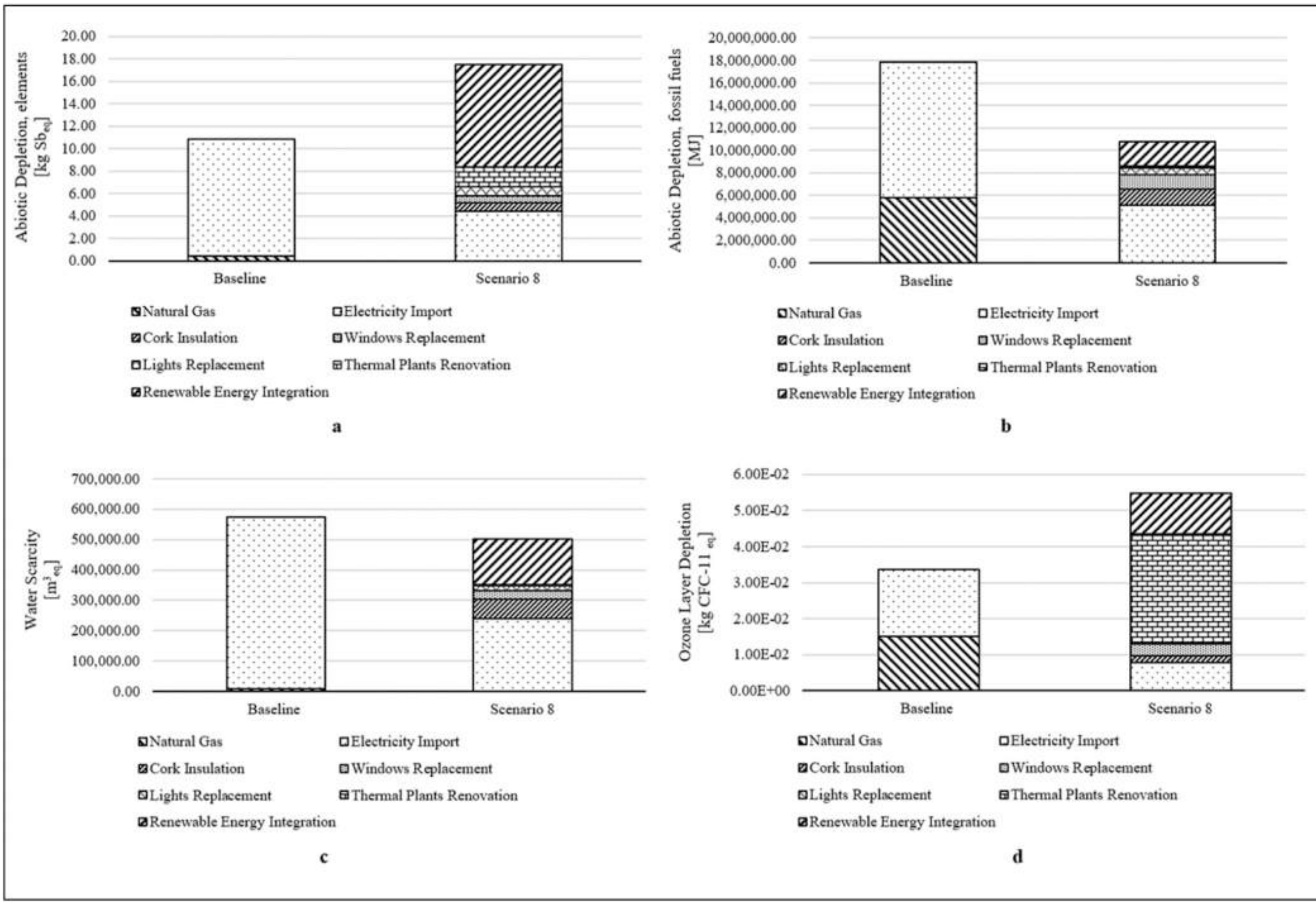


Fig. 11. Life Cycle Assessment. a Abiotic Depletion, elements: Baseline vs. Scenario 8. b Abiotic Depletion, fossil fuels: Baseline vs. Scenario 8. c Water Scarcity: Baseline vs. Full Scenario 8. d Ozone Layer Depletion: Baseline vs. Scenario 8.

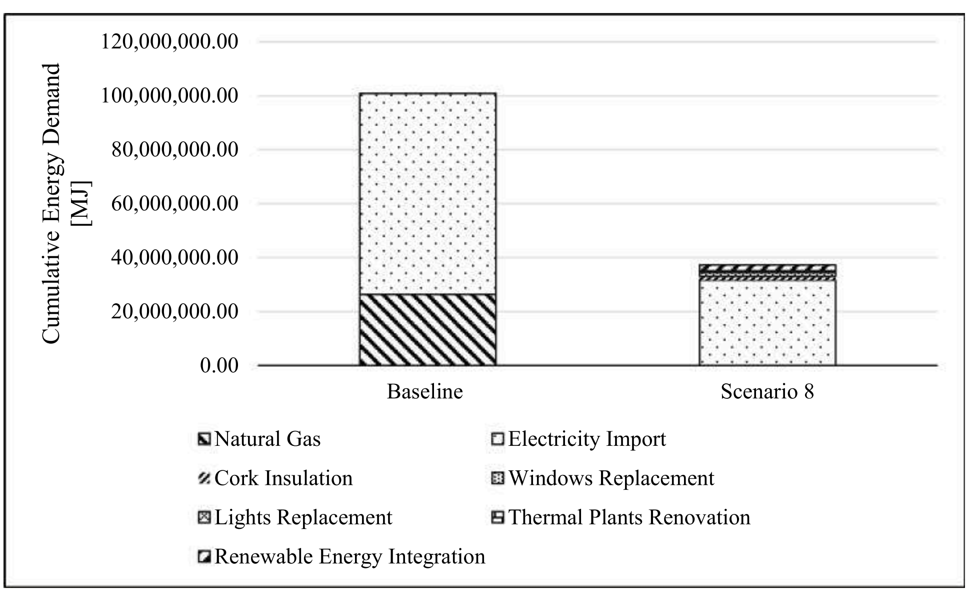


Fig. 12. Cumulative Energy Demand, Baseline vs. Scenario 8.

registered: in particular, a slight increase in the natural gas energy demand during the heating season (accounting in the maximum percentage of 3.18 % in March) can be noted in the colder season, while an electrical energy demand (for a maximum of 4.04 % in July) for cooling, is primarily ascribable to the lower Solar Heat Gain Coefficient associated to the new glazing systems.

- The lighting replacement laid out by the Scenario 4 resulted instead in a significant electricity demand reduction throughout the entire year (accounting for a maximum of

Table 17
Environmental impact indicators - scenarios comparison.

Impact Indicator	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Global Warming Potential [kg $CO_{2,eq}$]	1.32E+ 06	1.37E+ 06	1.34E+ 06	1.44E+ 06	1.10E+ 06	1.16E+ 06	1.08E+ 06	1.13E+ 06	8.73E+ 05
Acidification [kg $SO_{2,eq}$]	3.53E+ 03	4.21E+ 03	3.89E+ 03	4.19E+ 03	2.77E+ 03	3.31E+ 03	3.92E+ 03	3.28E+ 03	4.05E+ 03
Eutrophication [kg $PO_{4,eq}$]	9.33E+ 02	1.07E+ 03	1.11E+ 03	1.13E+ 03	7.88E+ 02	8.72E+ 02	1.04E+ 03	1.07E+ 03	1.44E+ 03
Photochemical oxidation [kg NMVOC]	3.57E+ 03	3.83E+ 03	3.93E+ 03	4.01E+ 03	2.86E+ 03	3.24E+ 03	3.39E+ 03	3.17E+ 03	3.21E+ 03
Abiotic depletion, elements [kg Sb_{eq}]	1.09E+ 01	1.13E+ 01	1.14E+ 01	1.13E+ 01	8.29E+ 00	1.03E+ 01	1.39E+ 01	1.56E+ 01	1.74E+ 01
Abiotic depletion, fossil fuels [MJ]	1.78E+ 07	1.81E+ 07	1.83E+ 07	1.90E+ 07	1.48E+ 07	1.56E+ 07	1.42E+ 07	1.50E+ 07	1.08E+ 07
Water scarcity [m^3_{eq}]	5.74E+ 05	5.94E+ 05	6.28E+ 05	5.95E+ 05	4.01E+ 05	5.47E+ 05	6.64E+ 05	4.87E+ 05	5.02E+ 05
Ozone layer depletion [kg CFC_{eq}]	3.36E−02	3.20E−02	3.29E−02	3.71E−02	2.88E−02	2.85E−02	5.18E−02	3.70E−02	5.47E−02
Cumulative Energy Demand [MJ]	1.01E+ 08	9.73E+ 07	9.73E+ 07	1.02E+ 08	7.85E+ 07	9.00E+ 07	8.70E+ 07	7.18E+ 07	3.73E+ 07

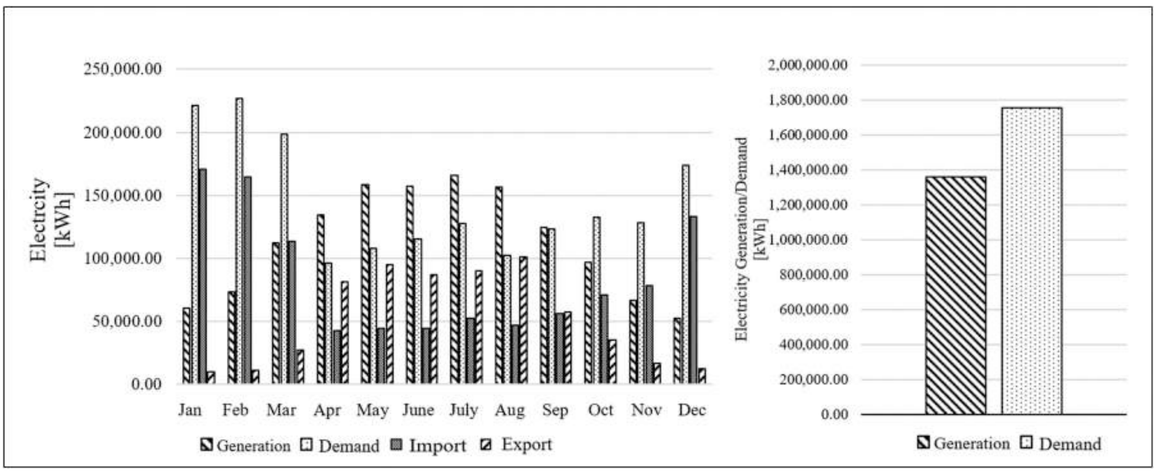


Fig. 13. PED balance assessment. a: Monthly trends of district-level photovoltaic generation, electricity demand, import and export. b: Yearly district-level photovoltaic generation and electricity demand.

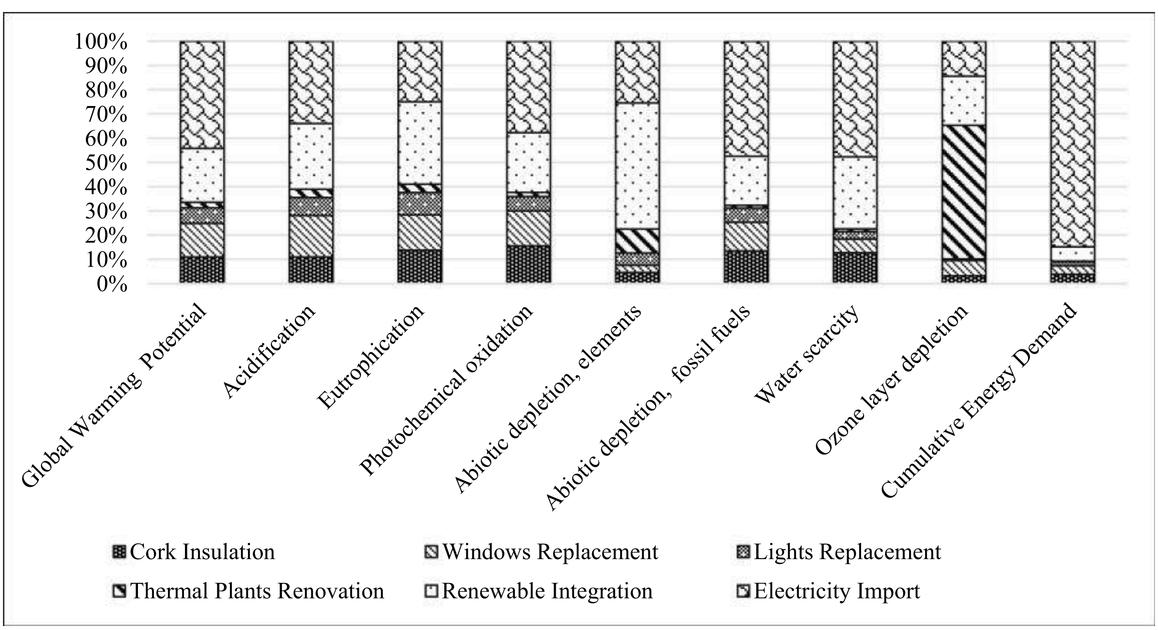


Fig. 14. PED balance assessment, Scenario 8, also involving all the environmental indicators analysed on an annual basis and for all the different energy renovations.

37.11 % in December), while the natural gas demand increasing registered for the winter season can be clearly related to the reduced interior heat gains due to the new lighting systems.

- The thermostat settings optimization devised by the fifth scenario reveal interesting results in terms of both electricity and natural gas demand during the entire year: in this case the maximum demand reduction registered accounts for 32.05 % of the natural gas heating demand in March. However, during the non-conditioning months, the demand deviation is significantly minimized, ultimately becoming negligible, or

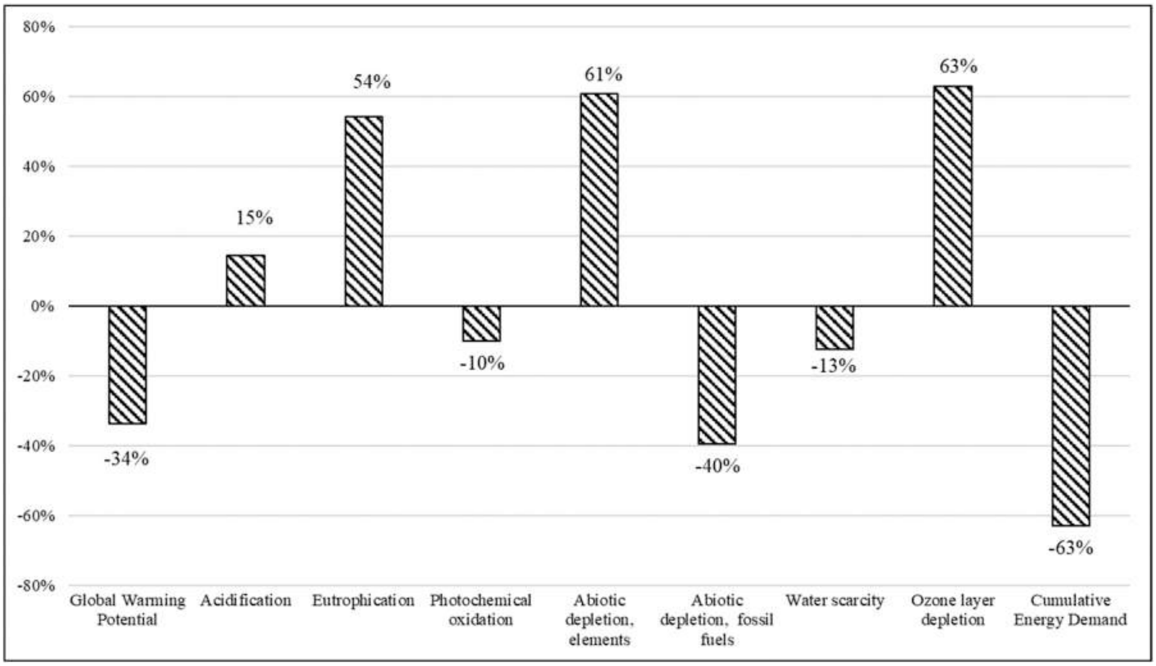


Fig. 15. further PED assessment. Scenario 8, with the analysis of the annualized environmental indicators percentage variation.

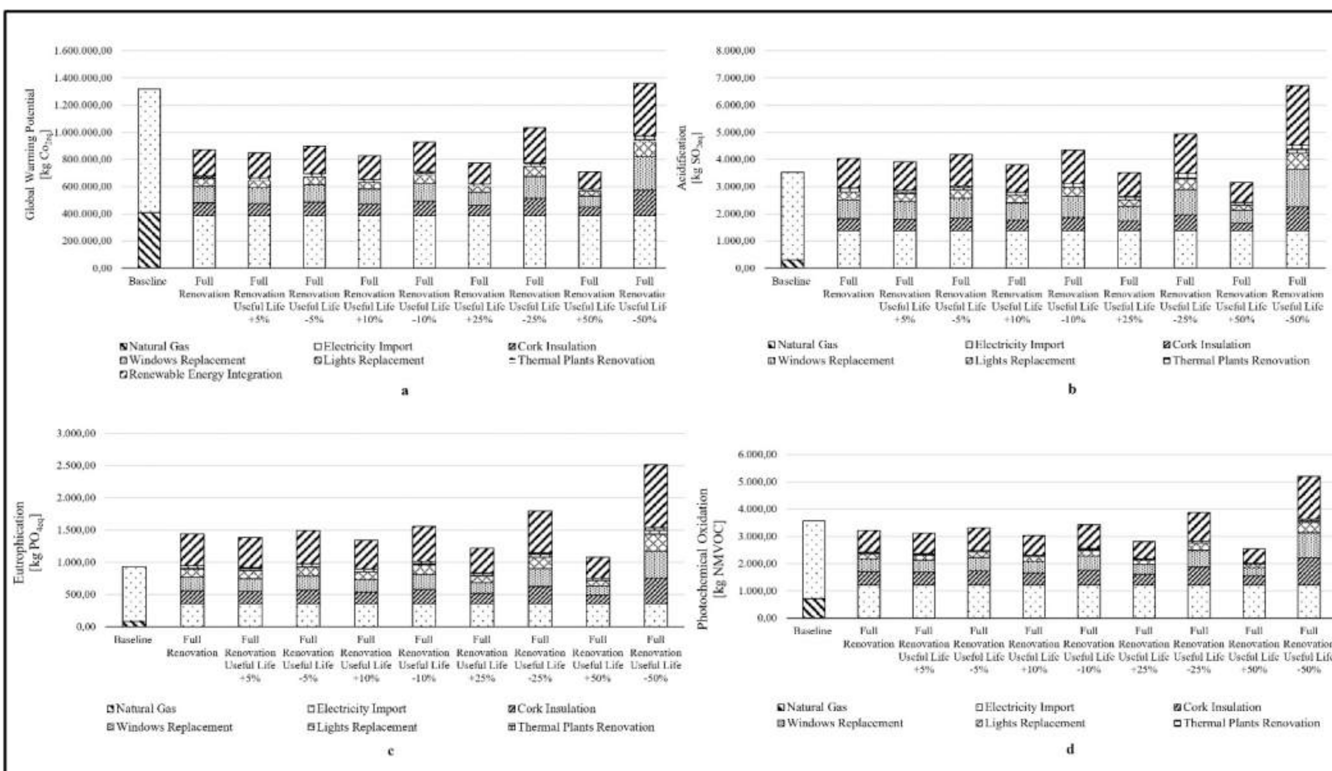


Fig. 16. Life Cycle Assessment - sensitivity analysis in terms of: a: Global Warming Potential. b: Acidification. c: Eutrophication. d: Photochemical Oxidation.

completely disappearing (dropped to 0 %) in April, October, and November.

- By analysing the sixth scenario, the effects of the overall heating and cooling systems replacement for the majority of the district's buildings (now only relying on electrically powered air conditioning systems), clearly led to the exclusion of natural gas demand and to a general, sensible increase of electricity demand (ranging between almost 40 % in December and 56.45 % in February) during the heating season. Notwithstanding, thanks to the adoption of centralised air conditioning systems and by removing the majority of autonomous cooling devices (namely single split units) a slight energy demand reduction can be registered during the cooling period.

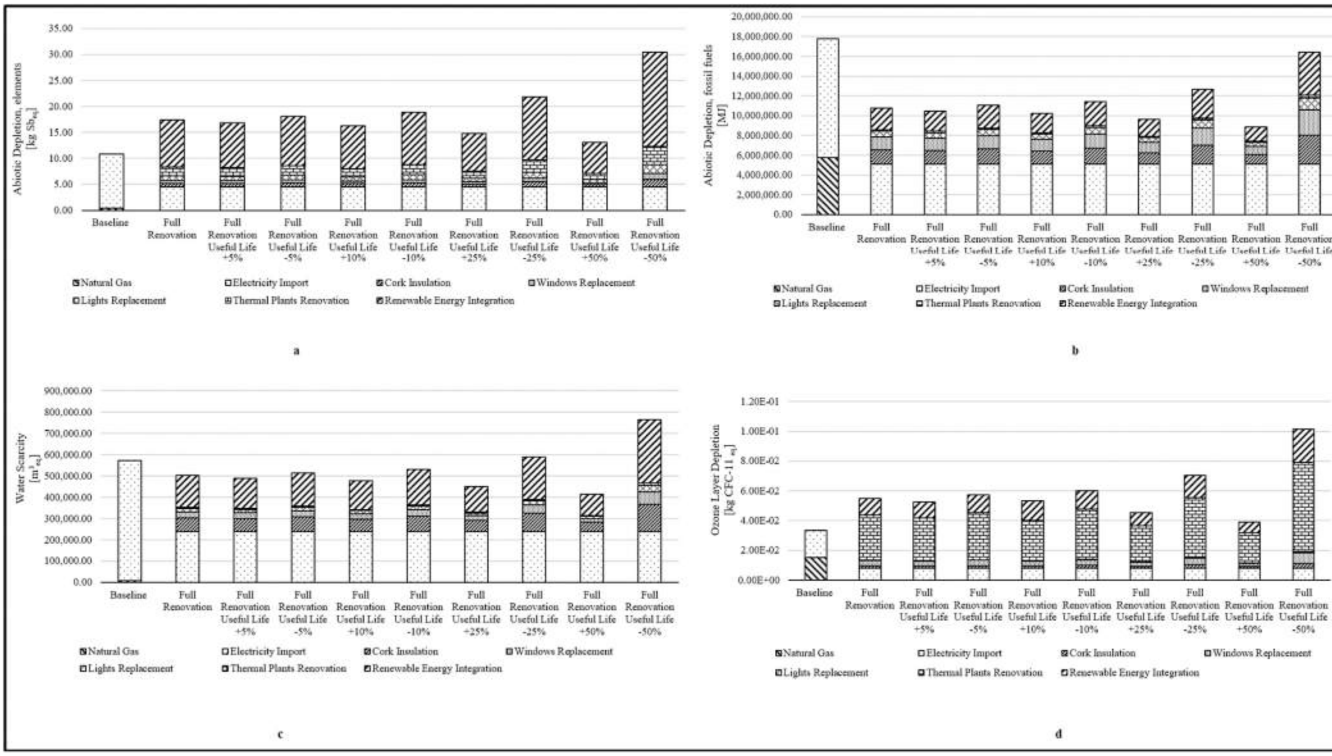


Fig. 17. Life Cycle Assessment - sensitivity analysis in terms of: a: Abiotic Depletion, elements. b: Abiotic Depletion, fossil fuels. c: Water Scarcity. d: Ozone Layer Depletion.

- Relevant results are associated to the different renewable energy generation values that summarize the effects due to roof-mounted photovoltaic panels for all the case-study buildings; as expected, the wider the roof surfaces available (and the larger the buildings), the more effective outcomes can be registered. Namely, for the largest Building 8 (where the total annual generation from PV panels amounts to 960,250.78 kWh (with a peak during the summer season, reaching 117,096.02 kWh in July), compared to Building 7 (the smallest one, with the lowest available roof surface, (which generates 76,222.24 kWh per year from PV).
- By combining all the more relevant renovation actions above-discussed, significant observations can be inferred from the overall results' summary: in particular, by analysing the energy consumption trend within the entire district on a monthly base, it is possible to highlight a relevant difference between the monthly electricity during the heating season (with lower energy reduction values ranging between 1.92 % in January and 11.61 % in December and even an increase of demand in e 7.44 % during February) compared to the consistent energy production during the cooling season (characterized by a significant sun radiation) with the subsequent availability of exportable energy from the whole district.

  Results about the PED assessment and Life Cycle Assessment of the integrated design choices highlight also significant results:
- Differentiating climate neutral districts and positive energy districts is not mere semantics. Results in Fig. 15 for Global Warming Potential and Cumulative Energy demand vary from −34 % to −63 %. Significantly different results are also found when approaching the remaining indicators with very high variability from −63 % for CED to + 63 % for the ozone layer depletion. This strengthens the need for a careful choice of the metric of the balances as a core aspect of the PED definition.
- According to the sensitivity analysis presented in paragraph 4.6, an incremental variation ranging from ± 5 % to ± 50 % in the useful lifetime of energy retrofit actions resulted in corresponding changes across all impact categories. Specifically, for all renovation actions, the variations ranged from a reduction of 4.76 % to an increase of 5.26 % (with a ± 5 % variation) and from a decrease of 33.33 % to an increase of 100 % (with a ± 50 % variation), meaning that in the latter case, the values doubled compared to the original ones.
- For some of the indicators proposed, not renovating is actually the solution preferrable. This clearly highlights the need for careful eco-design of the materials and systems being used in the renovation (i.e., HVAC systems in the case of ozone depletion layer, insulation materials in the case of abiotic depletion) to be able to encompass a wide spectrum of environmental impacts, otherwise limiting largely the scope of the sustainability approach.
- Achieving a strict mathematical energy balance is challenging and, in some cases, actually impossible, especially in high-rise buildings neighbourhoods. Referring to the less challenging definition of "Virtual" PED is easier but not fully achievable in all contexts. It is arguable that a sequential approach should be followed in general, by maximizing all available potential for energy efficiency and renewable energy planning on – site and then recourse to the virtual option.
- Multidisciplinarity and holistic approaches are required when dealing with PEDs and in general with complex systems where approaching complexity with simple solutions is not always the most appropriate choice.
- Based on the outcomes of this research and in line with the key findings from analogous non-residential case studies, the following key remarks can be highlighted:

– Defining and establishing a consistent, systematic, and widely applicable retrofit strategy for an urban district is particularly complex, given its multifaceted nature in terms of user profiles, construction features, materials, systems, equipment, and internal articulation.

– This challenge becomes even more difficult when considering the environmental burdens and ecological impacts associated with building renovations.
– The goal of concurrently meeting PED targets adds an additional layer of complexity, especially when striving to develop a renovation strategy that is both adaptable and broadly applicable across a diverse range of contexts, each one characterized by its own distinct factors, including climate peculiarities too.
– Nevertheless, as demonstrated by the final results of this study, it is still possible to outline a valid and consistent framework that enables professionals and involved stakeholders to compare results and make informed decisions across different retrofit actions.
– This could set the groundwork for sharing best practices and strategies, promoting replicability and preventing misleading conclusions from environmental outcomes, while also setting realistic and achievable goals for reaching PED targets.

6. Conclusion

The paper has investigated the potential for renovating an existing typical university district in southern Italy, towards potentially meeting a Positive Energy target within a one-year timespan.

The results obtained through this study show that a significant reduction in energy demand can be achieved by implementing a set of effective retrofit measures. Specifically, the district's buildings underwent several improvements, including opaque envelope insulation (with rock wool), window replacement, relamping interventions, heating and air conditioning system enhancements, and the optimization of thermostat settings. These measures were combined with the installation of renewable energy generation systems, specifically roof-mounted photovoltaic panels.

Thanks to these actions, the renovated district recorded a monthly overall energy demand decrease ranging from 1.92 % to 48.50 % for electricity, while natural gas demand was entirely eliminated. The renovation led to a moderate increase in electricity consumption (up to 7.44 %) only in February.

However, this can be attributed to the shift from natural gas-powered heating systems to electrical heat pumps introduced in the post-retrofit district configuration.

Positive Energy Districts and solutions for sustainable urbanization need to shift from the typical fragmented approach and limited perspective and be oriented more towards a holistic view which takes in consideration the whole life cycle of the buildings and including a wider angle and perspective.

It is crucial to emphasize that, while focusing on energy efficiency and renewable energy solutions is essential, these factors alone are not enough. A comprehensive approach also requires attention to the Product Environmental Footprint (PEF), product declarations (EPD), and the full life cycle of the buildings and their components.

Thus, further solutions must be considered, such as expanding PV areas, applying more effective measures, and optimizing energy-efficient renovations, all within a life cycle approach. This will help ensure that the district reaches Positive Energy District (PED) targets while considering long-term sustainability.

Through a complete electrification of the district, large applications of energy efficient solutions and a wide deployment of renewable energy systems, the generation is able to cover up to around 80 % of the overall energy consumption of the district.

In this perspective, it is worth mentioning that this is a result that can be extended to large areas of the built environment in the Mediterranean area for similar buildings, thus not meeting the strict mathematical PED clause as defined. It must be also highlighted that the definition of PED needs to be expanded from a mere mathematical computation and properly formulated by adapting and calibrating its peculiar features and distinguishing characteristics according to different boundary conditions, urban restrictions, and specific area requirements. Having high buildings performances and pushing decarbonization is actually the core aim of the PED concept: thus, having higher flexibility in its definition could be beneficial for PEDs diffusion.

Also from the environmental perspective, and by investigating the most relevant impacts due to ecological footprint, a consistent embodied impacts variation must be highlighted.

All the different results illustrated and discussed in this study (also considering all the main assumptions formulated and adopted throughout the entire research and its outcomes' assessment) lead to the main consideration that Positive Energy Districts must be conceived (and analysed as such) as a complex, structured, and multifaceted system: they go beyond the simple building level (considered as an isolated building, without any interaction with neighbourhoods) and require a deeper analysis and evaluation, also involving a conscious and adequate assessment in environmental terms, as well as towards social and urban impacts in a broader perspective.

The shift to Positive Energy Districts is becoming pivotal for sustainable urban development, driven by the need to decarbonize cities and neighbourhoods with different features, energy and social requirements.

Achieving this goal requires innovative technologies, integrated policies and forward-thinking strategies to reduce greenhouse gas emissions and create more live able and resilient urban environments.

PEDs are gaining increasing recognition, yet defining and tailoring replicable and flexible methodologies, along with fostering collaborative and proactive learning, remains pivotal to supporting the effective adoption of targeted policies, able to suit different contexts and boundary conditions.

As future work's tasks, the analysis herein discussed will be progressively fine-tuned and gradually extended to broader contexts, up to wider application scales: this process can be actually useful to define and assess a customised concept of PEDs for selected pilot areas in the city of Palermo, also helping to formulate fruitful guidelines that can be applied to similar contexts within the Mediterranean area. Sustainability analyses will also be integrated in order to consider the articulated aspects mentioned in the PED definition, with a focus on the possibility of achieving an actual positive energy balance and a reasonable concurrent environmental embodied carbon burden within the geographical boundaries of the specific district case-study.

CRediT authorship contribution statement

Ilardi Lorenzo: Writing – review & editing, Visualization, Software, Data curation. **Panno Domenico:** Writing – review & editing, Visualization. **Di Pilla Lorenza:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation. **Cellura Maurizio:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Franzitta Vincenzo:** Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Guarino Francesco:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Longo Sonia:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Curto Domenico:** Writing – review & editing, Resources, Data curation, Conceptualization.

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.

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Data availability

Data will be made available on request.

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