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Research Paper

A simplified tool for early-stage planning of positive energy districts

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ABSTRACT

The challenges of climate change and energy poverty necessitate innovative solutions for sustainable urban development. This study introduces TREEPED (Tool for Resource and Environmental Evaluation for Positive Energy Districts), a simplified framework designed to support the early-stage planning of Positive Energy Districts (PEDs) within existing urban areas. TREEPED integrates energy performance analysis with environmental impact assessment, utilizing an archetype-based approach evaluating urban energy performances of newly built areas or renovations of existing ones from an integrated energy-environmental perspective. TREEPED was tested in the social housing neighborhood of San Pedro in Pamplona (Spain), where buildings share homogeneous characteristics. By developing and calibrating representative archetypes, multiple retrofit strategies were assessed to lower energy demand and greenhouse gas emissions, including insulation enhancements, window replacements, transitioning from gas boilers to heat pumps and integrating photovoltaic systems with battery storage. In the renovated scenario, heating demand fell by 17 %, cooling demand decreased by 84 % and electricity consumption rose by 43 %. Although rooftop photovoltaics alone were insufficient to meet PED objectives, integrating a nearby photovoltaic system enabled the district to surpass PED requirements by 0.67 GWh and achieve a positive annual energy balance. Life cycle assessment demonstrated a 60 % reduction in Global Warming Potential and a 69 % decrease in Cumulative Energy Demand. A comparative analysis with the City Energy Analyst tool confirmed TREEPED's consistency. The deviations observed were as follows: −8 % for heating demand, −12 % for cooling demand and 1 % for electricity consumption. These findings highlight the importance of integrative strategies for advancing sustainable urban transformation.

1. Introduction

The year 2023 marked the warmest year on record since global temperature data collection began in 1850, with average temperatures soaring 1.48°C above pre-industrial levels of 1850–1900 (Copernicus, 2023). This alarming rise underscores the significant role cities play in global warming, as they account for 67–72 % of total global emissions (Shukla et al., 2022).

Climate change not only affects the environment but also directly impacts human comfort levels. Alterations in humidity and temperature demand increased energy consumption to maintain comfortable living conditions (Tahir and Al-Ghamdi, 2023). This increased energy requirement exacerbates energy poverty—the inability to access modern energy services. In 2022, 40 million Europeans, representing 9.3 % of the European Union's population, struggled to keep their homes adequately warm. This situation highlights the intersection of energy poverty with the environmental and social challenges posed by climate change (Simson, 2023).

Addressing these complex issues necessitates a comprehensive approach that considers the multifaceted relationship between climate change, urban carbon emissions, energy poverty and other user-related issues. The data underscores an urgent need for policies and actions that not only mitigate the impacts of climate change but also ensure equitable access to energy resources, particularly for vulnerable populations.

In response to these multifaceted challenges, the European Union has instituted the Energy Performance of Buildings Directive (EPBD), a legislative framework aimed at fully decarbonised building stock by 2050 s. The EPBD seeks to not only enhance the energy efficiency of buildings but also to pave the way for the adoption of nearly zero-energy buildings (nZEBs) across the EU. By setting rigorous standards for

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energy performance and mandating the issuance of energy performance certificates, the EPBD represents a cornerstone in the EU's strategy to mitigate climate change impacts, promote sustainable energy use and address energy poverty head-on (European Union, 2024).

In this context, the development of new Positive energy districts emerges as an innovative approach to address the multifaceted challenges of urban sustainability, climate change and energy equity. By reimagining how energy is produced, consumed and managed at the district level, PEDs aim to reduce greenhouse gas emissions and enhance the resilience of cities. They establish a framework for achieving energy efficiency, integrating renewable energy sources and balancing local energy generation with consumption.

Moreover, PEDs promote the development of interconnected and adaptable energy systems that facilitate regional cooperation and respond to fluctuating energy demands. Their role extends beyond technological advancements; PEDs offer an opportunity to create urban environments that are not only energy-efficient but also inclusive, equitable, and aligned with long-term sustainability objectives. By incorporating environmental, social and economic considerations, they contribute to broader strategies to mitigate climate change and drive sustainable urban transformation. According to the most common definition from JPI, 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 information and communication technology (ICT) systems, while securing the energy supply and a good life for all in line with social, economic, and environmental sustainability" (Urban Europe-Positive Energy Districts PED, 2025). This definition highlights how PEDs represent an integrated approach to urban energy. In this context, the synergy between the EPBD and PEDs not only amplifies efforts toward energy efficiency and carbon emissions reduction but also contributes to a sustainable, resilient and equitable urban development model. However, the implementation of PEDs faces various challenges that must be acknowledged for effective planning and execution. These challenges stem from technical, financial, regulatory and social dimensions, each impacting the feasibility and success of PED projects. Recognizing and addressing these obstacles is fundamental to realizing the full potential of PEDs.

The ambition to establish 100 PEDs by 2025 (Urban, 2018) underscores a significant commitment toward scaling up energy-efficient and carbon-neutral urban planning solutions. In this context, focusing on transforming social housing into PEDs becomes particularly important.

Realizing this ambitious vision presents significant challenges, particularly in the early design phases. Decisions at this stage must carefully balance energy efficiency, environmental sustainability and practical feasibility, often with limited data and resources.

In this context, the role of analytical tools becomes critical. Urban Building Energy Models (UBEMs) support the assessment and planning of PEDs by enabling the evaluation of energy performance, environmental impacts and the integration of renewable energy systems at the district scale.

1.1. State of the art

UBEMs are tools designed to analyze and simulate the energy consumption and performance of buildings within urban districts or entire cities. UBEM methodologies fall into two main categories: top-down and bottom-up (Swan and Ugursal, 2009). Each approach employs distinct methodologies, data requirements and applications offering unique advantages and facing specific challenges.

Top-down approaches depend on aggregated city-level (Kavgic et al., 2010),This kind of approach link energy use to broader socio-economic, technical and physical factors, enabling the analysis of long-term trends and the development of high-level energy scenarios. Top-down models can be subdivided as follows:

1. Socio-Econometric Models (van Vuuren et al., 2009);
2. Technical Models (Huo et al., 2019);
3. Physical Models (Kavgic et al., 2010).

These approaches excel at identifying macro-scale energy patterns, informing policy measures and supporting long-term strategic planning. However, they lack fine-grained temporal and spatial detail and they are less suitable for technical assessments requiring hourly simulations (Lim and Zhai, 2017). This limitation in granularity renders top-down methods inadequate during phases where precise building-level data and highly resolved energy profiles are essential, such as the early design stages of a project.

Bottom-up approaches work at the level of individual buildings, then aggregate the results to represent entire districts and can be further divided into physics-based and data-driven.

Physics-based models rely on fundamental principles of heat transfer, thermodynamics and building physics. They come in two primary forms:

- o Resistor-Capacitor (RC) Models: These simplify building thermal dynamics into equivalent electrical circuits. Tools such as City energy analyst (CEA) (Fonseca et al., 2016), CityBES (König et al., 2016), SimStadt ("SimStadt.", 2024) and TEASER (Remmen et al., 2018) implement RC methodologies. They integrate geospatial data, building typologies and climate information, providing scenario testing, retrofit potential identification and support for strategic energy planning. Recent versions have also introduced semi-automated workflows and standardized input formats, enhancing accessibility for planners and decision-makers. For instance, CEA supports early-stage PED planning by evaluating energy performance and environmental impacts with limited initial data. However, RC models trade some accuracy for speed and computational efficiency (Hong et al., 2020).
- o Multizone Models: These involve detailed building simulations (e.g., EnergyPlus (U.S, 2020) TRNSYS (Univ. of W.-M. Solar Energy Laboratory, 2018), DOE-2 (L. J. Berkeley National Laboratory James Hirsch and A. Volume, 2018), eQUEST (eQUEST the QUick Energy Simulation Tool)) that represent multiple thermal zones and complex system interactions. They deliver high accuracy but demand extensive input data on building geometry, materials, and systems, as well as substantial computational resources. Such complexity often proves challenging at early design stages, where detailed data are not yet available.

Data-driven techniques employ statistical and machine learning methods (e.g. Intelligent Community Design (IES, 2023), Intelligent Communities Life Cycle ("IES Intelligent Communities Lifecycle ICL, 2023)) to deduce energy use from extensive historical datasets. They offer flexibility and can operate with fewer upfront inputs, but their accuracy depends on the quality and representativeness of the available data. In contexts lacking robust datasets or featuring innovative construction practices, these models may not perform optimally.

Table 1 provides a concise overview of the main approaches used in UBEMs. The table compares top-down and bottom-up methods, highlighting subcategories, data requirements, level of granularity, strengths, limitations and contexts of applicability.

Initially, many UBEM tools focused only on operational energy consumption (Natanian et al., 2024). Recently, there has been growing recognition that environmental performances should extends beyond operational phases. Previous studies have emphasized the need for integrating life cycle assessment (LCA) in evaluating the energy performance of buildings to better understand both operational and embodied impacts (Cusenza et al., 2022). Recent advancements have

Table 1
Comparative summary of different approaches of UBEM tools.

	Top-Down Models	Bottom-Up Models	
		Physics-Based	Data-Driven
Approach	Aggregate city-level data to estimate overall energy demand.	Construct energy demand estimates from individual buildings and aggregate them	
Subcategories	Socio-Econometric Models -Technical Models -Physical Models	-	
Data Requirements	- Historical energy use -Demographics - Socio-economic indicators	- Building geometry - Materials - Systems	- Large datasets - Historical energy data
Granularity	Low – Provides city-wide or district-level estimates.	High – Detailed at individual building or archetype level before aggregation.	
Strengths	-Suitable for macro-scale analysis - Useful for long-term planning - Less data-intensive initially	- High accuracy - Detailed energy flow representation	- Flexibility - Can handle complex patterns without explicit physical laws
Limitations	- Lack of granularity - No detailed hourly predictions	- Requires extensive input data - High computational demand - Complexity unsuitable for early design stages	- Dependent on data quality and availability - May not perform well in new or unique contexts
Use Case Suitability	-Policy development - Urban planning at city scale	- Detailed energy assessments - Early design phase (for tools like CEA)	- Situations with abundant data and need for flexible modeling

extended this approach to urban-scale assessments, as demonstrated by Pei (Pei et al., 2024).

Integrating LCA into early-stage UBEM analyses faces challenges due to incomplete data on materials, building systems and final configurations. As these details are often not defined at preliminary planning stages, direct application of traditional physics-based UBEMs can be limited.

Adopting building archetypes significantly reduces data requirements, complexity and computational demand. Archetypes, representing standard building categories, encapsulate typical geometric, material and operational parameters, allowing simpler yet representative modeling. This approach delivers several benefits, among which it is possible to mention the reduced complexity in physics-based modelling, enhanced computational efficiency and versatility for integration in urban contexts.

Recent research focuses on tools that combine simplified physics-based simulations with archetypal modeling to support both operational energy analyses and LCA metrics in the early design phase. The tool under development in this research follows these trends, leveraging an archetype-based, physics-driven approach that offers early insights into energy and environmental performance without requiring the comprehensive data inputs of fully detailed models. By embedding operational and embodied energy assessments within a single framework, this approach provides holistic evaluations suitable for early-stage district planning and decision-making.

1.2. Research gap and contribution of the paper

The state of art shows that despite the significant advancements in UBEMs, several critical gaps remain that hinder their comprehensive application in urban planning and sustainability assessments. Top-down approaches, while valuable for macro-scale analysis and long-term policy development, fall short in providing the necessary granularity and temporal resolution required for detailed energy interventions and design decisions at the district or neighbourhood level. Their inability to offer detailed hourly consumption predictions, limits their utility in scenarios that demand precise and dynamic energy modeling.

On the other hand, bottom-up approaches, particularly physics-based models, offer high accuracy and detailed energy flow representations by simulating energy demand at the individual building level. However, these models are often constrained by their extensive data requirements and high computational demands, making them less feasible for early design stages where detailed building specifications are typically unavailable. Additionally, the complexity of these models poses a steep learning curve for practitioners who may lack specialized expertise in energy modeling or geospatial analysis, thereby restricting their accessibility and broader application.

Furthermore, while data-driven bottom-up techniques provide flexibility and can handle complex patterns without relying on explicit physical laws, their effectiveness is heavily dependent on the availability and quality of historical data. This dependency poses challenges in new or unique urban contexts where such data may be sparse or unrepresentative, thereby limiting the applicability and reliability of these models in diverse urban settings.

The integration of LCA with UBEMs represents a promising advancement in capturing the full spectrum of environmental impacts associated with urban buildings. However, this integration faces significant challenges, particularly during the early design stages, due to incomplete or unavailable inputs related to specific materials, building systems and configurations. Existing UBEM tools have begun to incorporate LCA frameworks, but the dependence on detailed data inputs and the complexity of combining operational and embodied energy assessments remain substantial barriers.

Addressing these gaps requires the development of UBEM tools that can balance the need for detailed, accurate energy modeling with computational efficiency and ease of use. Specifically, there is a need for tools that can operate effectively in the early design phases with limited data inputs while still providing reliable energy and environmental performance assessments. The adoption of an archetypal approach, as explored in the current research, offers a potential solution by simplifying the modeling process and enhancing the scalability and applicability of both UBEMs and LCA at the urban scale.

The objective of this study is to address the gaps identified in existing tools for the early design of PEDs. By providing a robust framework, the proposed tool aims to overcome current limitations in integration, adaptability and usability. The application in a case study of the Spanish district, characterized by significant energy poverty challenges, serves a dual purpose: it contributes to refining and validating the tool, while also exploring potential solutions to address the district's specific energy and environmental issues. This dual approach ensures that the tool not only advances methodological capabilities but also delivers practical benefits for vulnerable urban contexts. Achieving this goal aims not only to reduce energy poverty but also to facilitate the development of more PEDs. This approach addresses the urgent need for sustainable urban development while ensuring social equity.

2. Methods

TREEPED is developed to support the early-stage planning and evaluation of PEDs. It aims to:

1. Assess energy performance of new and existing building districts: Provide an estimation of the baseline energy demand of existing urban districts and evaluate whether the analysed district could achieve a Positive Energy District level after implementing renovation and renewable energy systems measures;
2. Analyse environmental impacts: Integrate LCA across all life cycle stages—use, production and end-of-life (EoL)—to provide a holistic understanding of how the interventions could influence the district's overall sustainability;
3. Facilitate renewable energy integration: Support the planning and evaluation of renewable energy systems, such as photovoltaic panels and battery storage, to enhance self-consumption and energy flexibility;
4. Streamline early-stage decision-making: Enable quick and accurate assessments with minimal data input, focusing on archetype-based modeling to reduce complexity.

To achieve these results, it uses an archetype-based approach which simplifies the modeling process by grouping buildings with similar characteristics, such as construction materials, operational patterns and thermal properties.

The aim of choosing the archetypical approach is to find a balance between representativeness, computational efficiency and data availability, which is decisive for scalable, early-stage assessments of large urban districts. By considering the similarity among buildings, our method significantly reduces the complexity and volume of required input data, making it particularly advantageous when detailed, building-specific data are limited or unavailable. The rationale behind the formulation of the single archetype is, for the case at hand, that all the buildings in the district are residential, constructed during the same period using similar materials, and exhibiting similar shapes. This homogeneity allows us to group them into a representative archetype, ensuring that the chosen model accurately reflects the building stock.

Additionally, the tool incorporates LCA to evaluate environmental impacts across the use, production, and EoL phases.

The results that can be obtained are comprehensive evaluations of the district's energy and environmental performance, including energy demand reductions, life cycle impacts (e.g., Global Warming Potential and Cumulative Energy Demand) and the district's ability to meet PED targets. These outputs support decision-making by identifying effective retrofit strategies and promoting the development of energy-efficient, low-carbon districts aligned with long-term sustainability goals.

In detail, TREEPED uses the methodology summarized within Fig. 1 and briefly described in the next paragraph.

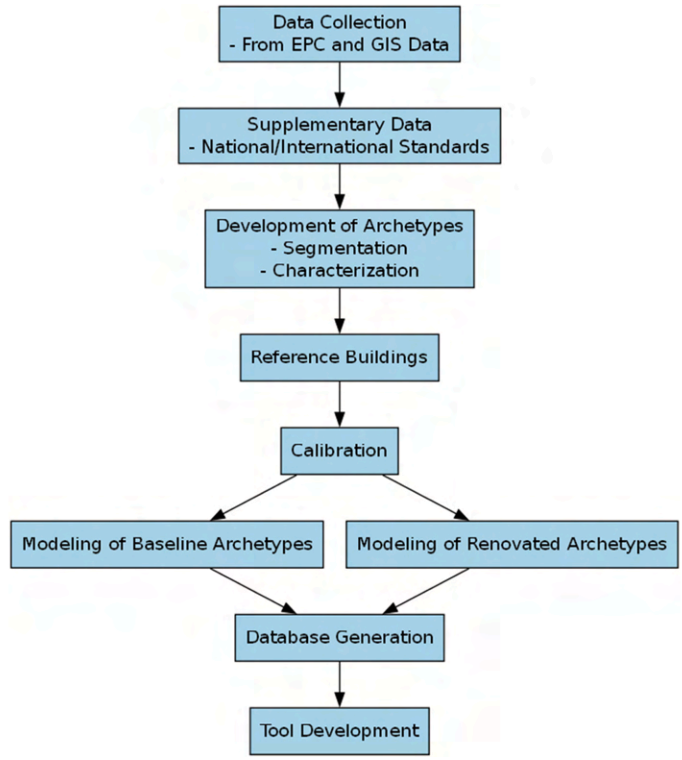

Fig. 1. Flow chart methodology.

2.1. Methodology

The following methodology section will include the main steps followed in the preparation of the tool and will address all preparatory work required to develop its database.

1. Data collection
2. Archetype generation and modelling
3. Modelling and simulation of the baseline archetypes and renovated archetypes
4. Database generation
5. Tool development.

2.1.1. Data collection

The data used within the tool are derived from three main categories: case study-specific data, national standards and international standards. This approach ensuring consistency and adaptability across different case studies.

Case study-specific offering localized and detailed information about the district. Spatial data, including building geometries, footprints, heights and orientations, were extracted from cadastral maps and GIS datasets, providing a foundational layer for district-scale modeling. Additionally, Energy Performance Certificates (EPCs) were instrumental in characterizing building envelope properties, such as stratigraphy and thermal transmittance (U-values), as well as system typologies for heating and cooling.

To ensure methodological rigor, national standards are employed to align the analysis with local regulations and practices. When national standards are insufficient for certain parameters, international standards are referenced.

For non-residential buildings, internal heat gains, including occupancy, lighting and appliance loads, were defined using ISO 18523–1 (ISO 18523:1, 2016). Residential building schedules and internal heat gains were determined according to EN 16798–1:2019 (British Standards Institution, 2019) while lighting energy performance was modeled using EN 15193–2 (CEN, 2017).

2.1.2. Archetype generation and modelling

The development of the archetypes involved several phases to ensure a robust and comprehensive model:

1. Segmentation: Buildings are categorized into homogenous groups based on structural and operational characteristics. This step identifies the number of archetypes required to represent the diversity of the building stock while maintaining modeling efficiency.
2. Characterization: Non-geometric parameters, including thermal properties, construction materials, HVAC systems and occupancy patterns, are collected and defined. This step captures the essential physical and operational characteristics of each archetype.
3. Reference building: A detailed geometric model is created for a representative building of each archetype. The model integrates the

characterized data, providing a comprehensive framework for simulating energy performance.

2.1.3. Modelling and simulation of baseline and renovated archetypes

The reference building, developed from the segmentation and characterization of the building stock, was modeled and analyzed using SketchUp (Sketchup, 2023), incorporating geometric and spatial features obtained from relevant data sources. This 3D model was then imported into OpenStudio (Brackney et al., 2018), which interacts with the EnergyPlus simulation engine to perform detailed energy simulations. Local weather files were employed to accurately represent environmental conditions. The simulation outputs included energy demands for heating, cooling, lighting, and domestic hot water.

A calibration process was conducted to ensure the model's accuracy and reliability. Standard occupant behavior profiles were initially used to define usage patterns. During calibration, these profiles were adjusted based on utility data and observed deviations, including real-world occupant behavior to minimize discrepancies between simulated and actual energy performance.

The calibration process also included a comparison with results from the CEA. This tool was chosen as it aligns closely with the archetype-based approach used in this study and provides an effective balance between computational efficiency and accuracy. .Table 2. below summarizes key differences between TREEPED and CEA.

The table shows that TREEPED incorporates features—such as detailed hourly simulations via EnergyPlus/OpenStudio, pre-calculated energy consumption profiles and comprehensive LCA integration—that distinguish it from CEA. CEA, in turn CEA, excels in areas like spatial data integration and is an advanced tool for urban energy analysis. However, TREEPED is particularly well-suited for early design stages where detailed data are scarce. By depending on an extensive internal database and an archetype-based approach, TREEPED requires minimal user inputs while still delivering robust energy and environmental assessments. At the same time, TREEPED's dependance on pre-calculated data may limit its adaptability in more heterogeneous urban environments. Overall, these differences underscore TREEPED's unique contributions to early-stage PED planning, while also highlighting both the strengths of CEA and potential areas for future improvement in TREEPED.

The calibration achieved an acceptable error margin, with deviations maintained below 10 %, ensuring confidence in the model's outputs for further analyses.

Table 2
Comparative analysis of TREEPED and CEA key features and capabilities.

Features	TREEPED	CEA
Simulation engine	EnergyPlus (via OpenStudio, pre-simulated and simulation results embedded in the database)	RC network model (internal CEA engine)
Hourly simulation	Yes (import of dynamic simulation from other tools)	Yes
Spatial Data Integration	Limited (case-specific inputs)	Yes (direct integration with OpenStreetMap)
Archetype-based modeling	Yes	Yes
Minimal user inputs required (via archetype scaling)	Yes	No
Calibration with utility data	Yes	Yes
Integration of Life Cycle Assessment (LCA)	Yes	Yes
Modeling of renewable energy integration	Yes	Yes
Detailed and integrated simulation	Yes (pre-simulated)	Yes

Following calibration, renovated archetypes were developed to represent buildings that have undergone energy efficiency improvements. These archetypes incorporated upgrades to the building envelope, such as enhanced insulation and advanced glazing systems, designed to meet or exceed applicable energy performance standards.

2.1.4. Database generation

The results of both baseline and renovated archetype models were systematically stored in a structured database. This repository includes detailed information on energy demands for heating, cooling and domestic hot water, as well as electricity consumption for lighting and internal appliances. The database provides a centralized framework to facilitate the analysis and comparison of energy performance metrics across different building scenarios.

2.1.5. Tool development

TREEPED is designed to support the early-stage design and evaluation of PEDs through an archetype-based approach. The tool enables users to conduct energy performance and environmental impact assessments while minimizing the complexity of input requirements.

TREEPED analyzes a wide range of energy systems, including heating, cooling and domestic hot water (DHW) systems. For each type, the tool evaluates technologies such as heat pumps, gas boilers, district heating and electric water heaters, ensuring flexibility in modeling diverse district scenarios. The tool also integrates renewable energy technologies, within a modular and flexible framework, enabling users to tailor renewable energy inputs and configurations according to local conditions and emerging technologies. Specifically, the renewable energy generation potential is calculated using site-specific inputs, such as geographic coordinates and meteorological data, to estimate energy production. For photovoltaic systems, TREEPED utilizes a connection through an Application Programming Interface (API) with the PVWATTs (NREL, 2023) toolallowing users to choose between monocrystalline, polycrystalline and thin-film photovoltaic technologies. In parallel, solar thermal systems are independently modeled based on parameters defined by users, including collector area and system efficiency. The modular architecture also supports future extensions; in particular is planning to incorporate wind energy modeling, further increasing TREEPED's adaptability and comprehensiveness in urban energy planning. Surplus PV energy is allocated according to a defined priority hierarchy. The energy allocation framework within TREEPED prioritizes immediate consumption, followed by storage in battery systems, with any surplus directed to the grid. This hierarchical approach enhances self-consumption rates and reduces external dependencies. Mathematically, this is represented through equations such as Eq. 1, which determines the electricity delivered from the battery to meet district consumption, factoring in the state of charge (SoC) and battery capacity:

$$El_{BS-EC} = \delta_{SOC} \bullet C \tag{1}$$

Where:

- $El_{BS\text{-}EC}$ represents the electricity delivered from the battery system to feed the electricity consumption [kWh]
- δ_{SoC} represents the difference of state of charge
- C represents the battery energy capacity [kWh].

Dynamic modeling ensures that TREEPED captures temporal variations in energy flows. For instance, if photovoltaic energy at time t-1 is insufficient to meet demand, the SoC calculation (Eq. 2) ensures continuity by drawing from stored energy. Conversely, surplus energy at $t-1$ is used to recharge the battery, as described in Eq. 3, while maintaining efficiency.

$$SoC(t) = SoC(t-1) - \frac{El_{BS-EC}\quad(t-1)}{C(t)} \tag{2}$$

Where:

- *SoC* represents the state of charge
- *SoC(t-1)* represents the SoC at time (t-1)
- $El_{BS\text{-}EC}(t)$ the electricity delivered from the battery system to feed the electricity consumption [kWh]
- *C(t)* represents the battery energy capacity [kWh].

$$SoC(t) = SoC(t-1) + \frac{El_{PV-BS}\quad(t-1) \bullet \varepsilon(t)}{C(t)} \tag{3}$$

Where:

- *SoC* represents the state of charge
- $El_{PV\text{-}BS}(t)$ represents the electricity delivered from the photovoltaic system to feed the battery system[kWh]
- $\varepsilon(t)$ represents the battery efficiency corresponding at the time step (t).

Achieving a PED requires renewable energy generation to exceed total district energy consumption, which includes all energy carriers. TREEPED performs a primary energy balance, accounting for both renewable energy generated and total energy consumed, weighted by their respective primary energy factors (TPEFs). The TPEFs are sourced directly from ISO 52000 (International Standard Organization, 2017), ensuring standardization and consistency in evaluating the energy contributions of different carriers.

Beyond energy performance, TREEPED incorporates a comprehensive Life Cycle Assessment (LCA) framework to evaluate environmental impacts across baseline and retrofitted districts.

The tool explicitly evaluates environmental impacts across three key lifecycle phases—production, operational and End-of-Life (EoL)—focusing primarily on Global Warming Potential (GWP) and Cumulative Energy Demand (CED), employing standardized methodologies (CED method (Frischknecht et al., 2007) EF 3.0 (Castellani et al., 2018)).

The tool computes embodied impacts that are connected with the renovation actions, e.g., computing the embodied carbon generated by the production and installation of the insulation materials or PV modules and comparing it with the corresponding variation in global warming potential connected to the use stage of the building. The baseline scenario focuses exclusively on the operational phase, highlighting the environmental burdens of existing systems. Conversely, the retrofitted scenario accounts for the full lifecycle, including production, operational, and EoL phases.

The environmental assessment during the production phase is guided by key assumptions that simplify complex calculations. For example, the total insulated area, including roofs, walls and floors, is estimated using minimal input data. Insulation thickness is determined by archetype-specific thermal transmittance requirements and the resulting volume of insulation material is adjusted by density to ensure consistent evaluations across archetypes. Similarly, windows are assessed using predefined ratios, such as the Window-to-Wall Ratio (WWR) and Frame Ratio, enabling precise differentiation between glazing and frame materials. For energy systems, solar thermal panels are evaluated based on their collector area, while district heating impacts are derived from the energy input required for central thermal generation.

At the EoL phase, TREEPED evaluates the environmental impacts associated with the disposal or recycling of materials. The assessment adjusts key characteristics based on lifecycle stages; for instance, photovoltaic systems are assessed by total panel area, batteries by mass and district heating systems by the dismantling impacts of central generators.

These calculations are annualized according to the expected lifespans of each component, such as 30 years for insulation (Dodd and Donatello, 2021) and PV system (Wernet et al., 2016), 20 years for batteries system (Cusenza et al., 2019) 30 years for heat pumps (Guarino et al., 2020) and 20 years for boilers (Wernet et al., 2016).

Equations such as Eq. 4 is used to estimate the environmental impacts of energy consumption during the operational phase.

$$EI_k = \sum_{j=1}^{n} EC_J \times CF_{J,k} \tag{4}$$

Where:

- EI_j, is the total environmental impact associated with the use of energy carrier j under impact category *k*;
- EC_J is the amount of the energy carrier j consumed (e.g., in kWh for electricity, in m^3 for natural gas, etc.);
- $CF_{J,k}$ is the characterization factor for carrier *j* in impact category *k*. For instance, $kgCO_{2eq}$/kWh for electricity under GWP or MJ/kWh for electricity under CED.

Eq. 5 evaluates the impact of total environmental impact of the production and EoL phases for all components.

$$EI_{e,k} = \sum_{i=1}^{n} \frac{(EI_{P,i} + EI_{EoL,i}) \times CF_{i,k}}{L_i} \tag{5}$$

Where:

- EI_e Represents total embodied environmental impact for all components, normalized over their respective lifespans under impact category *k;*
- $EI_{p,i}$ is the environmental impact associated with the production phase of component *i*;
- $EI_{EoL,i}$ is the environmental impact associated with the EoL phase of component *i*;
- $CF_{i,k}$ is the characterization factor for component *i* in impact category *k*;
- *Li* is the useful life of component *i.*

Table 3. shows the main dataset used for the environmental analysis at different stages.

3. Tool functionality

Following the explanation of the underlying methodologies and equations integrated into TREEPED, this section focuses on the tool's interface and operational framework. TREEPED's functionality is structured to enable seamless interaction with its complex analytical capabilities, guiding users through a systematic process from data input to result interpretation.

The tool's interface is divided into modular sections that reflect the core steps of district-level analysis, allowing users to transition between baseline and renovated scenarios. Fig. 2, the TREEPED flowchart, provides a comprehensive visual representation of this workflow. It begins with the pre-calculated energy demands of baseline and renovated buildings, derived from national norms and archetype-based inputs and progresses through district-level aggregations based on the number of buildings per archetype. User-defined inputs for existing and post-retrofit systems, as well as renewable energy sources, are then integrated into the analysis.

In TREEPED, energy consumption and savings are estimated using detailed hourly energy demand data for each building archetype. These data are generated through comprehensive simulations conducted with EnergyPlus/OpenStudio using representative meteorological inputs from EPW files, resulting in hourly profiles for both thermal demand (heating and cooling) and electricity consumption (for appliances and

Table 3
Life Cycle Inventory (LCI) datasets used for environmental impact assessment in the district.

Phase	Layer	Dataset
Production Phase	Insulation	Polystyrene foam slab {RER}| polystyrene foam slab production | Cut-off, U
	Window frame	Window frame, poly vinyl chloride, U= 1.6 W/m2K {RER}| window frame production, poly vinyl chloride, U= 1.6 W/m2K | Cut-off, U
	Window glass	Glazing, double, U< 1.1 W/m2K {RER}| glazing production, double, U< 1.1 W/m2K
	Photovoltaic system	Photovoltaic slanted-roof installation, 3kWp, single-Si, laminated, integrated, on roof {CH}| photovoltaic slanted-roof installation, 3kWp, single-Si, laminated, integrated, on roof | Cut-off, U
	Battery	Self-developed dataset based on (Cellura et al., 2021)
	Heat pump	Heat pump, brine-water, 10 kW {CH}| heat pump production, brine-water, 10 kW | Cut-off, U
Use phase	Electricity Import	Electricity low voltage
	Natural gas consumption	Natural gas, burned in boiler modulating > 100 kW
EoL	Window frame	Disposal, building, window frame, plastic, to final disposal
	Glazing	Disposal, building, glazing 2-IV, U< 1.1 W/m2K, to final disposal
	Insulation	Disposal, building, polystyrene isolation, flame-retardant, to final disposal
	Photovoltaic system	Calculated based on (Longo et al., 2020)
	Battery	
	Heat pump	

lighting). By aggregating these hourly values, the tool produces annual energy consumption estimates that capture the dynamic performance of the district without requiring real-time data processing.

The workflow ends in a comparison of energy performance and environmental impacts between the baseline and renovated scenarios, considering both operational and embodied phases.

Fig. 3 provides an overview of the TREEPED tool interface, highlighting the key stages of resource and environmental evaluation. The tool guides the user through a structured process:

1. Input district
2. District balance calculations
3. Renovation district
4. PED environmental assessment.

3.1. *Input district*

The "Input District" section is the only part of the TREEPED tool that requires user input, while all subsequent sections provide results.

TREEPED relies on the following assumptions:

1. Building energy models: TREEPED uses pre-calculated hourly energy consumption profiles per square meter for each archetype, users are not required to upload or create detailed building models themselves
2. Required user inputs: The user will need to input information on the areas of the buildings, availability of roof area, heated areas and choose among a selection of drop-down menus choosing between the available archetypical building envelope features and the corresponding HVAC systems
3. Simulation data acceptance: The tool accepts any kind of simulation results which are treated as data series regardless of their simulation engine

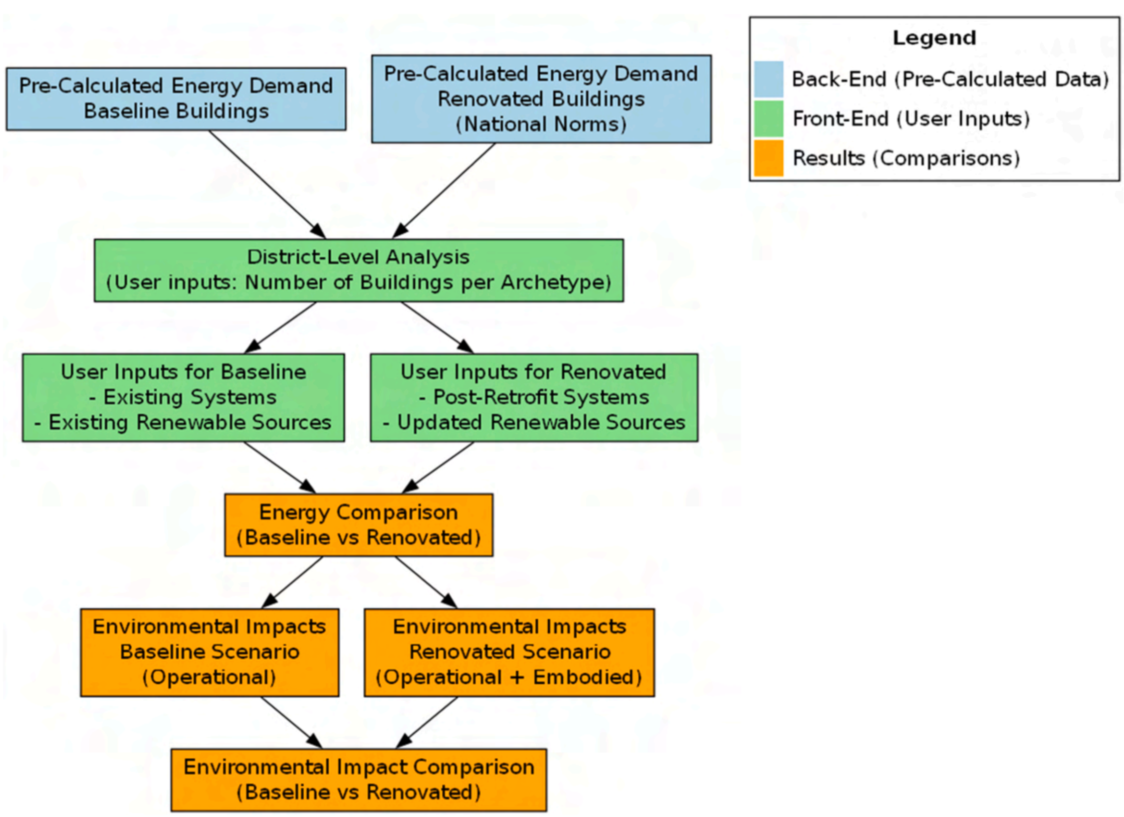

Fig. 2. Flow chart TREEPED.

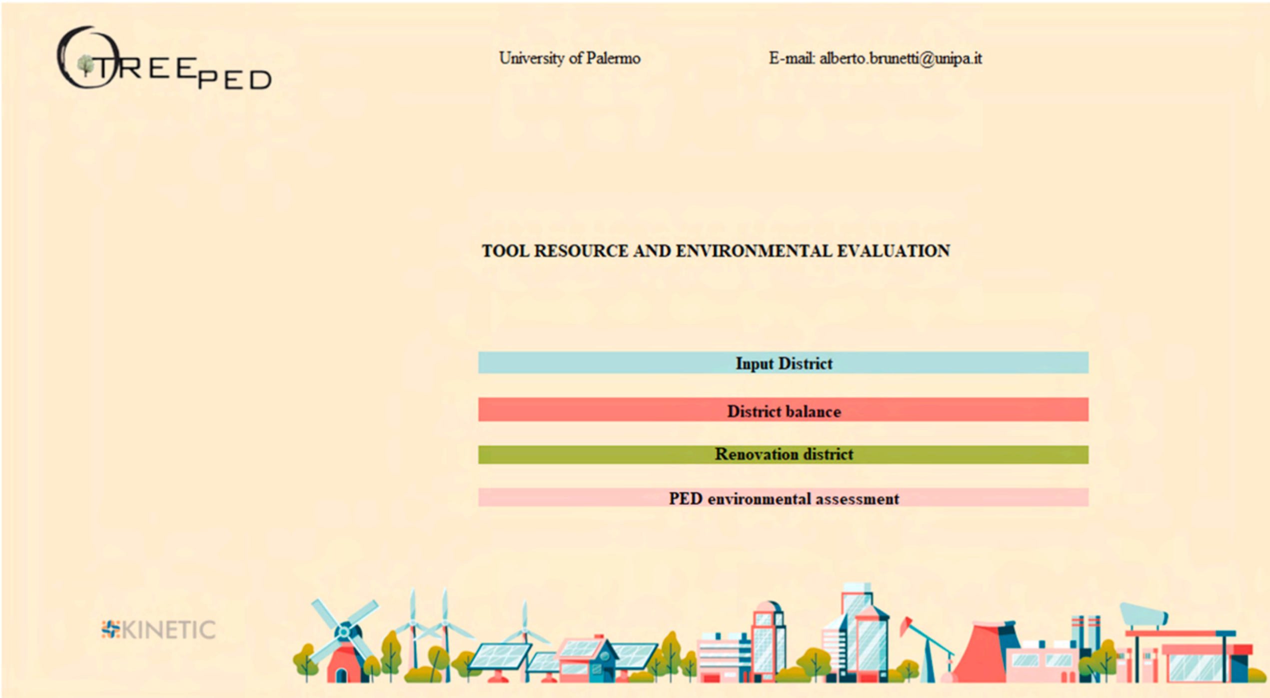

Fig. 3. Main page of the tool.

4. Weather data: Weather data are computed in the pre-simulation stage and are not connected to the tool itself. Our database adopts standard energy plus weather data files for the simulations
5. Building archetypes definition: Archetypes are defined by prior studies and input in the database through some simple macros in VBA environment. The database is constantly updated by the authors but it is possible for users to directly input data themselves.

The inputs required are:

Users define the district through segmentation, based on parameters such as:

- Construction period of buildings
- Building typologies, such as single-family house, multifamily house, apartment block, office
- Other relevant characteristics, such as number of floors.

In addition, users must provide geographic information, including:

- Latitude of the district
- Longitude of the district.

Fig. 4 showcases the segmentation process and additional information inputs including construction period, building typology and geographical data.

In this section, users define the district's existing energy systems, including heating, cooling, and DHW systems, specifying their efficiencies to ensure accurate performance assessments. For archetypes representing multiple buildings, users must indicate the percentage of buildings served by each system, allowing for a detailed representation of the district's energy infrastructure.

TREEPED's flexible framework captures the diversity of energy generation and distribution technologies, ensuring the analysis reflects the complexity of real-world urban districts.

3.1.1. Efficiencies of heating systems, cooling systems, DHW systems and renewable systems

The TREEPED tool includes a comprehensive modeling framework for energy systems, including heating, cooling, DHW and renewable energy technologies. This section outlines the key system configurations and parameters required for analysis, ensuring compatibility with a wide range of district-level scenarios and promoting the integration of renewable energy for self-sufficiency and flexibility.

Heating Systems

- Technologies: Heat pumps, boilers and district heating networks.
- Performance metrics:
- Heat pumps: Seasonal Coefficient of Performance (SCOP).
- Boilers and district heating: Overall efficiency.
- Solar thermal integration: Prioritized for DHW demand, with surplus heat allocated to space heating.

Cooling Systems

- Technologies: Heat pumps and centralized cooling systems.
- Performance Metric: Seasonal Energy Efficiency Ratio (SEER).

Section 1: DISTRICT INFORMATIONS														
SEGMENTATION						OTHER INFORMATIONS								
Country	Construction period	Building type	Number of floors	Windows replaced	Insulated	Number of buildings for archetype	Floor area conditioned (for single building) [m^2]	Latitude	Longitude (est)	Total Roof	Total external Walls (N)	Total external Walls (S)	Total external Walls (W)	Total external Walls (E)

Fig. 4. Input district (Segmentation and other information).

DHW Systems

- Technologies: Boilers, heat pumps and electric water heaters.
  Renewable Energy Systems
- Solar Thermal Systems: Users input efficiency; heat is prioritized for DHW and space heating.
- Photovoltaic Systems: Users specify panel type.
- Integrated Framework: Evaluates renewable energy generation, storage, and the district's potential for self-sufficiency and energy flexibility.

Fig. 5 highlights the settings available for energy systems such as heating, cooling, and DHW. Users can configure system types, efficiencies, and their distribution across the district.

Fig. 6 focuses on the parameters for renewable energy systems, enabling the configuration of photovoltaic and solar thermal systems. This includes selecting panel types, system efficiencies, and storage integration options.

3.1.2. *Retrofit definition for systems*

The third part focuses on defining retrofit measures for the district's energy systems. Users specify new systems, their efficiencies, and additional renewable energy sources. For photovoltaic systems, users can also include a battery, with the load cover factor (Voss et al., 2010) provided to optimize installation size by measuring on-site electricity generation coverage. This step enables comprehensive modeling of baseline and retrofitted scenarios, supporting energy balance calculations, renovation evaluation, and PED environmental assessments. Moreover, TREEPED is designed to model the impact of specific retrofit measures rather than merely providing an overall energy balance for the district. From an energy perspective, users can observe the effects of various retrofit interventions on a district scale. For instance, improvements in insulation and window upgrades are directly reflected in reduced thermal demand, while the integration of renewable energy—such as photovoltaic installations—is quantifiable by comparing the generated energy in the baseline scenario with that in the renovated scenario.

3.1.3. *Dynamic input adjustment and iterative capabilities*

The tool employs an iterative input methodology, allowing users to dynamically adjust key parameters during the analysis.

These include:

1. Archetype configurations: Adjust segmentation parameters (e.g., construction period, building typology) to refine archetypes and energy metrics.
2. Baseline system characteristics: Existing heating, cooling and DHW systems, including type and efficiency.
3. Renovated system configurations: Define or modify retrofit measures (e.g., HVAC systems, insulation, windows) to explore alternative strategies.
4. Renewable energy integration: Adjust the capacity and type of photovoltaic systems, batteries and solar thermal systems to optimize renewable energy deployment and self-consumption.

3.2. *District balance calculations*

The district balance calculations section focuses on assessing the current energy performance of the district in its baseline scenario. Based on the inputs provided during the segmentation and archetype

	Cooling System (heat pumps)											
Archetype	Heat pump	SEER (average)	% of buildings	Heat pump	SEER (average)	% of buildings	Heat pump	SEER (average)	% of buildings	Heat pump	SEER (average)	% of buildings
1	Air to air	4.0	0%	Air to water	4.0	0%	Ground to water	4.0	0%	Water to water	4.0	100%

	Cooling System (District cooling)								
Archetype	Heat pump	Global efficiency	% of buildings	Heat pump	Global efficiency	% of buildings	Heat pump	Global efficiency	% of buildings
1	Air to water	4.0	0%	Ground to water	4.0	0%	Water to water	4.0	0%

	Heating System (heat pumps)											
Archetype	Heat pump	SCOP (average)	% of buildings	Heat pump	SCOP (average)	% of buildings	Heat pump	SCOP (average)	% of buildings	Heat pump	SCOP (average)	% of buildings
1	Air to air	4.0	0%	Air to water	4.0	0%	Ground to water	4.0	0%	Water to water	4.0	0%

	Heating System (Boiler)								
Archetype	Boiler	Efficiency (average)	% of buildings	Boiler	Efficiency (average)	% of buildings	Boiler	Efficiency (average)	% of buildings
1	gas	0.75	100%	Biomass	0.85	0%	Oil	0.85	0%

	Heating System (District heating)											
Archetype	Heat pump	Global efficiency	% of buildings	Heat pump	Global efficiency	% of buildings	Heat pump	Global efficiency	% of buildings	Global efficiency	Global efficiency	% of buildings
1	Air to water	4.00	0%	Ground to water	4.00	0%	Water to water	4.00	0%	Natural gas	0.75	0%

	Domestic hot water							
Archetype	Heat pump	Efficiency (average)	% of buildings	Boiler	Efficiency (average)	% of buildings	ElectricSystem	% of buiding
1	Air to water	5	0%	gas	0.75	100%	Heat Water System	0%

Fig. 5. Input district (System definition).

	Renewable thermal systems											
Archetype	Solar thermal systems	Tilt angle	m²	Efficiency	Solar thermal systems	Tilt angle	m²	Efficiency	Solar thermal systems	Tilt angle	m²	Efficiency
1	Flat-plate	30	0	0.5	Evacuated tube	30	0	0.6	Compound parabolic	30	0	0.7

	Renewable electric systems											
Archetype	Photovoltaic systems	Tilt angle	m²	Battery Capacity [kWh]	Photovoltaic systems	Tilt angle	m²	Battery Capacity [kWh]	Photovoltaic systems	Tilt angle	m²	Battery Capacity [kWh]
1	Monocrystalline Silicon	30	0	60	High efficiency monosilicon	30	0	0	Thin film	30	0	0

Fig. 6. Input district (Renewable systems).

definition phases, this step involves quantifying the district's heating, cooling and electricity demands.

In this section the tool provides a comprehensive analysis of the district's energy flows, including generation, consumption, heating and cooling demands over different timeframes and PED primary balance.

The graphs highlight the hourly and monthly energy dynamics, showcasing seasonal variations and peak demands. The results offer a comprehensive understanding of the district's energy needs and highlight the key areas contributing to its overall consumption. Similar approaches are followed in the renovated district tab.

This approach helps users refine their strategies and further optimize retrofit measures to achieve PED objectives.

3.3. PED environmental assessment

The final stage focuses on evaluating the environmental impacts of the district using LCA. This includes assessing only the operational phase for the baseline scenario and the full lifecycle—comprising production, use and EoL phases—for the retrofitted district (Wernet et al., 2016).

4. The case study

The case study is part of the broader OPEN LAB Pamplona project, (OpenLab-project., 2024) which aims to establish one of the first Positive Energy Neighborhoods (PENs) in Spain.

The San Pedro district includes an area of approximately 0.02 square kilometers. This district comprises 10 residential buildings designed as social housing, all constructed between 1930 and 1940.

4.1. Data collection

For the case study, national standards were central to the analysis. The Catálogo de Elementos Constructivos del CTE (Ministerio de Vivienda, 2010) provided material-specific properties and thermal transmittance values for building envelopes. Operational parameters, including internal loads (e.g., lighting, occupancy, and appliances) and infiltration rates, were defined using the Documento Básico HE Ahorro de Energía (DB-HE) (Ministerio de Fomento España, 2019) while ventilation rates were specified according to the Documento Básico HS (DB-HS) (Gobierno de España, 2019).

In addition to national standards, localized data specific to the case study were crucial. Energy consumption data from bills provided detailed information on operational energy use, which was instrumental in calibrating the model and characterizing the energy systems in the district. Moreover, data from the Open LAB project supplemented the analysis, offering insights into operational conditions and energy system performance at the district level.

The table below represents a list of the data sources used:

The following table describes the materials and thicknesses used in the external walls and the intermediate floor.

4.2. Archetype generation and modelling

Each of the ten residential buildings within San Pedro is classified as a multifamily house, encompassing a total volume of approximately 1854 cubic meters. This volume is distributed across three above-ground floors and a basement level allocated for technical services. The footprint of each building is roughly 665 square meters, facilitating an internal layout that accommodates four apartments per floor. Consequently, the total usable floor area per building amounts to about 1997 square meters, which includes common spaces, entrances, and internal areas.

The buildings in the San Pedro district, with similar structures and facades made of brick masonry, fiberglass insulation and plaster layers, still reflect the thermal performance of their 1970s retrofit, which does not meet current energy efficiency standards.

The current thermal systems across all residential buildings in the San Pedro district are dependent on gas boilers for both heating and domestic hot water (DHW). These systems are decentralized, with each apartment or residential unit equipped with an individual boiler. The existing boilers are gas-powered, featuring a nominal power output of 24 kW and operate within a radiator-based distribution system. This setup, while functional, underscores the necessity for modernization to align with the energy efficiency objectives.

Fig. 7 presents a cadastral map of the San Pedro district scaled at 1:5000 and oriented towards the north. Fig. 8. presents a collage of images showing the buildings in the San Pedro district.

Fig. 9 shows the SketchUp representation of the archetype selected for the San Pedro district.

The visual evidence demonstrates the uniformity in architectural design, structural characteristics and construction typology across all buildings in the district. This uniformity makes it an ideal candidate for archetype-based modeling, facilitating a comprehensive evaluation of its potential transformation into a PED.

From the collected data, the district was therefore segmented into a single archetype representing residential apartment blocks built in the 1930s, characterized by shared 1970s retrofits and consistent thermal properties, ensuring an accurate yet simplified analysis.

After the segmentation phase the non-geometric characteristics are identified during the characterization process. These characteristics include thermal properties, construction materials, HVAC systems as described in Tables 4 and 5.

The reference building model was developed by integrating non-geometric data, obtained during the archetype characterization phase, with geometric information derived from GIS data. The geometric modeling of the building was performed using SketchUp.

Fig. 7. View from GIS map of the district.

Fig. 8. Buildings in the San Pedro District.

The SketchUp model provided the geometric framework necessary for energy simulations. Non-geometric parameters, such as construction materials, thermal properties, insulation levels and occupancy schedules, were incorporated into the model. This integration ensured a comprehensive and representative energy simulation.

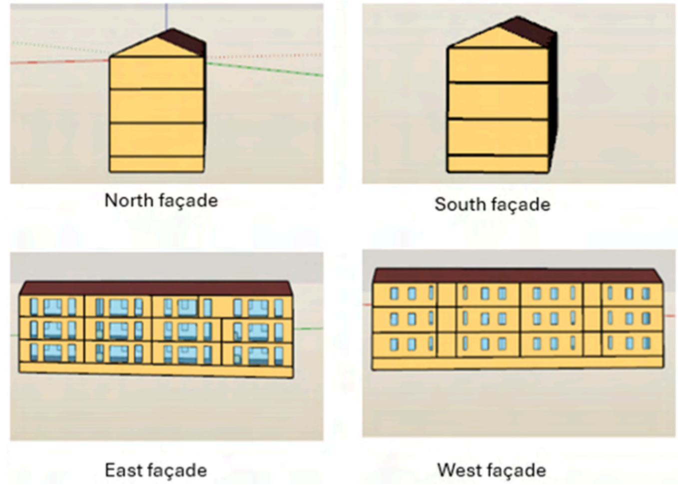

Fig. 9. The reference building for the archetype.

Table 4
Sources for archetype development.

-	Data	Sources	Unit	Value
Envelope	Stratigraphy	Open Lab	-	-
	Transmittance	Catálogo de elementos constructivos del cte (Ministerio de Vivienda, 2010)	[W/m^2-K]	External walls: 0.59 Roof: 3.48 Windows: 2.7
Internal loads	Occupancy	Documento Básico HE Ahorro de energía-Anejo D (Ministerio de Fomento España, 2019)	[m^2/person]	30
	Lights Appliances		[W/m^2]	4.4
Healthiness	Ventilation	Documento Básico HS Salubridad Seccion HS3 Calidad del aire interior (Gobierno de España, 2019)	[h^{-1}]	Daytime: 0.63 Nighttime: 3.36 (from June 1st to September 30th)
	Infiltration	Documento Básico HE Ahorro de energía-Anejo H (Ministerio de Fomento España, 2019)	[h^{-1}]	0.24
Systems	Typology	Open Lab	-	Boiler

Table 5
Materials and thicknesses of external walls and intermediate floor.

	Material	Thickness (cm)
External Walls	1/2 Brick Facing	12.0
	Non-ventilated Air Cavity	2.0
	Fiber glass Insulation	4.0
	Mortar Plaster	1.5
	Solid Brick (1 Brick)	24.0
	Gypsum Plaster	1.5
Intermediate floor	Gres	1
	Mortar for Bonding	2
	Vertical Steel Railing Plate	22
	Extruded Polystyrene Insulation	4
	Non-ventilated Air Cavity	-
	Gypsum Plaster and Finishing	1.5

4.3. Modelling and simulation of baseline and renovated archetypes

The calibration process was conducted using two complementary methods to ensure the accuracy and robustness of the TREEPED model. The first method relied on data from utility bills to validate heating and electricity consumption, focusing on operational performance derived from observed data. The second method benchmarked TREEPED's simulated energy demands against the CEA, providing an additional layer of validation through comparison with a recognized modeling framework.

Table 6 presents the results of the calibration based on utility bills, highlighting deviations between observed and simulated energy consumption values for heating and electricity. This analysis enabled a direct comparison of TREEPED's performance with real-world data, ensuring consistency with operational conditions.

Table 7 summarizes the benchmarking results against CEA, comparing TREEPED's simulated energy demands for heating, cooling and electricity. This comparison offers insights into the alignment of TREEPED with established modeling practices and highlights the model's ability to capture annual and seasonal variations effectively.

The discrepancies primarily depend on the different simulation engines and modeling approaches employed. TREEPED uses OpenStudio coupled with EnergyPlus to conduct detailed hourly simulations based on an archetype-based methodology. In contrast, the CEA tool uses a resistor-capacitor (RC) model, which, while computationally efficient, depend on simplified assumptions that tend to smooth out dynamic variations. Although the differences in cooling demand exceed 10 %, the authors consider these discrepancies acceptable.

Furthermore, a comparison of the monthly energy demands between TREEPED and the CEA offers a clearer understanding of seasonal variations.

Fig. 10 illustrates the comparison of heating demand, while Fig. 11 focuses on the cooling demand and Fig. 12 presents the comparison of electricity demand between TREEPED and CEA.

The figure shows that while the annual comparison aligns closely, the monthly breakdown reveals a consistent underestimation of heating demand by CEA compared to TREEPED. In peak winter months like January and December, the differences are −7 % and −8 %, respectively, highlighting CEA's lower sensitivity to extreme cold conditions.

During transitional months like May the underestimation becomes even more pronounced, reaching −10 %. These consistent monthly discrepancies result in an annual difference of approximately −7.5 %.

Despite slightly more pronounced monthly discrepancies, both tools consistently capture the district's overall modest cooling demand. These differences are balanced over the course of the year, resulting in a limited annual difference of −12 %.

The figure shows a consistency between TREEPED and CEA, with only a 1 % deviation. The electricity demand remains stable throughout the year, reflecting baseline consumption for lighting and appliances.

4.3.1. Renovated archetype

Given the absence of retrofits since the 1970s, particularly concerning building envelopes and windows, a renovated archetype was developed to assess the potential energy efficiency improvements. The retrofit measures were modeled to reflect upgrades such as enhanced insulation and high-performance windows.

The upgrades to the insulation and windows were implemented in compliance with Spanish national regulations (Ministerio de Fomento España, 2019), which mandate achieving minimum thermal transmittance for building elements based on the winter climate zone. Pamplona is in Climate Zone D and the retrofit measures were designed to meet the specific requirements for this zone, ensuring both regulatory compliance and enhanced energy efficiency.

Table 8 compares the U-values of opaque building elements, such as external walls and roofs, before and after retrofitting.

Table 9 evaluates the effects of replacing the windows on their thermal transmittance and solar heat gain coefficient (g-value).

The finalized models were then exported and used in Openstudio, to evaluate the building's energy performance, including heating and cooling demand as well as electricity consumption for lighting and appliances, are estimated per square meter. These values are then stored in a centralized database, ensuring standardized and efficient access for subsequent analyses within the tool.

Table 7
Comparison of energy results between CEA and simulation.

Parameter	CEA (Benchmark)	Simulated (TREEPED)	Deviation (%)
Heating Demand (kWh/m²)	68.33	73.90	−7.54
Cooling Demand (kWh/m²)	3.14	3.57	−12.15
Electricity Consumption (kWh/m²)	29.27	28.93	1.16

5. Results

5.1. Input district

The district under analysis is defined by a segmentation process that identifies its key characteristics, as illustrated in Fig. 13:

As detailed in Table 4 Sources for archetype development, the district depends on decentralized energy systems. Each building is equipped with individual gas boilers for both heating and DHW. These systems are characterized by relatively low efficiency and a lack of integration with renewable energy sources, resulting in high dependency on fossil fuels.

5.2. District balance

This section analyzes the energy performance of the baseline district, focusing on the demands for heating, cooling and electricity. By quantifying the district's energy consumption and dependency on non-renewable systems, the District Balance provides a clear understanding of the starting point for evaluating the impact of retrofit measures in subsequent phases.

Fig. 14 presents the analysis of the annual hourly heating and cooling demand of the San Pedro district.

The data highlights the significant dependence on heating which peaks with values exceeding 1000 kW during the coldest period and a comparatively lower demand for cooling with peaks reaching approximately 400 kW. The analysis shows significant challenges, primarily the high thermal energy demand resulting from the presence of older, low insulated buildings.

Table 6
Comparison of energy results between Bills and simulation.

Parameter	Observed (Utility Bills)	Simulated (TREEPED)	Deviation (%)	Additional Insights
Heating Demand (kWh/m²)	66.9	73.90	−9.37	Methane consumption for heating isolated from DHW consumption.
Electricity Consumption (kWh/m²)	27.13	28.93	7.12	Simulated values lower than Spanish standards, reflecting social housing energy usage.

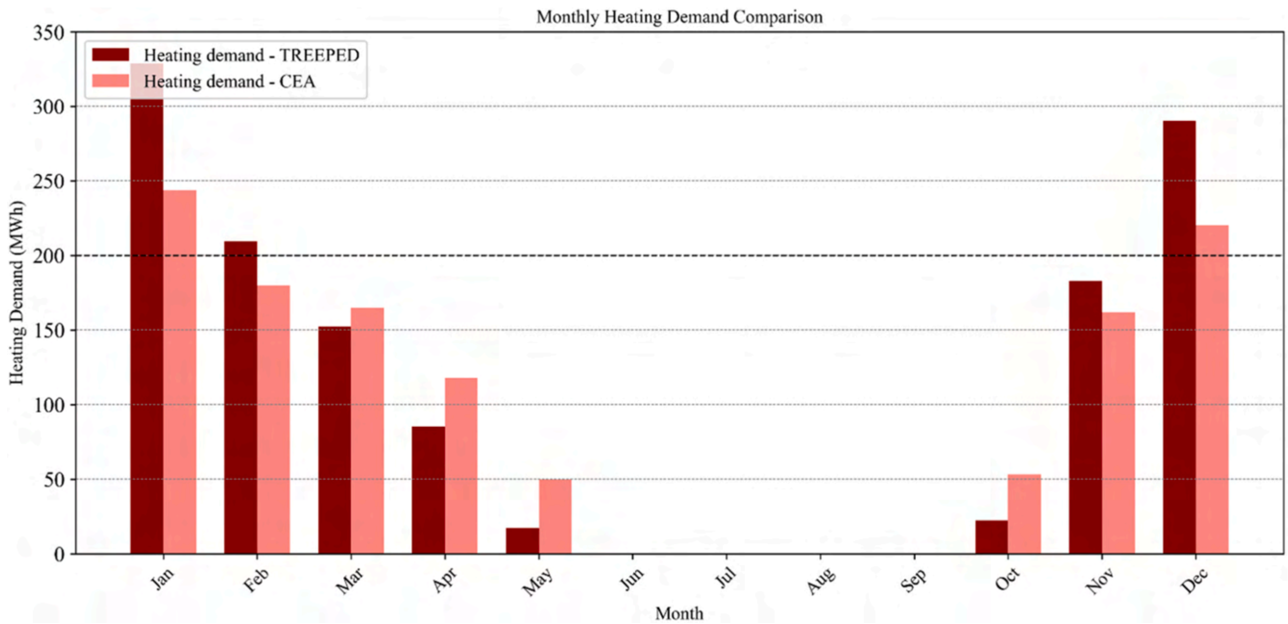

Fig. 10. Monthly heating demand comparison.

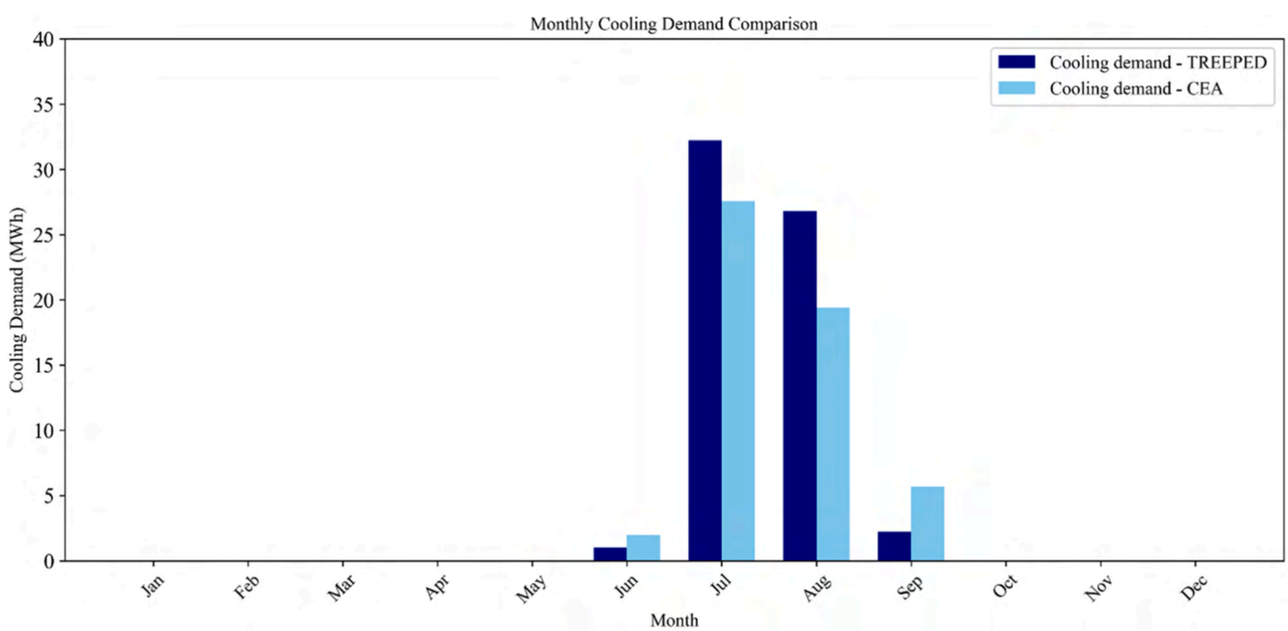

Fig. 11. Monthly cooling demand comparison.

5.3. Renovation district

In this section, the tool evaluates the thermal performance of the renovated archetype according to national standards and integrates these results with the information provided in the 3.1.2.

Furthermore, this section compares the energy performance of the renovated district with the baseline scenario from the District Balance phase. This comparison highlights the improvements achieved through the retrofit measures, providing a clear understanding of their impact in progressing toward PED objectives.

Based on the results obtained, the following retrofit scenarios were analyzed for the district:

1. Building envelope enhancements (insulation and window replacement): upgrading the building envelopes with appropriate insulation materials and modern, high-efficiency glazing to reduce thermal losses and further minimize energy consumption;
2. Replacement of decentralized gas boilers with centralized heat pumps; substituting existing fossil fuel-based heating systems in each apartment with centralized heat pumps;
3. Installation of photovoltaic systems and a battery system: deploying a 350 kW PV capacity on building rooftops with the integration of a 600 kWh battery storage system.
4. Utilizing renewable energy generated by a nearby parking area with 1.1. MW PV capacity.

5.3.1. Scenario 1: building envelope enhancements (insulation and window replacement)

Fig. 15 illustrates the monthly heating and cooling energy demand

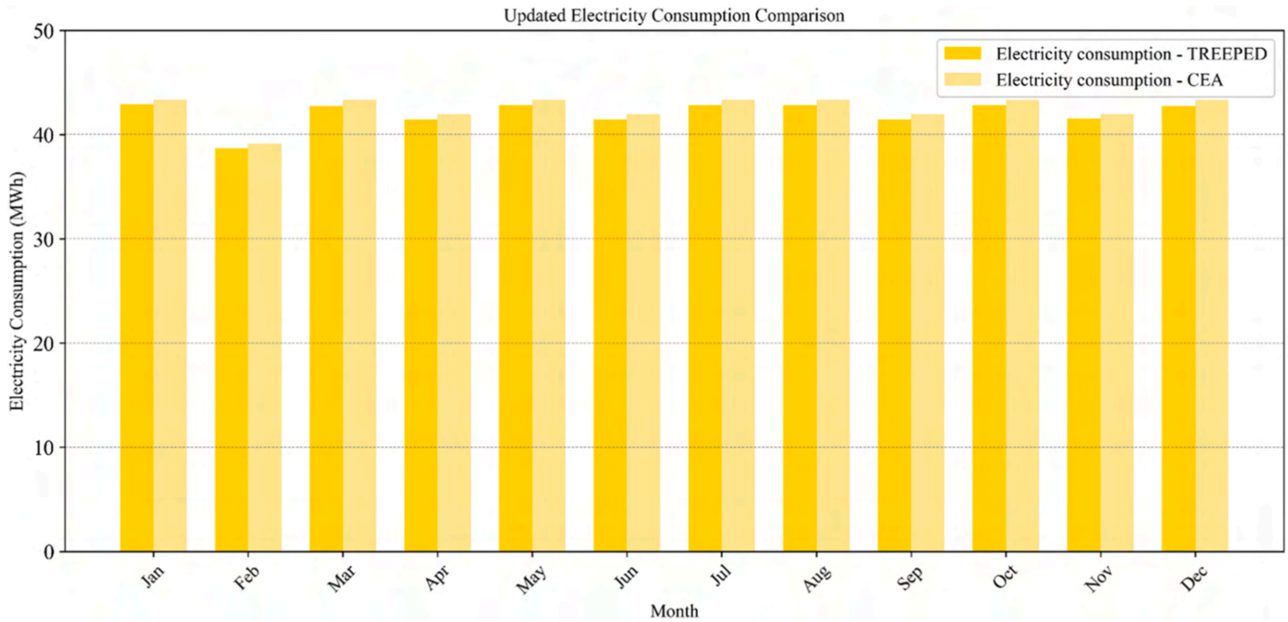

Fig. 12. Monthly electricity demand comparison.

Table 8
Impact of enhancing building insulation on transmittance of opaque surfaces.

	U-value [W/m^2-K]	
Opaque surface	Baseline archetype	Renovated archetype
External Walls	0.59	0.22
Roof	3.48	0.33

Table 9
Impact of window replacement on transmittance and g value.

	Windows	U-value [W/m^2-K]	g-value
Baseline archetype	Double Windows	2.7	0.8
Renovated archetype	Double Windows + argon	1.2	0.4

for the San Pedro district, comparing the baseline scenario with the "renovated" scenario.

For annual heating demand, the district with insulation exhibits a total consumption of 1.07 GWh, compared to 1.29 GWh for the district without insulation, representing a reduction of 17 %. Similarly, for annual cooling demand, the district with insulation achieves a significant reduction, consuming only 0.01 GWh, compared to 0.06 GWh for the district without insulation, corresponding to a decrease of 84 %.

On a monthly scale, in the baseline scenario, heating demand peaks in January at over 300 MWh, reflecting the high energy requirements due to poorly insulated buildings. After the renovation, January's heating demand drops to approximately 250 MWh, representing a reduction of around 26 %. Similar reductions are observed in other winter months, such as December, where the demand decreases from around 300 MWh to just over 200 MWh and February, where it falls from approximately 210 MWh to 170 MWh.

However, in transitional months such as April, May and October, the heating demand for the renovated scenario exceeds that of the baseline. This is due to the reduced solar heat gain from the new windows with lower g-values, which decreases passive solar heating during these months. As a result, additional heating is required to compensate for the lower internal gains, illustrating a trade-off between improved insulation and reduced passive solar contribution

In contrast, the cooling demand is much lower throughout the year. In the baseline scenario, peaking at approximately 30 MWh in July. Overall, the retrofit interventions reduce the district's energy demand for both heating and cooling. Heating demand, being the predominant energy need, experiences the largest reductions.

5.3.2. *Scenario 2: replacement of the existing decentralized gas boilers with centralized heat pumps*

Fig. 16 illustrates the monthly electricity consumption, comparing the baseline scenario with the renovated scenario after implementing wall insulation, replacing windows and transitioning from gas boilers to heat pumps for heating.

For annual electricity consumption, the district with insulation exhibits a total usage of 0.72 GWh, compared to 0.50 GWh for the district without insulation, representing an increase of 43 %. This rise is primarily due to the transition from gas boilers to electric heat pumps, which, despite being more efficient, require additional electricity to operate.

In the baseline scenario, electricity consumption is stable throughout

Section 1: DISTRICT INFORMATIONS														
SEGMENTATION						OTHER INFORMATIONS								
Country	Construction period	Building type	Number of floors	Windows replaced	Insulated	Number of buildings for archetype	Floor area conditioned (for single building) [m^2]	Latitude	Longitude (est)	Total Roof	Total external Walls (N)	Total external Walls (S)	Total external Walls (W)	Total external Walls (E)
Spain	1945-1969	APARTMENT BLOCKS	3	No	No	10	1743.35	42.81	1.66	3.33E+03	1.14E+03	1.14E+03	5.48E+03	5.48E+03

Fig. 13. Input District (Segmentation and other information) of San Pedro.

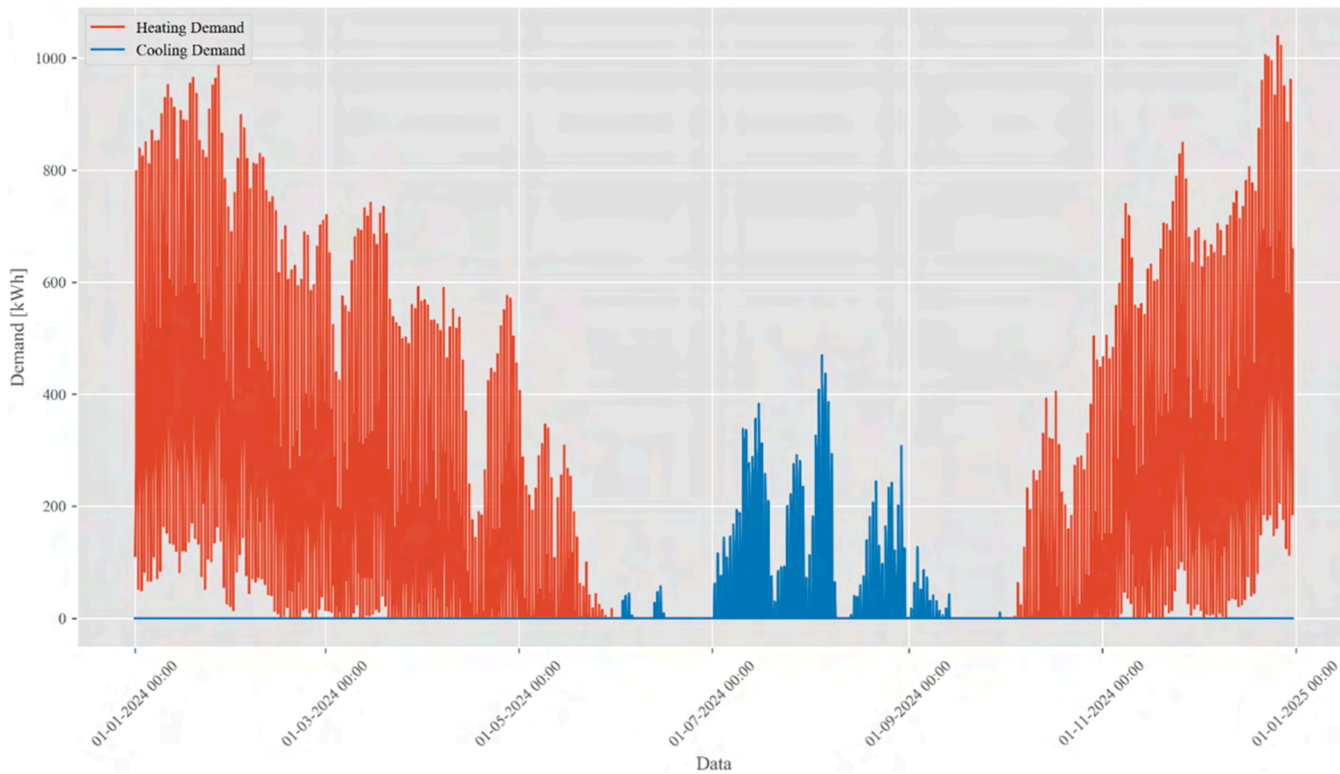

Fig. 14. Hourly heating and cooling demand of the San Pedro district over a year.

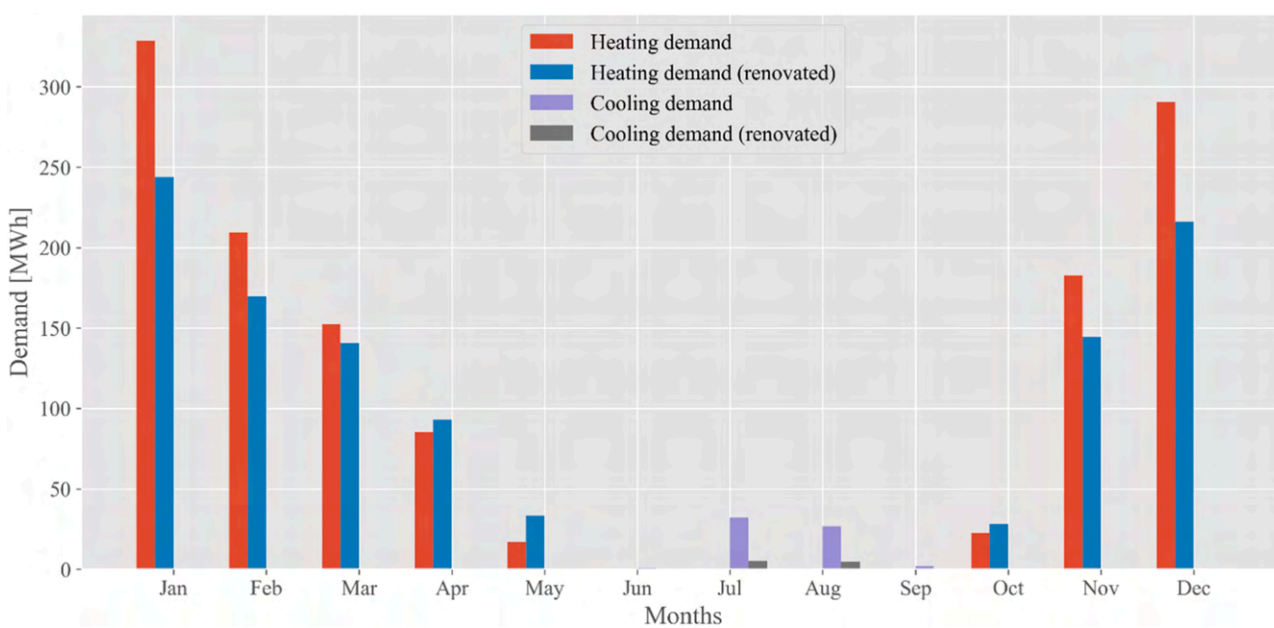

Fig. 15. Comparison of thermal results pre- and post-insulation installation and window replacement.

the year, averaging between 0.04 GWh and 0.05 GWh per month. This reflects the district's limited use of electricity, primarily for lighting and as heating demand and domestic hot water in the baseline are supplied by gas boilers.

After the renovation, electricity consumption increases significantly, particularly during the winter months. For instance, in January, electricity demand rises from approximately 0.05 GWh in the baseline to over 0.08 GWh in the renovated scenario.

During the summer months, the increase in electricity consumption is much less pronounced, as cooling demand remains moderate and the retrofitting measures reduce overall energy needs for cooling.

The next three figures illustrate weekly energy consumption profiles for spring, summer and winter, comparing original versus renovated conditions.

In the Fig. 17 the renovated heating profile has lower peaks due to the insulation upgrades that reduce the overall heating requirements while the electricity usage rises because the system switches from a methane-based system to reliant on electric power.

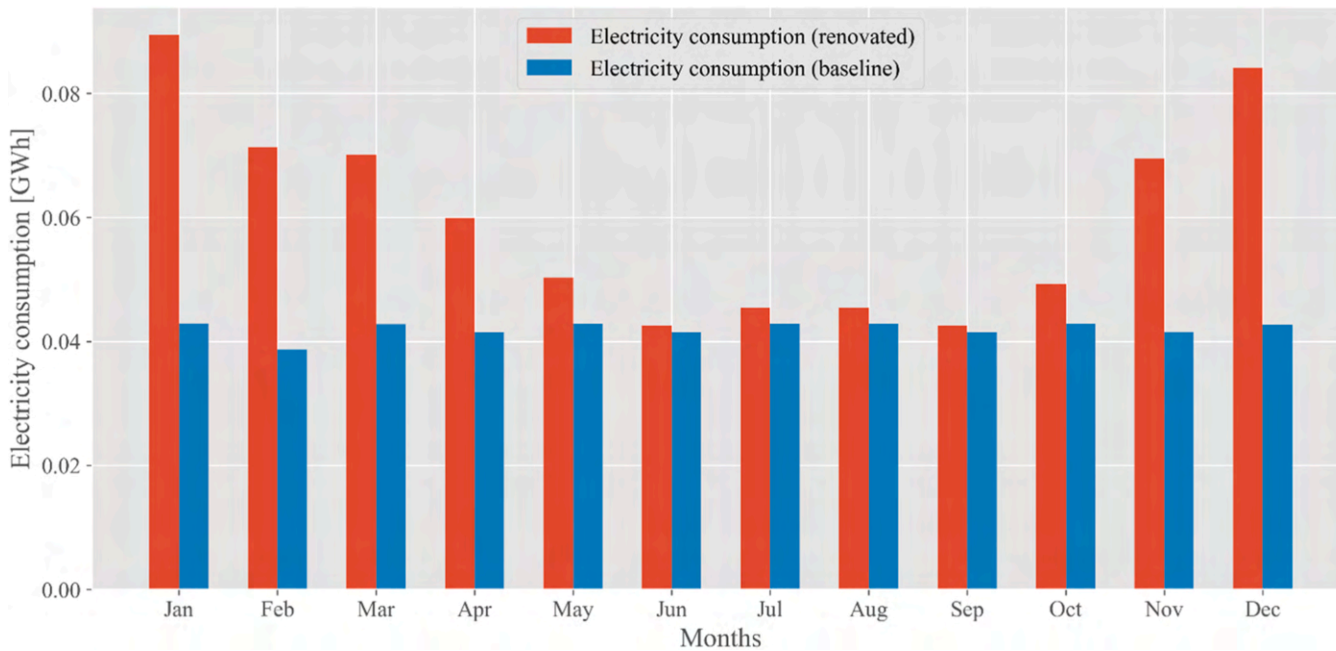

Fig. 16. Comparison of electricity consumption variation pre- and post-retrofit in the district.

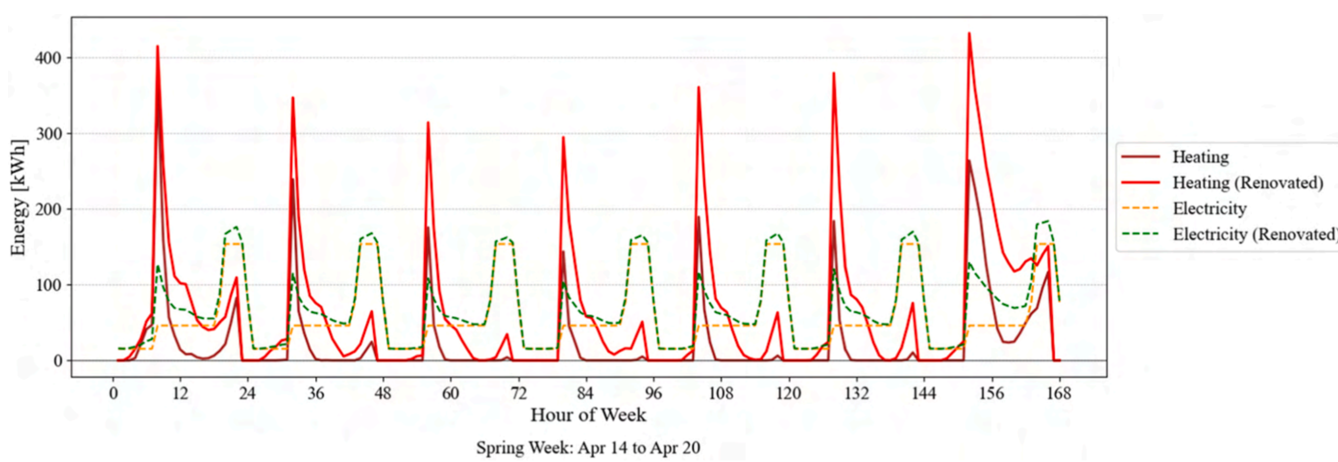

Fig. 17. Comparison of spring week with heating and electricity demand profile (April 14–20).

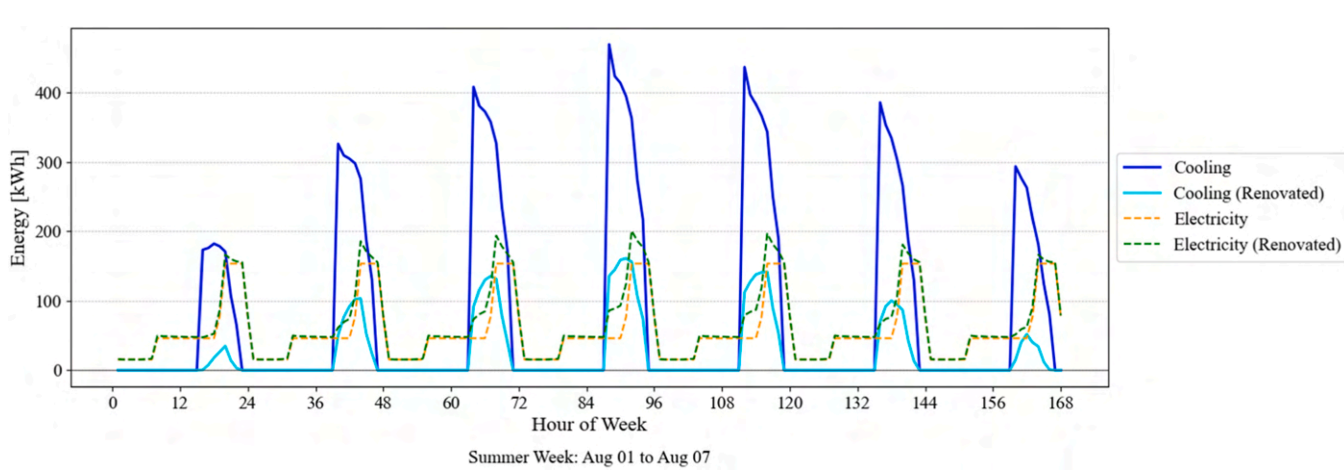

Fig. 18. Comparison of summer week with cooling and electricity demand profile (August 01–07).

In the Fig. 18, the original and renovated cooling profiles indicate that the retrofit lowers the baseline cooling demand, which is now satisfied by the new heat pump system. However, this shift has only a minor impact on total electricity consumption and, in fact, leaves it unchanged.

In the Fig. 19 a significant reduction in the overall heating demand is observed. Consequently, although the winter load is now supplied entirely by electricity, the associated increase in consumption remains relatively moderate.

5.3.3. Scenario 3: installation of photovoltaic (PV) systems with an integration of a battery storage system

Fig. 20 illustrates the monthly electricity dynamics after the installation of 350 kW of PV systems combined with 600 kWh of battery storage. The figure highlights the interplay between electricity generation, consumption, imports, exports and self-consumption.

Electricity generation exceeds consumption only during July. This indicates that, despite the installation of the PV system, the district does not achieve the PED target. The seasonal mismatch between generation and consumption highlights the district's continued dependence on grid imports during the winter and transitional months, underscoring the limitations of rooftop PV systems alone in meeting the district's annual energy balance requirements.

Fig. 21 shows how the battery capacity for the San Pedro district was selected in the tool using the LCF as the primary metric.

The plateau for the LCF is reached at approximately 1300 kWh, where further increases in battery capacity yield minimal improvements in the load cover factor. However, the graph also reveals that the reduction in grid electricity imports starts to diminish beyond 600 kWh, indicating a point of diminishing returns. Therefore, to balance energy flexibility with cost-effectiveness, a battery capacity of 600 kWh was conservatively chosen, ensuring significant performance improvements without overestimating storage requirements.

The JPI definition of a PED allows renewable energy not only to be produced locally within the district but also to be sourced from nearby areas. This flexibility emphasizes the integration of renewable energy systems at a broader regional level, enabling districts to meet their energy needs through a combination of local and adjacent renewable energy resources. This approach supports the PED objective by optimizing resource use and encouraging regional energy cooperation.

5.3.4. Scenario 4: iterative analysis of photovoltaic integration from nearby parking area

Fig. 22 illustrates the monthly results of this integration, showing how the additional energy generation from the solar park affects the district's overall energy balance.

Incorporating the additional photovoltaic energy from the nearby solar park, electricity generation significantly exceeds the district's consumption. This surplus highlights the effectiveness of integrating external renewable energy sources to achieve a positive energy balance.

Given that thermal energy needs are met through electricity, the energy balance is entirely electrical. The balance evaluates the annual difference between generation and consumption. If electricity generation exceeds consumption, the district achieves the PED target.

The district achieves a positive balance with a surplus of + 0.67 GWh, confirming its alignment with the PED target. This result was achieved through the integration of renewable energy sources, particularly photovoltaic systems installed both locally on rooftops and in the nearby parking area. This outcome underscores the importance of regional energy cooperation and the integration of nearby renewable energy sources to ensure energy balance and sustainability throughout the year. The results emphasize the effectiveness of the retrofit measures while also highlighting the need for continued optimization of renewable energy systems to further reduce grid dependency.

5.4. PED environmental assessment

In this section, the tool integrates embedded environmental datasets with input from earlier phases to comprehensively evaluate the life cycle impacts of the district. For the production and EoL phases of the renovated district, the analysis relies on embedded datasets and information gathered during the existing district phase. The use phase of the baseline district is assessed using data from the District Balance phase, while the use phase of the renovated district is evaluated based on inputs from the District Renovate phase. This approach ensures a thorough and detailed assessment of environmental impacts across all life cycle phases, providing a solid foundation for informed decision-making.

Table 10 presents the results of the environmental impact assessment for the district, comparing the baseline and renovated scenarios focusing on the analysis of GWP and CED.

In the baseline scenario, the GWP is 614 tCO_{2eq}, reflecting the greenhouse gas emissions from the current state of the district, which depend on inefficient energy systems and fossil fuels. The CED in the same scenario is 12,710.35 GJ, indicating high energy consumption due to operational inefficiencies and the absence of renewable energy integration.

In the renovated scenario, the GWP decreases to 243 tCO_{2eq}, demonstrating a substantial reduction in emissions resulting from the retrofit measures. The CED also drops significantly to 3876.97 GJ, showing a marked decrease in energy demand due to improved efficiency and the use of renewable energy. This comparison underscores the effectiveness of the renovation in reducing both energy consumption and greenhouse gas emissions, aligning the district with sustainability objectives and PED targets.

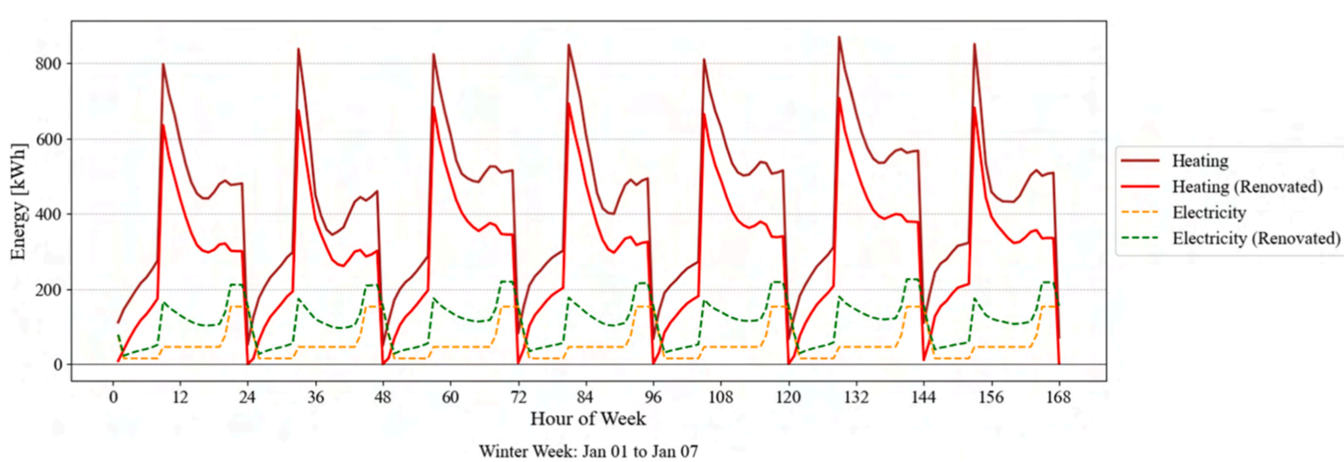

Fig. 19. Comparison of winter week with heating and electricity demand profile (January 01–07).

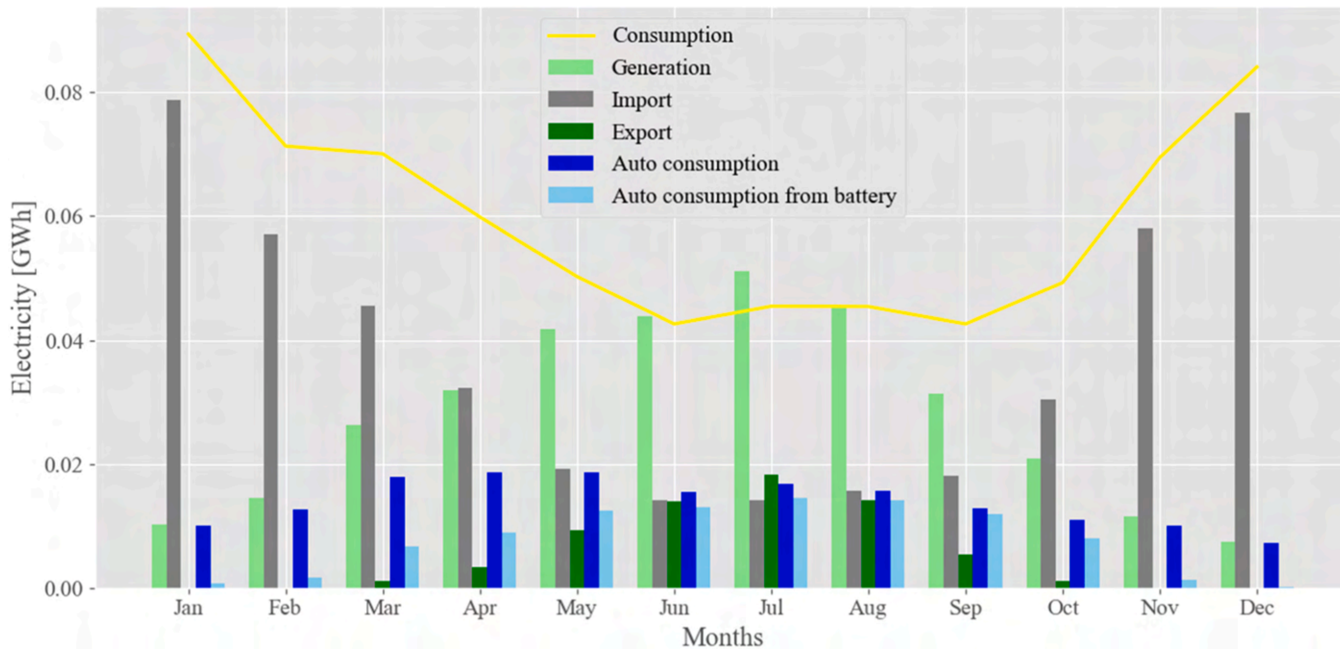

Fig. 20. Comparison of district electricity generation and consumption.

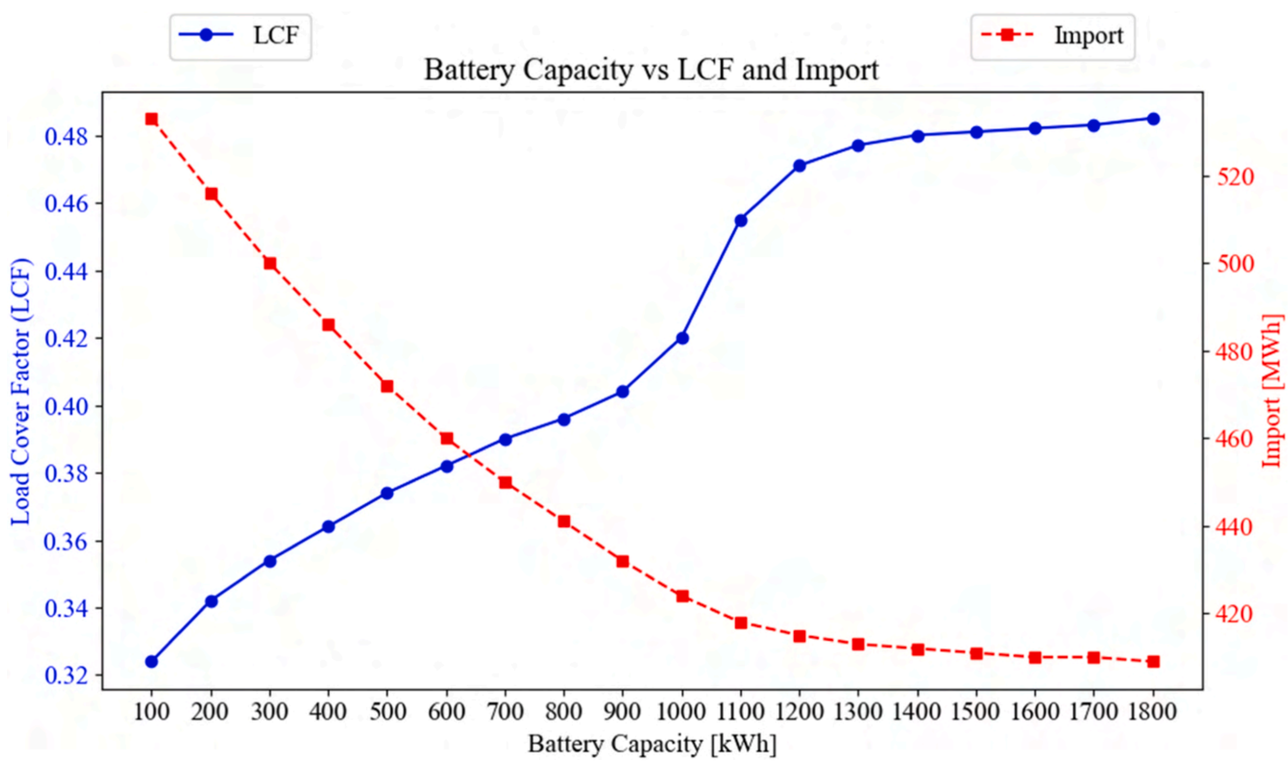

Fig. 21. LCF based on battery size.

When focusing exclusively on the use phase, distinct trends emerge for both GWP and CED.

For GWP, in the baseline scenario, electricity imports, contributing 166 tCO_2eq and methane consumption, which accounts for 448 tCO_2eq.

Conversely, in the renovated scenario, the electrification of heating systems significantly reduces reliance on methane, eliminating its contribution to emissions during the use phase. As a result, emissions from electricity imports are reduced to 107 tCO_2eq, demonstrating the effectiveness of renewable energy integration and energy efficiency measures in reducing greenhouse gas emissions.

Regarding CED, the baseline scenario reflects a substantial energy demand, with 4.98 TJ attributed to electricity imports and 7.73 TJ to methane consumption, resulting in a total operational energy demand of 12.71 TJ. In the renovated scenario, the transition to renewable electricity and enhanced energy efficiency leads to a marked decrease in energy consumption, with 3.21 TJ of CED attributed solely to electricity imports. This represents a significant reduction compared to the baseline scenario, underscoring the improvements achieved through retrofit

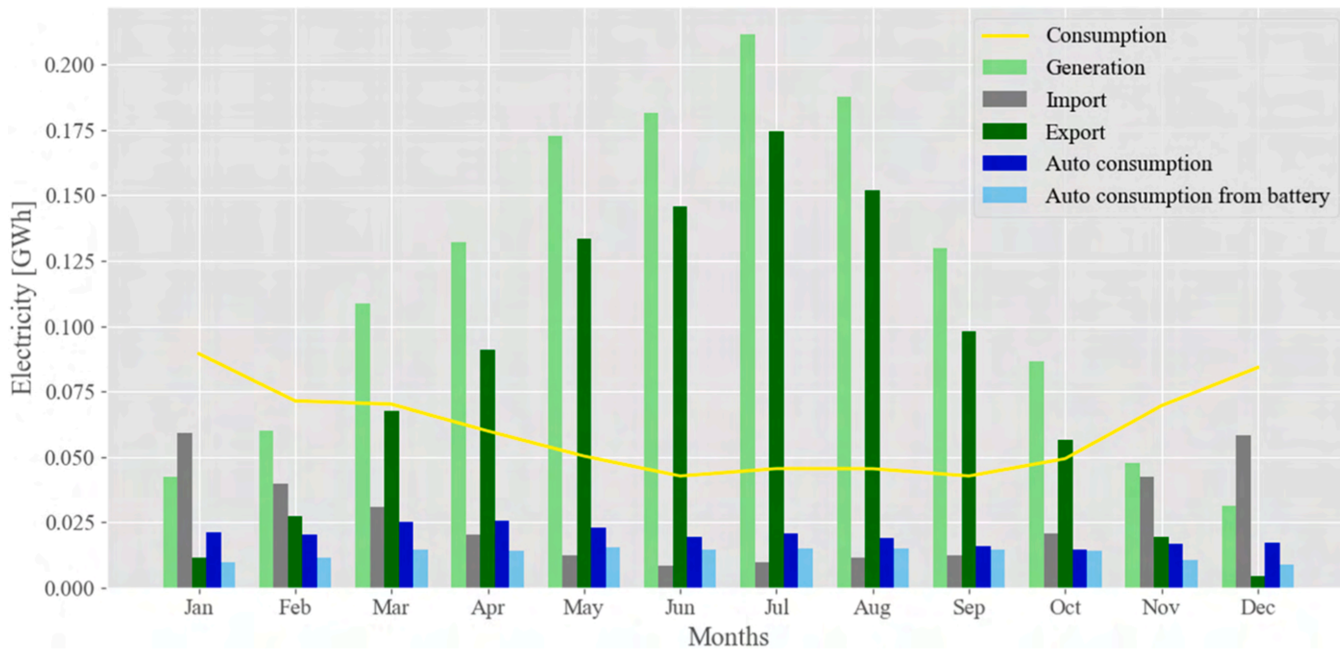

Fig. 22. Comparison of district electricity generation and consumption.

Table 10
Environmental impact assessment in the district.

Scenario	GWP $[tCO_{2eq}]$	CED [GJ]
Scenario baseline	614	12,710.35
Scenario renovated	243	3876.97

measures.

Fig. 23 represents a dominance analysis of the GWP across the life cycle phases of the renovated district. It breaks down the environmental impact into three main phases: Use Phase, Production Phase and EoL, highlighting the contribution of each to the total GWP.

The environmental impact of the photovoltaic system considered in this assessment refers only to the newly installed panels on the rooftops of the district buildings. The photovoltaic system located in the parking area is pre-existing, and its environmental impact is not included in the calculation. This ensures that the results focus solely on the impacts associated with the new retrofit interventions.

The Use phase dominates the analysis representing about 4 % of the total GWP, primarily attributed to electricity imports required for the district's operation after retrofitting.

The production phase, which includes the manufacturing of new materials and systems, contributes a smaller share, with impacts from the photovoltaic system (12.3 %), the battery (2.6 %), windows (0.9 %) and other elements such as insulation and heat pumps.

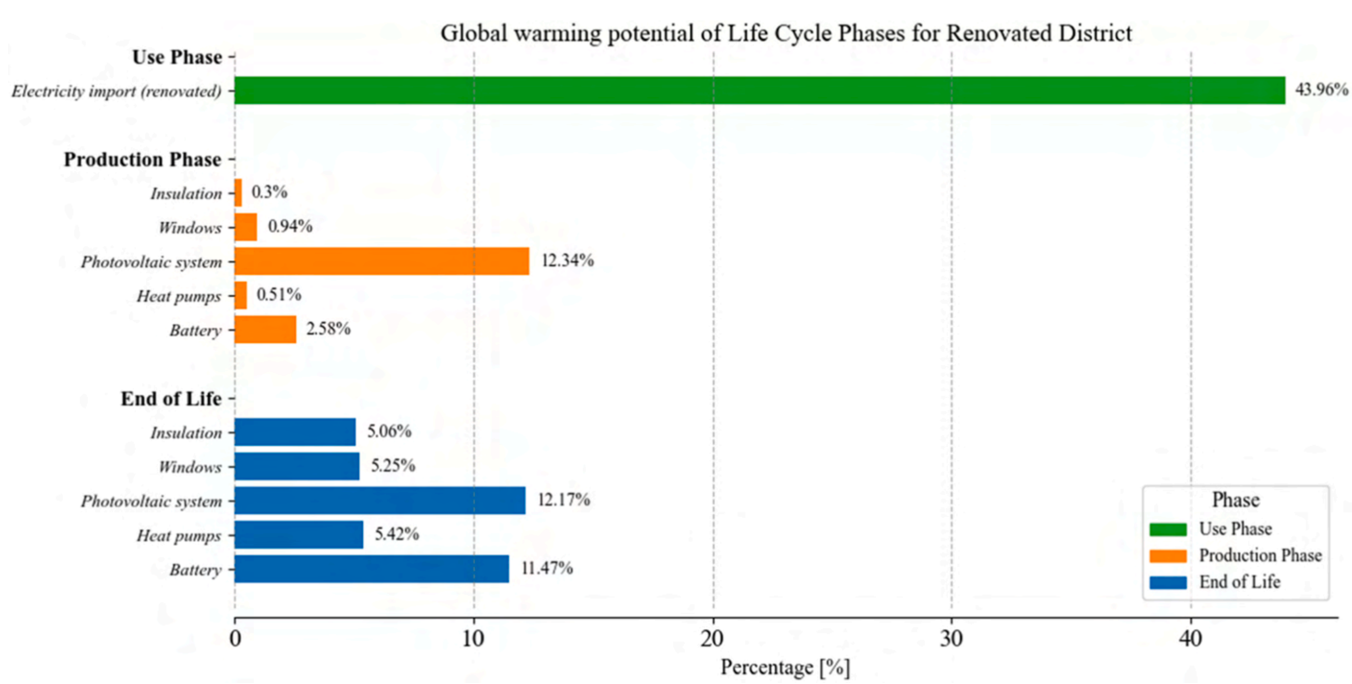

Fig. 23. Environmental impacts: GWP dominance analysis.

Within the EoL phase, the disposal of the photovoltaic system is with 12.2 % the largest contributor, followed by battery 11.5 %, heat pumps and other components like insulation and windows, each contributing around 5 %.

This analysis underscores that while retrofitting significantly reduces operational impacts during the use phase, the environmental burdens of production and EoL stages, especially for systems like photovoltaic panels, play an important role. It highlights the importance of considering the full life cycle when designing and implementing retrofit strategies to optimize environmental performance.

Fig. 24 illustrates a dominance analysis of the CED across the life cycle phases of the renovated district.

The Use Phase is the most significant, accounting for 82.8 % of the total CED. This dominance reflects the energy required for electricity imports during the operational phase of the renovated district. The Production Phase contributes a smaller share, with the photovoltaic system having the largest impact at 12 %, followed by the battery (2.7 %), windows (1 %), insulation (0.3 %) and heat pumps (0.2 %).

The EoL Phase represents a minor portion of the total CED, with the photovoltaic system contributing 0.3 %, followed by heat pumps (0.4 %), windows (0.1 %) and other elements such as insulation and batteries with negligible impacts.

This analysis highlights the critical role of the use phase in determining the district's overall energy demand, emphasizing the importance of improving operational energy efficiency to minimize long-term environmental impacts. At the same time, it shows that while production and EoL impacts are smaller, they remain non-negligible, particularly for photovoltaic systems and batteries, underlining the need for sustainable material and technology choices in retrofitting strategies.

6. Discussion

The results highlight TREEPED's potential to drive sustainable urban transformations, particularly in early-stage planning for PEDs. Its archetype-based approach simplifies the complexity of urban building energy modeling, making it accessible for large-scale district assessments with minimal data input. Furthermore, its capacity for integrating LCA across production, use and EoL phases ensures a comprehensive understanding of the environmental trade-offs associated with retrofit measures. The tool's iterative capabilities allow for dynamic scenario testing, offering decision-makers a flexible resource for optimizing strategies toward achieving PED targets. This combination of usability, scalability and analytical depth positions TREEPED as an asset in advancing sustainable urban development initiatives. This ensures a holistic understanding of environmental trade-offs and supports decisions that balance operational efficiency with life cycle sustainability.

The generalizability and adaptability across diverse geographical and urban contexts constitute key strengths of TREEPED. The archetype-based methodology significantly reduces data input requirements while maintaining analytical consistency. Specifically, TREEPED use internationally recognized standards. Specifically, internal heat gains—including occupancy, lighting, and appliance loads—for non-residential buildings are defined according to ISO 18523–1, while residential building schedules and internal heat gains follow EN 16798–1:2019. Additionally, lighting energy performance in residential buildings is modeled based on EN 15193–2. This standards-based approach provides planners with flexibility to adapt critical parameters—including local climate data, building characteristics, regulatory frameworks, and construction practices—according to specific local contexts. The database currently includes the case-studies of the KINETIC (https://kinetic-project.eu/ (Natanian et al., 2024)) project (Italy, Romania, Denmark) plus the case of Pamplona but is being updated and expanded.While showing versatility and potential for supporting the design of district at a very early design stage, the tool proposed in this paper cannot perform more detailed simulations of final design level, such as investigate thermal comfort assessment for occupants or detailed district heating sizing.

The annual deviations observed when comparing TREEPED's outputs to those of the CEA, such as −8 % for heating demand and −12 % for cooling demand, reflect methodological differences but confirm the tool's overall reliability as a simplified yet robust framework for early-stage planning.

Site-specific solutions also emerged as a crucial aspect of retrofit planning. TREEPED's iterative capabilities facilitated the testing of various configurations tailored to the unique characteristics of the San Pedro district.

One of the key insights from the renovation is the substantial reduction in heating demand (17 % annually) achieved through

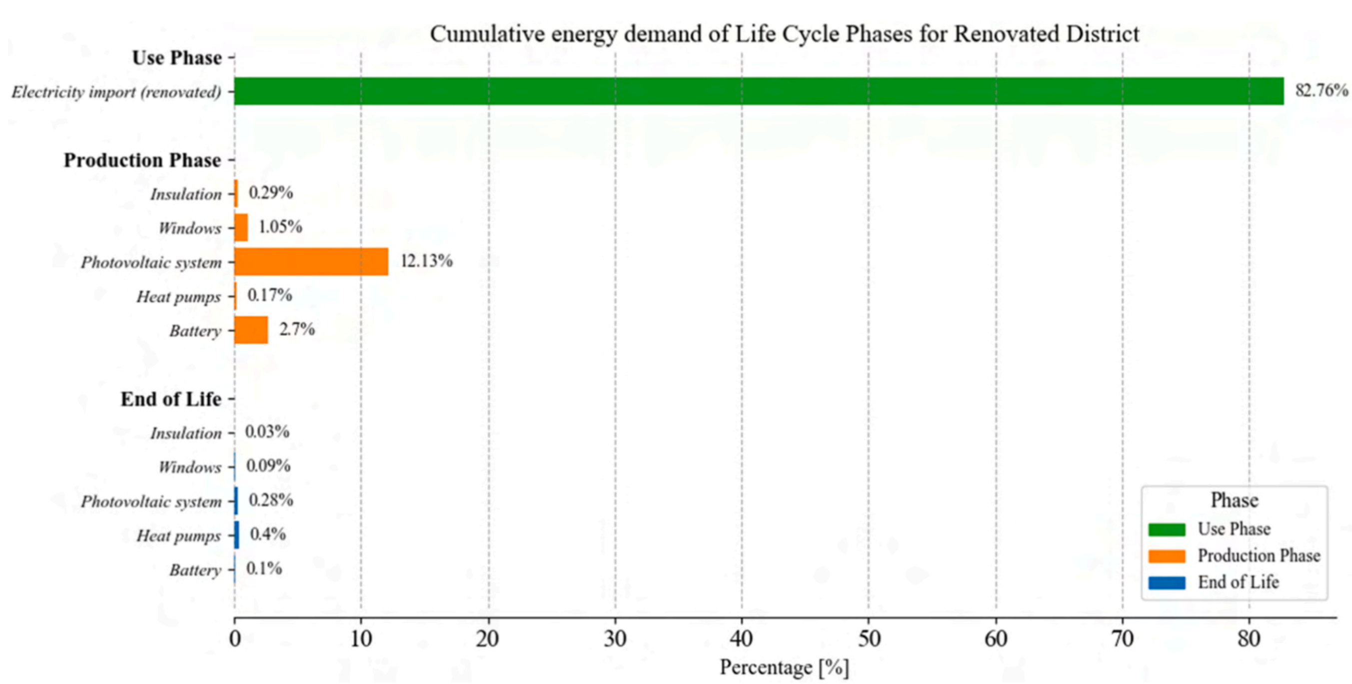

Fig. 24. Environmental impacts: CED dominance analysis.

building envelope enhancements. Equally significant is the replacement of fossil-fuel-based systems with electric heat pumps, which, although leading to a 43 % increase in annual electricity consumption, completely eliminated the district's reliance on fossil fuels.

The installation of rooftop photovoltaic (PV) systems demonstrates the limitations of relying solely on local renewable energy generation to meet PED objectives. Despite significant contributions from rooftop PVs, the energy balance of the district remained insufficient to achieve a net-positive status. This highlights the necessity of adopting a regional approach for PEDs, incorporating renewable energy systems located in nearby areas rather than being confined strictly within the district's boundaries. The inclusion of energy from the nearby solar park was critical in achieving a net-positive energy balance, showcasing the value of interconnected renewable energy systems.

Such strategies enhance the energy resilience of districts and align with international PED standards, bridging gaps between theoretical frameworks and practical implementation. These implications emphasize the role of holistic planning approaches in driving sustainable urban transformation.

Another significant aspect is the environmental trade-offs revealed through the life cycle assessment.

The results underscore the importance of balancing operational impacts with life cycle considerations. While retrofitting significantly reduces operational energy use and greenhouse gas emissions, the production and EoL phases introduce significant environmental burdens. For instance, the EoL phase of PV systems represented approximately 12.2 % of the total GWP. This finding highlights the need for policies that prioritize sustainable materials and technologies during retrofit planning and implementation to minimize the overall environmental footprint of urban districts.

In addition to its environmental and energy benefits, the retrofit measures evaluated with TREEPED hold significant potential for addressing energy poverty within the district. Although the tool does not explicitly conduct economic analyses, the substantial reduction in energy demand, coupled with the increased renewable energy, suggests a decrease in household energy costs. For residents of social housing, this translates into greater affordability and accessibility to modern energy services, thereby mitigating energy poverty. These outcomes are particularly relevant in contexts like the San Pedro district, where vulnerable populations face high risks of energy insecurity. Integrating such insights underscores the broader societal value of retrofit strategies, aligning sustainability objectives with social equity goals.

Finally, the broader implications of this study extend beyond energy performance and environmental sustainability. By addressing energy poverty within the San Pedro district, the retrofit measures demonstrate the potential for social benefits.

Specifically, the retrofit measures proposed by TREEPED directly contribute to social equity by lowering household energy costs and improving affordability. Such outcomes could not only enhance the residents' living conditions but also offer tangible solutions to mitigate energy poverty in vulnerable communities, highlighting the interconnected nature of energy efficiency and social sustainability. The tool therefore allows stakeholders and practitioners to investigate said issues at the pre-feasibility phase, investigating affordability and potential impacts to the vulnerability of the district.

These outcomes highlight the importance of coupling technical solutions with social equity considerations to ensure holistic and inclusive urban development.

Future research should explore the incorporation of social and economic dimensions into TREEPED, allowing for a more comprehensive assessment of sustainability. Expanding the tool's capabilities to evaluate affordability and community acceptance could further enhance its utility in addressing the multifaceted challenges of PEDs.

7. Conclusions

This study underscores the potential and practical effectiveness of TREEPED as an integrated tool for guiding the early-stage planning of PEDs in existing urban environments. By combining energy performance analysis with LCA, TREEPED offers a structured, yet accessible, framework for urban decision-makers. In doing so, it provides essential support for aligning climate mitigation goals with tangible strategies for enhancing both building stock efficiency and district-level energy resilience.

The application to the San Pedro district in Pamplona exemplifies how TREEPED can translate theoretical sustainability objectives into concrete, measurable outcomes. The comprehensive retrofit measures—encompassing building envelope improvements, the electrification of heating systems and the implementation of renewable energy—delivered a 17 % annual reduction in heating demand, an 84 % decrease in cooling demand and a 43 % increase in electricity demand due to the transition from gas boilers to electric heat pumps. These interventions resulted in a 60 % reduction in GWP and a 69 % decrease in CED, emphasizing the importance of combining efficiency measures with renewable energy sources. Moreover, the district's successful integration of energy from a nearby solar park underscores TREEPED's capability to facilitate the design of PEDs that extend beyond single-building interventions. This approach not only achieves a positive annual energy balance—exceeding PED requirements by 0.67 GWh—but also highlights the importance of regional energy cooperation in achieving climate targets and securing long-term energy autonomy.

These results were further validated through comparative analyses with the CEA tool. While discrepancies such as −8 % for heating demand and −12 % for cooling demand emerged due to methodological differences, the overall alignment confirms TREEPED's reliability as a robust and simplified tool for early-stage PED planning. By accounting for full life cycle impacts, TREEPED ensures that policymakers can make decisions informed not only by immediate efficiency gains but also by long-term sustainability and carbon reduction pathways.

In particular, this study highlights several concrete policy recommendations:

- TREEPED's analyses clearly identify and quantify the most effective retrofit strategies, enabling policymakers to prioritize measures with the highest potential impact on energy performance and emissions reduction
- By revealing the limitations of solely district-level renewable energy generation, TREEPED promote regional cooperation in renewable infrastructure planning. Policymakers can use this insight to encourage cross-district renewable energy networks, as demonstrated by the crucial role played by a nearby solar park in achieving PED targets
- The findings from the San Pedro case study underscore an urgent need for targeted interventions. Retrofit measures should be implemented to improve building envelope performance and transition heating systems from gas boilers to more efficient electric heat pumps. Moreover, to accelerate the shift toward PEDs, it is essential to promote regional energy cooperation by integrating renewable energy sources from adjacent areas. These focused actions will not only rapidly reduce energy consumption and greenhouse gas emissions but also help alleviate energy poverty in vulnerable communities by lowering energy costs
- The explicit integration of life-cycle assessments into TREEPED enables policymakers to establish policies prioritizing sustainable materials and comprehensive end-of-life management strategies, thus directly influencing procurement decisions and regulatory frameworks.

TREEPED's archetype-based methodology represents another key advantage, reducing input data requirements without sacrificing analytical robustness. This design ensures that the tool remains adaptable across a range of urban contexts—whether data-rich metropolitan centers or smaller municipalities with limited information. Through its holistic evaluation of life cycle considerations, TREEPED helps public authorities, urban planners and private stakeholders with a sophisticated yet user-friendly instrument. The resulting insights can inform effective, timely actions aimed at enhancing energy efficiency, lowering carbon footprints and fostering a more resilient built environment.

Even though the primary objective of the retrofit strategies is to achieve the PED target in the renovated district scenario, the LCA analysis of these strategies supports the transition to PEDs beyond mere energy savings. By revealing the full environmental impact—from production through operation to end-of-life—TREEPED contributes to broader sustainability goals and informs policymaking. Its integrated approach offers decision-makers quantifiable data that can boost targeted policies, thereby facilitating a comprehensive shift toward sustainable, climate-resilient urban environments.

Looking ahead, TREEPED's developmental trajectory involves an expanded scope that incorporates social and economic dimensions. Such an evolution is critical for reflecting the multifaceted reality of sustainable urban transformation, where technical performance criteria intersect with affordability, social inclusion and local acceptance. By incorporating indicators for energy poverty, the tool could help evaluate and address energy affordability challenges, especially in vulnerable districts like San Pedro. This integrative approach—aligning simplicity, adaptability and scalability with a comprehensive understanding of economic viability and social equity—positions TREEPED to become an important resource for the future of sustainable, equitable and climate-resilient urban districts.

CRediT authorship contribution statement

Longo Sonia: Validation, Supervision. **Diaz de Garayo Sergio:** Validation, Supervision, Data curation, Conceptualization. **Cellura Maurizio:** Visualization, Supervision, Formal analysis. **Brunetti Alberto:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation. **Ciulla Giuseppina:** Validation, Data curation, Conceptualization. **Guarino Francesco:** Validation, Supervision, Formal analysis, 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

No data was used for the research described in the article.

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Glossary

API: Application Programming Interface
EPBD: Energy Performance of Buildings Directive
CED: Cumulative Energy Demand
DHW: Domestic Hot Water
EPCs: Energy Performance Certificates
EoL: End-of-Life
GWP: Global Warming Potential
ICT: Information and Communication Technology
JPI: Joint Programming Initiative
LCF: Load Cover Factor
LCA: Life Cycle Assessment
nZEB: Net Zero Energy Building
PED: Positive Energy District
PEF: Primary Energy Factor
PV: Photovoltaic
RC: Resistor-Capacitor (thermal modeling method)
SCOP: Seasonal Coefficient of Performance
SEER: Seasonal Energy Efficiency Ratio
TREEPED: Tool for Resource and Environmental Evaluation for Positive Energy Districts
TPEF: Total Primary Energy Factor
UBEM: Urban Building Energy Model
WWR: Window-to-Wall Ratio