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Development of an early design tool for positive energy districts: energy assessment and carbon footprint through four real case studies

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Summary

Abstract

This research presents an integrated approach to support the early-stage design of Positive Energy Districts (PEDs), aiming to guide urban areas toward reduced energy consumption and a sustainable energy transition.

The primary objective of this study is to develop a decision-support tool tailored to address the scalability, data availability, and usability challenges in existing PED methodologies, enabling energy-environmental assessments at the district scale.

The analysis focuses on four real districts—Pamplona, Bucharest, Copenhagen and Parma—and combines insights from existing PED case studies with the development of a decision-support tool for energy-environmental assessment at the district scale.

The methodology consists of three phases:

1. A critical review of existing PED implementations and current analytical tools to identify effective strategies and methodological gaps.
2. The formulation of building archetypes and the evaluation of retrofit measures—including renewable energy integration and envelope improvements—using standardized data and simulations to compensate for missing information.
3. A comparative Life Cycle Assessment (LCA) of pre- and post-retrofit scenarios, accounting for both operational energy use and full lifecycle impacts of materials and technologies.

The results confirm the potential for significant reductions in energy consumption, yet they also highlight the difficulty of meeting stringent PED criteria, especially for larger or more complex districts. The LCA findings indicate substantial decreases in Global Warming Potential (GWP) during operation; however, the material production and end-of-life stages remain significant contributors to overall environmental impacts. These outcomes underscore the need for a holistic approach that harmonizes energy efficiency measures with careful material selection.

By demonstrating adaptability to diverse urban contexts, the proposed tool and methodologies support more informed decision-making. This research advances PED development as a key strategy in guiding cities toward energy sustainability, balancing efficiency gains with broader environmental considerations.

Abbreviations

A_i	Surface area of panel
A_f	Frame area
A_g	Area of windows glass
A_{PP}	Area of the premium panel
A_{SP}	Area of the standard panel
A_{TF}	Area of the thin-film panel
A_{TW}	Total vertical wall
A_w	Area of windows
API	Application Programming Interface
B	Balance results of the district
AC	Alternating current
C	Battery energy capacity
CED	Cumulative Energy Demand
CEN	European Committee for Standardization
DHW	Domestic hot water
DC	Direct current
E_b	Thermal energy produced by biomass combustion
E_c	Electricity consumption
E_e	Electricity exported
E_i	Electricity imported
E_M	Thermal energy produced by methane combustion
E_o	Thermal energy produced by oil combustion
ED	Energy demand
ED_C	Energy demand for cooling
ED_{C-HP}	Energy demand for cooling covered by heat pumps
ED_{C-DC}	Energy demand for cooling covered by district cooling systems
ED_{DHW}	Energy demand for domestic hot water
ED_{DHW-HP}	Energy demand for domestic hot water covered by heat pumps
ED_{DHW-WH}	Energy demand for domestic hot water covered by electric water heaters
ED_{DHW-B}	Energy demand for domestic hot water covered by boilers
ED_H	Energy demand for heating
ED_{H-HP}	Energy demand for heating covered by heat pumps
ED_{H-DH}	Energy demand for heating covered by district heating systems
ED_{H-B}	Energy demand for heating covered by boilers
EI_B	Environmental impact of the production phase of boilers
EI_{bc}	Environmental impact of biomass consumed
EI_{bs}	Environmental impact of the production phase of the battery system
EI_{DH}	Environmental impact of the production phase of the district heating
$EI_{end,B}$	Environmental impact of the end of life of the boiler
$EI_{end,bs}$	Environmental impact of the end of life of the battery system
$EI_{end,HP}$	Environmental impact of the end of life of the heat pumps
$EI_{end,i}$	Environmental impact of the end of life of the insulation
$EI_{end,p}$	Environmental impact of the end of life of the photovoltaic system
$EI_{end,st}$	Environmental impact of the end of life of the solar thermal system
$EI_{end,w}$	Environmental impact of the end of life of windows
EI_{HP}	Environmental impact of the production phase of heat pumps
EI_i	Environmental impact of the production phase of the insulation
EI_{ii}	Environmental impact of electricity imported
EI_{mc}	Environmental impact of methane consumed
EI_{oc}	Environmental Impact of oil consumed

EI_p	Environmental impact of the production phase of the photovoltaic system
EI_{st}	Environmental impact of the production phase of the solar thermal system
EI_w	Environmental impact of windows
El_{BS-EC}	Electricity delivered from the battery system to feed the electricity consumption
El_{PV-BS}	Electricity delivered from the photovoltaic system to feed the battery system
EPBD	Energy Performance of Bulding Directive
EPC	Energy Performance Certificate
EPT	Energy Payback Time
ERR	Energy Return Ratio
ETS	Emissions Trading System
EU	European Union
f	Frame ratio
F_{grid}	Grid interaction index
FC_b	Biomass characterization factor
FC_{bs}	Battery system characterization factor
FC_{DH}	District heating characterization factor
FC_e	Electricity characterization factor
$FC_{end,B}$	Boilers characterization factor (end of life)
$FC_{end,bs}$	Battery system characterization factor (end of life)
$FC_{end,f}$	Window frame characterization factor (end of life)
$FC_{end,HP}$	Heat pumps characterization factor (end of life)
$FC_{end,g}$	Window glass characterization factor (end of life)
$FC_{end,i}$	Insulation characterization factor (end of life)
$FC_{end,st}$	Solar thermal characterization factor (end of life)
FC_g	Window glass characterization factor
FC_{HP}	Heat pumps characterization factor
FC_i	Insulation characterization factor
FC_f	Window frame characterization factor
FC_m	Methane characterization factor
FC_o	Oil characterization factor
FC_p	Photovoltaic system characterization factor
FC_{ST}	Solar thermal system characterization factor
FEC	Final energy consumption
FEC_{DHW}	Final energy consumption used to cover the EDDHW
FEC_{DHW-El}	Electric final energy consumption used to cover the EDDHW
FEC_{DHW-Th}	Thermal final energy consumption used to cover the EDDHW
FEC_H	Final energy consumption used to cover the EDH
FEC_{H-El}	Electric final energy consumption used to cover the EDH
FEC_{H-Th}	Thermal final energy consumption used to cover the EDH
FEC_C	Final Energy consumption used to cover the EDC
FEC_{C-El}	Electric Final energy consumption used to cover the EDC
GHG	Anthropogenic Greenhouse Gas
GIS	Geographic Information System
GWP-PT	lobal Warming Potential Payback Time
GWP_b	Global Warming Potential caused by the baseline districts in manufacturing
$GWP_{b,o}$	Global Warming Potential caused by the baseline district during the operation phase
$GWP_{r,o}$	Global Warming Potential caused by the renovated district during the operation phase
GWP_r	Global Warming Potential caused by the renovated districts in manufacturing
GWP_s	Global Warming Potential avoids
G(t)	Electricity generated

HVAC	Heating Ventilation Air Condition
I_b	Beam normal input multiplied by the cosine of the angle of incidence
I_{beam}	Direct beam irradiance
I_d	Diffuse horizontal irradiance
$I_{d,ground}$	Ground reflected irradiance
$I_{d,sky}$	Total sky diffuse on the surface
I_{kj}	Fuel consumption of the kth energy carrier for a single jth archetype
I_{poa}	Plane of array irradiance
$I_{t,direct}$	Direct radiation on a panel
$I_{t,d}$	Total diffuse solar irradiance by a tilted surface
$I_{t,g}$	Global irradiance
I_{tr}	Transmitted plane of array
$I_{t,r}$	Ground-reflected irradiance on the tilted surface
ISO	Organization for Standardization
JPI	Joint Programming Initiative
KPIs	Key Performance Indicator
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
M_i	Amount of insulation
P_B	kW of the boiler installed
P_{dc}	Power output from the solar array
P_{HP}	Installed capacity of heat pumps
P_p	Installed capacity of photovoltaic system
PCS_k	Lower heating value of the kth energy carrier
Pdc	Power output from the solar array
Pdc0	Power output of the array under standard test conditions
PE_b	Primary energy consumed by the baseline districts in manufacturing
$PE_{b,o}$	Primary energy consumed by the baseline district during the operation phase
PE_r	Primary energy consumed by the renovated districts in manufacturing and end of life
$PE_{r,o}$	Primary energy consumed by the renovated district during the operation phase
$PE_{s,o}$	Net yearly primary energy saving
PED	Positive Energy Districts
PEF_{nre}	Primary energy factors non-renewable for electricity
PEF_{nrk}	Non-Renewable primary energy conversion factor for the kth energy source
POA	Plane-of-Array
PV	Photovoltaic
Q_{out}	Thermal energy output from the solar panel
S(t)	Energy balance of energy storage system
SCOP	Seasonal Coefficient of Performance
SEER	Seasonal energy efficiency ratio
sm_{st}	Area of solar thermal installed
SoC	State of Charge
STC	Standard Test Conditions
T_{cell}	Operating cell temperature
$TPEF_K$	Total primary energy factors of k^{th} renewable energy
$TPEF_s$	Total primary energy factors of s^{th} energy source
T_{ref}	Reference cell temperature
TREE PED	Tool for Resource and Environmental Evaluation for Positive Energy Districts
UBEM	Urban Building Energy Modeling
UL_B	Boilers useful life

UL_{bs}	Battery system useful life
UL_{HP}	Heat pump useful life
UL_i	Insulation useful life
UL_p	Photovoltaic system useful life
UL_{st}	Solar thermal useful life
UL_w	Windows useful life
UNIPA	University of Palermo
WWR	Window to wall ratio.
WP	World Package
W_{bs}	Mass of battery system installed
ZEB/NZEB	Zero Energy Building (Near)
β	Solar altitude
Θ	Incident angle
Y	Diffuse irradiance coefficient
γ_{load}	Load cover factor
Σ	Tilt angle of the surface
ρ_g	Ground reflectance
η_B	Average efficiency of boiler
η_i	Efficiency of panel
η_{PP}	Efficiency of the premium panel
η_{SP}	Efficiency of the standard panel
η_{TF}	Efficiency of the thin-film panel
ε_{C-DC}	District cooling system efficiency for cooling
ε_{H-DH}	District heating system efficiency for heating
$\varepsilon(t)$	Battery efficiency
δ_{SoC}	Difference of state of charge
$\delta(t)$	Energy losses in the system
γ	Temperature coefficient

Figures

Tables

1. Introduction

1.1 The Global climate crisis

Human activities have led to an increase in the average global surface temperature, rising by approximately 1.2°C above pre-industrial levels (1850-1900) as of 2023. This new peak surpasses previous records[1].

This rise in temperature is accompanied by a continuous increase in net anthropogenic greenhouse gas (GHG) emissions across all major global sectors since 2010. Cities, with their high population densities and intense economic activities, have become major contributors to this environmental issue. Emissions from urban areas were estimated at 25 $GtCO_{2\text{-}eq}$ in 2015, making up about 60% of global emissions. By 2020, this number had grown to 29 $GtCO_{2\text{-}eq}$, representing approximately 70% of global emissions[2].

Given the current environmental crisis, maintaining conventional urbanization methods is unsustainable. A significant shift from the standard 'business-as-usual' approach is necessary, requiring immediate and coordinated action characterized by innovative solutions that go beyond traditional sectoral and geopolitical boundaries.

In this worldwide effort, urban areas are vital. With over half of the world's population living in cities [3], they are centres of economic, cultural and political power. While cities significantly contribute to environmental problems, they also have the potential to drive transformative ecological solutions. The concentration of resources, human capital and infrastructure in cities can drive the transition towards sustainable practices by fostering innovation and accelerating the adoption of sustainable technologies. This dual role of cities, as both contributors to and facilitators of solutions for environmental issues, underscores their importance in the global ecological transition.

The European Union (EU) has maintained a strong commitment to promoting sustainability and combating climate change, as reflected in its progressive policies and initiatives over time. Below is a synthesis of the most relevant and recent EU initiatives on ecological transition within urban environments.

1.2 European Union initiatives and policies for sustainability

1. **European Green Deal (2019)** [4]

Introduced by the European Commission, this ambitious policy framework aims to transform Europe into the world's first climate-neutral continent by 2050. It includes various sector-specific and cross-sectoral initiatives directly affecting urban sustainability, such as significant enhancements in the energy efficiency of buildings, promotion of circular economy principles and increased deployment of renewable energy sources.

2. **European Climate Law (2021)** [5]

Building on the European Green Deal, the European Climate Law legally enshrines the EU's commitment to achieving climate neutrality by 2050. This law sets a binding target for a 55% reduction in greenhouse gas emissions by 2030, compared to 1990 levels. It also establishes mechanisms for monitoring progress and ensures that all EU policies contribute to these goals. The Climate Law is a critical component in ensuring that the ambitious targets of the Green Deal are met through enforceable legislation.

3. **Fit for 55 Package (2021)** [6]

The Fit for 55 package is a suite of proposals designed to align the EU's climate, energy, land use, transport, and taxation policies with the goal of reducing net greenhouse gas emissions by at least 55% by 2030. Key elements include:

- Revisions to the Emissions Trading System (ETS) to lower the cap on emissions and increase the cost of emitting CO_2.
- The introduction of a Carbon Border Adjustment Mechanism to prevent carbon leakage by imposing tariffs on imported goods based on their carbon content.
- Reforms to the Renewable Energy Directive to increase the share of renewable energy in the EU's energy mix.

This package is integral to operationalizing the European Green Deal, ensuring that the necessary regulatory frameworks and incentives are in place to meet the 2030 climate targets.

A critical sector addressed by the "Fit for 55" package is the building sector, which accounts for approximately 40% of the EU's total energy consumption and 36% of its CO_2 emissions. To meet the ambitious targets set out in "Fit for 55," improving the energy performance of buildings is essential. This is where the Energy Performance of Buildings Directive (EPBD) becomes fundamental.

4. **Energy Performance of Buildings Directive (EPBD)** [7]

Enacted in 2010, redacted in 2018 and adopted in April 2024, this directive sets minimum energy performance standards and mandates energy certification of buildings, promoting energy savings and reducing greenhouse gas emissions in the sector.

The key elements of this directive are:

- National Energy Reduction Targets:

Each Member State will set its own trajectory to reduce the primary energy use of residential buildings by 16% by 2030 and 20-22% by 2035. For non-residential buildings, the 16% worst-performing buildings must be renovated by 2030, and the 26% worst-performing by 2033. Certain buildings, such as historical or holiday homes, can be exempted from these requirements.

- Zero-Emission Standards for New Buildings:

From January 1, 2028, new publicly-owned buildings must have zero on-site emissions from fossil fuels. This requirement extends to all new buildings by January 1, 2030, with specific exemptions allowed. The directive promotes the installation of solar power and ensures new buildings are 'solar ready'.

- Phasing out fossil fuels:

The directive includes provisions to progressively phase out fossil fuels for heating in buildings. Subsidies for fossil fuel-powered boilers will be banned starting January 1, 2025.

- Support for Building Renovations:

The establishment of one-stop shops for advice on building renovation. Enhanced public and private financing options to make renovations more affordable and feasible.

The EPBD is a cornerstone of the European Union’s strategy to enhance energy efficiency and reduce greenhouse gas emissions from the building sector. By establishing a comprehensive legislative framework, the EPBD aims to improve the energy performance of buildings across the EU.

Building on this framework, the Renovation Wave strategy was introduced in 2020 to accelerate and deepen these efforts significantly. This strategy aims to enhance the energy and resource efficiency of buildings throughout Europe by promoting extensive renovations that go beyond basic improvements.

5. **Renovation Wave Strategy** [8]

The Renovation Wave strategy, a vital component of the EU's environmental and economic plans, focuses on:

- Doubling renovation rates: The initiative aims to double the annual rate of renovations over the next decade, ensuring a substantial reduction in energy consumption and greenhouse gas emissions.
- Enhancing energy and resource efficiency: The strategy emphasizes comprehensive renovations that significantly improve energy and resource efficiency, integrating renewable energy sources and adopting sustainable construction practices.
- Improving living conditions: By enhancing the energy performance of buildings, the strategy aims to improve living standards, particularly in residential buildings. This includes providing better comfort, reducing energy bills, and improving indoor air quality.
- Stimulating economic growth: The Renovation Wave is expected to drive job creation and innovation within the construction sector, which is crucial for local economies. This initiative will boost demand for clean technologies and sustainable materials, linking environmental benefits with social and economic gains.

Achieving climate neutrality requires a holistic approach that transcends individual sectors and addresses broader geopolitical implications. In this context, two additional initiatives play a crucial role: the New Circular Economy Action Plan (CEAP) and the REPowerEU Plan:

1. **New circular economy action plan (CEAP) (2020)** [9]

This plan adopted in December 2015 aims to make sustainable products the norm, reduce waste, and ensure that resources are kept in the EU economy for as long as possible. This plan, essential for achieving the EU's goal of climate neutrality by 2050, focuses on key value chains such as electronics, batteries, packaging, plastics, textiles and construction.

2. **REPowerEU Plan (2022)** [10]

This plan aims to reduce dependence on Russian fossil fuels by diversifying energy supplies, accelerating the green transition, and improving energy efficiency. It includes measures to increase renewable energy production, improve energy storage, and boost energy efficiency.

To fully realize the ambitions of the European Green Deal, the role of research and innovation is fundamental. Horizon Europe, the EU's funding program for research and innovation, plays a critical role in this context by providing the necessary resources and support to develop cutting-edge technologies and solutions that address the multifaceted challenges of climate change and sustainable development.

Horizon Europe (2021-2027)[11] This framework program supports research and innovation across various fields, including climate action and sustainable development, with specific missions to address global challenges.

In addition to these initiatives, the EU supports several urban-level policies to foster sustainability and mitigate climate change:

1. **European Regional Development Fund (ERDF):** This fund enhances economic, social, and territorial cohesion by addressing regional disparities and supporting investments in a smarter, greener, more connected, and more inclusive Europe.
2. **European Urban Initiative:** This initiative promotes cooperation and the exchange of best practices among European cities to develop innovative and sustainable solutions to urban challenges.
3. **Covenant of Mayors for Climate and Energy:** This initiative brings together local and regional authorities committed to tackling climate change and promoting sustainable energy, encouraging cities to develop Sustainable Energy and Climate Action Plans (SECAPs).
4. **European Sustainable Cities Platform:** This platform accelerates the transition to sustainable and carbon-neutral cities by promoting cooperation, networking, and knowledge transfer among European cities.
5. **Urban Transition Mission:** Launched at COP26, this mission mobilizes decision-makers to embrace innovative solutions and expedite capacity-building for urban transitions.

6. **Smart Cities and Communities:** The EU supports the development of smart and sustainable cities through pilot and demonstration projects that integrate smart technologies, sustainable energy, mobility, and innovative solutions.
7. **Urban Agenda for the EU:** This agenda promotes integrated and sustainable urban development, focusing on better regulation, better funding, and better knowledge.
8. **Climate-Neutral and Smart Cities Mission:** This mission aims to support the realization of at least 100 climate-neutral cities across the EU by 2030 [12] and encourages all EU cities to strive towards climate neutrality by 2050.
9. **The New European Bauhaus:** This initiative connects art, culture, science, and technology to address societal challenges and improve quality of life through inclusion, sustainability, and beauty.
10. **European Green Capital Award:** This annual competition recognizes cities for their efforts and achievements in environmental sustainability, encouraging the adoption of green policies and raising awareness about environmental issues.

1.3 Challenges in urban areas and opportunities in districts

One of the primary obstacles to urban sustainability is financial barriers. Sustainability initiatives, such as implementing renewable energy systems, constructing energy-efficient buildings, and adopting smart technologies, require significant initial investments. Many cities struggle to secure the necessary funds for these projects due to limited budgets and competing priorities. Additionally, the return on investment can be perceived as uncertain or too long-term to attract private financing. Overcoming these financial barriers could open new investment opportunities and create jobs in the green sector, promoting sustainable economic growth alongside environmental conservation.

Institutional and regulatory barriers also pose significant challenges. Existing laws or regulations may be unsuitable for new technologies or approaches, thereby impeding the transition. For example, rigid building codes can limit the adoption of sustainable materials and techniques. Reforming these institutional structures can create a more conducive environment for innovation and empower local communities and businesses to become active participants in the ecological transition.

Social barriers, such as resistance to change from established interest groups or a lack of public awareness and acceptance, can also impede progress. People may be reluctant to change their habits or support new initiatives if they do not fully understand the benefits or fear negative impacts on their lifestyle. Strategies to overcome these barriers include effective communication and community engagement, as well as education and training programs to improve understanding of the benefits and necessity of ecological transition.

Governance challenges can arise from the complex nature of urban governance, with responsibilities fragmented across various levels of government and different agencies. This fragmentation can lead to inefficiencies and a lack of coordination, making it difficult to implement integrated sustainability strategies. Improving governance requires creating effective coordination mechanisms and strengthening institutional capacity at the local level to manage complex and interdisciplinary projects.

Despite these barriers, cities offer immense potential for positive change. The concentration of resources, human capital, and infrastructure in urban areas can drive innovation and accelerate the adoption of sustainable practices. However, working on a smaller scale, such as that of a district, can help overcome many of the challenges observed at the city level.

Positive Energy Districts (PEDs) exemplify this approach by focusing on smaller, more manageable urban areas that generate more energy than they consume. PEDs can address financial barriers by requiring smaller initial investments compared to city-wide projects, making it easier to secure funding and attract private investors. The smaller scale allows for quicker returns on investment and reduced financial risk.

Institutionally, PEDs can operate with greater flexibility, as they can be designed to work within or adapt to existing regulatory frameworks more easily than larger city-wide initiatives. This flexibility can facilitate the adoption of innovative technologies and practices that might otherwise face regulatory hurdles in a larger context.

Socially, PEDs offer more opportunities for community engagement and participation. The smaller scale makes it easier to involve residents in planning and decision-making processes, fostering a sense of ownership and increasing public support for sustainability initiatives. This community buy-in is crucial for the success of ecological transitions.

In terms of governance, the smaller scale of PEDs reduces complexity and allows for more straightforward management and coordination. Localized governance structures can be more responsive and adaptable, ensuring that sustainability strategies are effectively implemented and monitored.

Moreover, PEDs can serve as incubators for innovation, testing new technologies, strategies, and policies that, once proven successful, can be scaled up to the city level. This approach allows for iterative learning and adaptation, ensuring that broader urban sustainability initiatives are informed by practical, real-world experience.

1.4 Positive energy district

1.4.1 Definition of PED

Typically, a PED is an urban area that generates more energy than it consumes. This is achieved using renewable energy technologies, such as solar panels and wind turbines, alongside efficient energy practices like smart building designs and energy management systems. Despite the lack of a universally accepted definition, these principles are commonly found in most descriptions of PEDs. These early descriptions focused on the technical and infrastructural components necessary to achieve energy positivity. This included incorporating renewable energy sources, enhancing energy efficiency, and developing smart grids for effective energy management. The primary objectives were to reduce reliance on fossil fuels, decrease greenhouse gas emissions, and improve energy security at the district level.

Because of the dynamic nature of PEDs, their definitions have varied and evolved over time, in alignment with technological progress, policy changes and shifting societal expectations. A definition is provided by JPI Urban Europe for PEDs ("Positive Energy Districts are energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility and ICT systems, while securing the energy supply and a good life for all in line with social, economic and environmental sustainability" [13].

This definition underscores the significance of involving citizens and local stakeholders in the design and operation of PEDs, recognizing that social acceptance and participation are critical to the success of these districts. The drive for this perspective stems from a more comprehensive understanding of sustainability, which include not only energy balances but also social justice and behavioural change. People's actions, attitudes and decisions are crucial, and for any solution to be genuinely sustainable, it must be socially accepted and equitable. This involves supporting equal access to energy services, reducing energy poverty and promotion a culture of sustainability where everyone is aware of and participates in energy management.

Other definitions of PEDs focus more on technical aspects, highlighting the significance of energy flexibility, emphasizing the need for efficient management of energy demand and supply, while accounting for different energy scenarios and interaction with the larger energy grid. Some definitions also consider carbon emissions during the district's operational phase, calculated from the energy used in building operations.

1.4.2 Development of PED

The development of PEDs is acknowledged as a complex process requiring a multifaceted approach. This development involves various stakeholders and employs a range of strategies as outlined in the SET-Plan ACTION n°3.2 Implementation Plan[14], emphasizing the necessity for a comprehensive approach in advancing urban sustainability objectives through PEDs.

Key elements include the need for:

1. Integrated and innovative technologies;
2. Societal innovation and citizen participation;
3. New energy markets and sustainable funding models;
4. Regulatory frameworks, certification and standardization;
5. Capacity-building, education and training;
6. Co-creation, open innovation, public sector innovation and procurement;
7. Replication, upscaling, and mainstreaming;
8. Business models for implementation and operation of PEDs.

These points will be briefly discussed as follows:

Integrated and innovative technologies for PEDs

The development and implementation of PEDs involve several key areas. Reducing primary energy demand is crucial, utilizing high-efficiency energy management systems, insulation, integrated photovoltaics (PV), solar-thermal facades and smart metering. Maximizing the use of local and adjacent renewable energy systems is also important to ensure a positive energy balance.

Integrated energy system designs provide robust and flexible infrastructures that support efficient energy exchange and sector coupling. Flexibility requires developing microgrids and real-time management systems to balance energy demand and supply.

Long-term energy storage is a significant challenge that needs addressing to make PEDs cost-effective and competitive. Integrating electric vehicles into PEDs is important for power load management, requiring careful planning and infrastructure development.

Additionally, distributed ledger technology offers potential for managing power exchange at the community level, encouraging local energy generation and supporting the transition from traditional consumer-producer roles to a prosumer model.

Societal Innovation, social entrepreneurship, and citizen participation

The financial and regulatory aspects of development PEDs are closely tied to societal factors, including citizen participation from both occupants and property owners. The affordability and success of PEDs also depend on innovative business models that consider economic accessibility for citizens. Public acceptance hinges on offering tangible incentives and improving the urban environment.

New energy markets and sustainable funding models for implementation of PEDs

Current retrofitting and near-zero energy projects face financial challenges due to low profitability, requiring innovative financing and subsidies. PEDs also encounter regulatory and financial hurdles, amplified by a lack of standards and high investment risks. To attract investment, new financing schemes, such as citizen-centric funding chains and cooperation between various entities are essential. Transitioning to PEDs requires a consumer-centric approach blending digital and energy markets with modern technologies. Investments and project replication can be stimulated through decentralized platforms, innovative public procurement, and blended finance. Overall, broad-ranging innovation and community engagement are crucial for successful PEDs deployment.

Regulatory framework, certification and standardization

Implementing PEDs requires robust regulations, shifting from individual buildings to district-wide policies. A primary challenge is managing the transition from consumers to 'prosumers' in energy trading, necessitating new technologies and legal frameworks. Regulations also need to consider the role of local energy communities, as per the EU's Winter Package. These frameworks should evolve alongside PEDs, catering to their growing complexity.

Capacity building, education and training

Building and education are vital for sustainable PEDs development. This requires multidisciplinary programs, designed nationally but driven by collaboration between governments and the European Commission. Partnerships among EU cities enhance resource sharing and knowledge. These capacity-building efforts must stay current with research, innovation, and community engagement.

Co-creation, open innovation, public sector innovation and procurement

Transitioning towards PEDs requires structured leadership, comprehensive cooperation and consistent public engagement. City and regional strategies should support PEDs development. Stakeholder involvement is promoted through an open innovation framework, utilizing regular collaborative sessions. The role of cities, especially smaller ones and understanding local barriers is critical in scaling up Smart City initiatives. Innovative public procurement strategies can push the adoption of innovative energy solutions, with both public and private sectors playing key roles.

Replication, upscaling, and mainstreaming

Implementing PEDs at a regional level through city partnerships enables broader benefits by sharing capacity, knowledge and financial resources. Adjustments should be made to these replicated solutions to suit specific local and regional conditions, facilitating cooperative innovation, market access and sustainable technological innovation cooperation.

Business models for implementation and operation of PEDs

The development of PEDs, involving the construction of new buildings and deep retrofitting of existing ones, is expensive. Optimizing subsidies is essential, particularly for demonstrator projects or specific local priorities like social housing. To ensure large-scale transition, sustainable business models involving all stakeholders need to be developed. These models should accommodate national circumstances and be geared towards supporting the upscaling and future replication of PEDs. This process should involve mapping and evaluating existing successful models and identifying necessary modifications for application to PEDs.

1.4.3 Advantages of implementing of PEDs

The development of PEDs offers several significant advantages. One major benefit of PEDs is their ability to reduce greenhouse gas emissions. By using renewable sources such as solar and wind power, along with energy efficiency measures to reduce energy consumption, PEDs not only lower emissions but also help balance energy demand and supply. This can reduce the reliance on non-renewable energy resources.

This transition away from fossil fuels directly and positively impacts air quality. By reducing reliance on fossil fuels and promoting alternative transportation methods, PEDs create a series of benefits. For example, the implementation of green spaces and urban forestry becomes not just an aesthetic choice but a scientifically based strategy for carbon sequestration, further improving the local environment.

The development of PEDs showcases a systematic approach to transforming urban areas towards sustainable energy models. This involves creating an integrated energy system that uses various renewable energy sources, with sustainable infrastructure like electric vehicle charging stations and energy-efficient building designs. This approach surpasses simple energy production and distribution, offering a complex, interconnected model tailored for urban sustainability. A key aspect of this interconnected model is the decentralization of energy production within PEDs. Localizing energy generation reduces transmission losses, which enhances the overall efficiency and resilience of the energy grid. Additionally, this approach aligns with broader economic goals, potentially lowering energy costs for consumers while still maintaining the core objective of sustainability.

Self-sufficiency and urban resilience, fundamental principles of PEDs, arise from this interconnected approach. Generating an energy surplus and having the capability for storage or distribution enhances urban stability and bolsters resilience against external disruptions, clearly connecting localized production with broader urban well-being.

Economic considerations are further strengthened by job creation in renewable energy, energy efficiency, and sustainable construction sectors. These growing industries, driven by the principles within PEDs, align well with societal needs and opportunities.

Improving the quality of life is a key goal within PEDs, and it naturally follows from this alignment. Lower energy costs, better security, people-friendly public spaces and active community involvement are all interconnected elements that contribute to a vibrant urban living experience.

As quality of life improves, property values within PEDs also rise, creating an economic incentive that supports sustainable principles.

Additionally, the concept of PEDs includes "living labs," which bring together these diverse elements into a cohesive framework for ongoing testing and improvement. These labs play a crucial role in shaping broader sustainable urban development policies.

1.4.4 Challenges in implementing PEDs

From the most accepted definition of PEDs, several questions remain unresolved, particularly regarding quantitative aspects that lack a common standard:

1. **Definition of Boundaries:**

- Geographical boundaries: These pertain to the actual physical limits encompassing the energy services and supplies within the PED. In some cases, these boundaries can extend to include offsite renewable energy sources (RES).
- Functional boundaries: These define specific energy functions, uses, or demands included in the PED, regardless of their location. Functional boundaries can further distinguish between renewable energy supply within the system boundary, termed "onsite" (not necessarily spatially onsite but within the system boundary) and energy services accounted for in the balance.

Depending on the boundary, the PED can be:

- **Autonomous PED:** A district with clear geographical boundaries that is entirely self-sufficient in terms of energy, meeting all its energy demands through internal renewable energy production, without importing energy from external networks.
- **Dynamic PED:** A district with clear geographical boundaries that interacts with external energy networks and other PEDs, provided it generates more renewable energy onsite annually than it consumes.
- **Virtual PED:** A district that expands geographical boundaries by allowing the implementation of renewable energy systems and storage outside the district's geographical boundaries, if the total energy production from these systems, combined with onsite generation, exceeds the district's annual energy consumption.

2. **Energy balance calculation**

The calculation of energy balance can vary significantly:

- Net Energy Balance: Some definitions consider only the net energy balance over a year, focusing on the annual difference between energy production and consumption.
- Real-Time Balance: Other definitions may require a real-time balance, accounting for energy flows continuously.

Types of energy: Definitions may differ on the types of energy considered, including electricity, heating, cooling and transportation energy.

3. **Energy source**

Definitions of acceptable renewable energy sources can vary:

- Onsite renewable energy: Some definitions limit acceptable sources to those generated within the PED boundaries.
- Offsite renewable energy: Others may recognize renewable energy produced offsite, provided it is used within the PED.

4. **Other sustainability considerations**

Beyond energy, definitions of PEDs might vary on what other sustainability aspects are considered. Considering these and other possible variations, this context emphasizes the urgent need for clear standards, precise definitions and strong methodologies for evaluating PED status, all grounded in quantifiable metrics. Such measures will provide a comprehensive understanding of the complex factors essential for advancing PED initiatives.

5. Financial barriers

- Upfront investments: Significant upfront investments are required for renewable energy systems, energy-efficient buildings, and smart grids.
- Funding: Securing adequate funding can be challenging, requiring innovative financing mechanisms and public-private partnerships.

6. Institutional barriers

- Regulatory framework: Existing regulatory frameworks may not be conducive to PED innovation, necessitating reforms to support PED-specific regulations.
- Coordination complexity: Managing the diverse range of stakeholders involved in PED projects can be complex, requiring effective coordination and communication strategies.

7. Social barriers

- Resistance to change: Overcoming social resistance to new technologies and practices is crucial. Effective communication, public engagement, education, and training are essential to garner broad support.
- Awareness: Increasing public awareness about the benefits and opportunities of PEDs is vital for their acceptance and success.

8. Challenges and strengths

The diversity in PED definitions can complicate efforts to compare and benchmark different initiatives. This variability allows PEDs to be customized to local contexts, fostering innovation and context-specific solutions.

9. Developing common frameworks

Creating common frameworks and metrics that accommodate this diversity while allowing for meaningful comparison and shared learning is essential. Sharing best practices, lessons learned and case studies among various PED initiatives can help overcome these challenges and promote the adoption and effectiveness of PEDs.

10. Data analysis and management

Analysing large volumes of data is another critical aspect of implementing PEDs. The management and optimization of energy production, consumption and storage within PEDs require sophisticated data analysis tools. These tools are essential for monitoring and controlling energy flows in real-time, predicting maintenance needs to reduce downtime, enhancing efficiency through advanced algorithms and facilitating stakeholder coordination through data visualization and sharing.

11. Urban planning tools

The design and implementation of PEDs face significant challenges due to the complexity of urban environments and the need for advanced planning tools. A critical barrier is the lack of standardized urban planning tools, which limits the ability to create PEDs that are both efficient and scalable. To overcome this, it is essential to develop robust frameworks that incorporate energy balance calculations, enable the integration of renewable energy systems and align with sustainability metrics.

12. Life-Cycle carbon emission calculation

The accurate calculation of life-cycle carbon emissions is another critical challenge in the development of PEDs. Beyond operational efficiency, PEDs must minimize their environmental footprint by addressing emissions associated with all phases of energy system implementation—production, operation and decommissioning. Current methodologies for LCA, while widely used, often lack consistency and fail to account for all relevant factors, leading to incomplete assessments of the environmental impact.

2. State of the art of PED and tools

2.1 State of the art on PED projects

The transition to PEDs requires not only a theoretical foundation but also practical examples that demonstrate the feasibility and benefits of such initiatives. This section presents a review of current projects and significant case studies that offer a detailed analysis of the strategies adopted, technologies implemented, and results achieved.

The methodology followed involves analysing various case studies under different parameters and variables. PED case studies were catalogued, investigated to identify common grounds and features useful for providing recommendations to stakeholders in the early stages of district design. General lessons learned were synthesized at the end of the process from the analysis, resulting in a set of energy and urban planning statistical facts of interest. The methodological steps can be summarized as follows:

1. Literature review;
2. Data collection;
3. Data analysis;
4. Interpretation and reporting.

2.1.1 Methodological approach to the analysis of existing PED

2.1.1.1 Literature Review

The literature review is the initial stage in the analysis of PEDs. This step is characterized by a comprehensive and detailed exploration of various types of sources to gain a thorough grounding in the field of PEDs.

A database of PEDs was assembled, mapped from existing projects throughout Europe. The following sources were adopted:

- The booklet on PED [15];
- The PED Database [16]
- Scientific literature and PED web pages.

The PED Booklet is a comprehensive guide and resource providing detailed information about PEDs. Edited by the PED Programme Management of Joint Programming Initiative

(JPI) Urban Europe, it serves as a fundamental reference point for those interested in understanding and implementing PEDs.

The booklet includes 29 projects that declared a PED ambition and 32 projects that did not, offering an overview of different projects, challenges and success factors.

The status of PED implementation is classified into four phases:

- Planning: Projects in the early stages of conceptualization and design;
- Implementation: Projects that have moved past planning and are in the process of actual construction or execution;
- Implemented: Projects that have finished all developmental phases;
- In Operation: Projects that are not just completed but are actively functioning.

A summary of the PED projects reported in the booklet investigated is following in Table 1.

Table 1 Booklet PED grouping

Case-study category	Phases	Number of case-studies
PED PROJECTS	Implemented	1
	In operation	1
	In implementation stage	19
	In planning stage	8
TOWARDS POSITIVE ENERGY DISTRICTS	Implemented	1
	In operation	10
	In implementation stage	15
	In planning stage	6

The information included in the booklet was further supplemented by other sources to determine whether there were additional advancements in the implementation of the district projects.

The Positive Energy Districts European Network (PED-EU-NET), in collaboration with IEA EBC Annex 83 and JPI Urban Europe, has developed an evolving resource known as the PED Database. This dynamic database is dedicated to tracking and documenting PED projects, serving as a comprehensive repository for stakeholders interested in PEDs. Despite being a relatively new resource, it has already gathered information on 21 distinct cases, providing a snapshot of the various projects in progress. Of the 21 cases analysed by the database, 8 are also featured in the booklet, and information was aggregated as necessary.

The database categorizes the PEDs in two dimensions, providing a detailed understanding of each project's nature and progress. Firstly, the projects are categorized by 'type.' There are three distinct types defined:

- PED Case Study: A district-level project with a high level of aspiration in terms of energy efficiency, energy flexibility and energy production. The project must address most aspects listed in the JPI UE PED Framework Definition, including the ambition to achieve an annual energy positive balance.
- PED Relevant Case Study: A district-level project with a high level of aspiration in terms of energy efficiency, energy flexibility, and energy production. The project does not necessarily have to achieve an annual energy positive balance but must address some aspects listed in the JPI UE PED Framework Definition.
- PED Lab: PED Labs are pilot actions that provide opportunities to experiment with the planning and deployment of PEDs and serve as a seeding ground for new ideas, solutions, and services to develop. PED Labs follow an integrative approach, including technological, spatial, regulatory, financial, legal, social, and economic perspectives.

The following tables show the breakdown of ped projects included in the database.

Table 2 PED database grouping

Case-study category	Numbers of case-studies
Ped case study	9
Ped LAB	5
Ped relevant case study	5
Ped relevant case study/Ped Lab	2

Secondly, the projects are divided according to their operational 'phase'. The four phases documented are like the booklet:

- **Planning phase**:
- **Implementation phase**;
- **Completed;**
- **In operation**.

The following tables show the breakdown of PED projects included in the database.

Table 3 PED phases

Phases	Numbers
Planning phase	8
Implementation phase	8
Completed	2
In operation	3

Incorporating additional sources such as scientific literature and web pages into the analysis of PEDs can substantially enhance both the depth and breadth of the research. These sources, being more up-to-date than the booklet, provide access to the latest information, including recent news, developments and outcomes. They offer detailed insights into individual projects, technologies, and strategies that might not be extensively covered in official publications like booklets and the PED database.

2.1.1.2 Data collection

The data collection phase initiates with a comprehensive gathering of data about each PED under study. It involves obtaining a broad spectrum of information to ensure the most complete understanding of the district's operations, performance and context.

2.1.1.3 Data analysis

The process starts by turning raw data into valuable insights to better understand PEDs. The first step after collecting data is cleaning it. Since the data comes in many forms, like numbers from energy output readings and text from survey responses. Data cleaning means making sure all measurements use the same units, filling in any missing information when possible, and converting different data formats into one cohesive and usable format. The goal is to make sure the data is accurate and consistent, setting a strong foundation for further analysis.

Once the data is cleaned, the next step is descriptive analysis. This means looking at the basic features of the data to get a summary view of PEDs. For example, examining the different types of energy technologies used in PEDs, can highlight which technologies are most common and what that might mean. This stage also includes creating visual representations of the data, like graphs, charts, or maps, to quickly spot trends, outliers, and patterns. For instance, mapping out where PEDs are located and their sizes can reveal geographical patterns, such as whether PEDs are more prevalent or perform better in certain regions or climates.

The final step is identifying patterns in the data. This involves digging deeper to find correlations, trends, and recurring themes that can provide meaningful insights into how PEDs operate and how they can be optimized. This helps to identify best practices and areas where improvements can be made.

2.1.1.4 Interpretation

After analysing the collected data, general lessons learned were compiled and organized into a set of energy and urban planning statistical facts. These findings aim to offer practical suggestions and insights for stakeholders involved in the early-stage design of districts. This structured approach ensures a comprehensive understanding of PEDs, facilitating informed decision-making and effective planning in urban development projects.

2.1.2 Key findings from the analysis of PEDs

The analysis will focus on the current state of these districts to extract crucial information that will enable a more comprehensive assessment of PEDs. The analysis will concentrate on the following aspects:

- Geographical distribution of PEDs;
- Stages of PED development;
- PEDs through the Köppen climate classification;
- Spatial extension of PEDs;
- Land use of PEDs;
- Analysis of renewable technologies in PEDs;
- Climate zone and renewable technology correlation;
- Comparison of energy needs and area;
- Thermal and electricity balance.

This approach aims to provide an in-depth understanding of the various dimensions of PEDs, facilitating a more effective and insightful analysis of their status and future potential.

2.1.2.1 Geographical distribution of PEDs

The figure shows a map of Europe highlighting the number of PEDs in each country based on data updated to 2024. The color scale ranges from light blue (indicating a lower number of PEDs) to dark blue (indicating a higher number of PEDs).

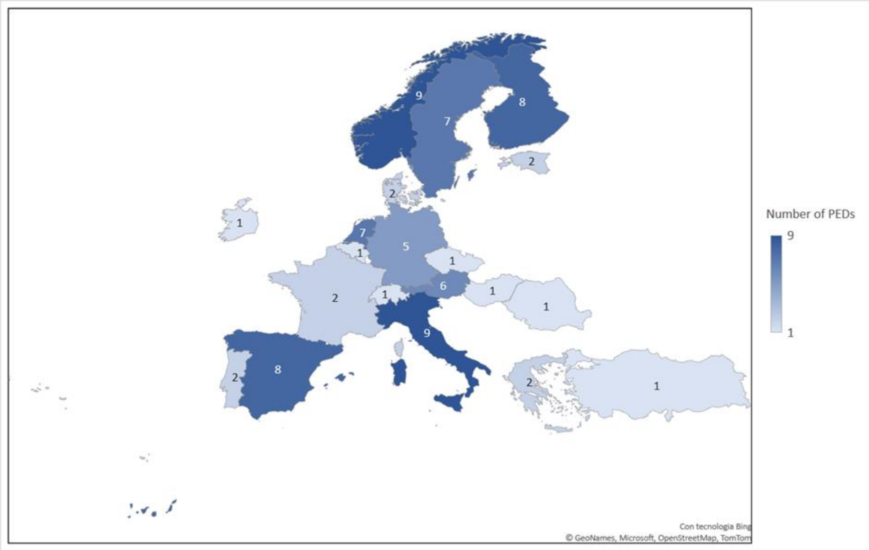

Figure 1 European distribution of PEDs (2024 data)

This map illustrates the distribution of PEDs across various European countries, with a particularly high concentration in Italy and Norway.

2.1.2.2 Stages of PEDs development

A considerable proportion of the PEDs under study are either in advanced stages of planning or have already been realized. This trend signifies a global shift towards more sustainable, energy-efficient urban districts, with concrete steps being taken to bring this vision to fruition. The advanced planning stages for many of these PEDs indicate that the theoretical groundwork has been laid and initial barriers have been addressed, with detailed strategies and plans now in place. The analysis reveals that:

- 21% of PEDs are in the planning phase;
- 48% are in the implementation phase;
- 11% are completed;
- 20% are operational.

This section is expanded to consider the current locations of the completed PEDs and to project the number of PEDs expected to be completed by 2050 based on current trends and initiatives.

Geographical distribution of completed PEDs

The figure illustrates the number of PEDs that have been realized in various countries.

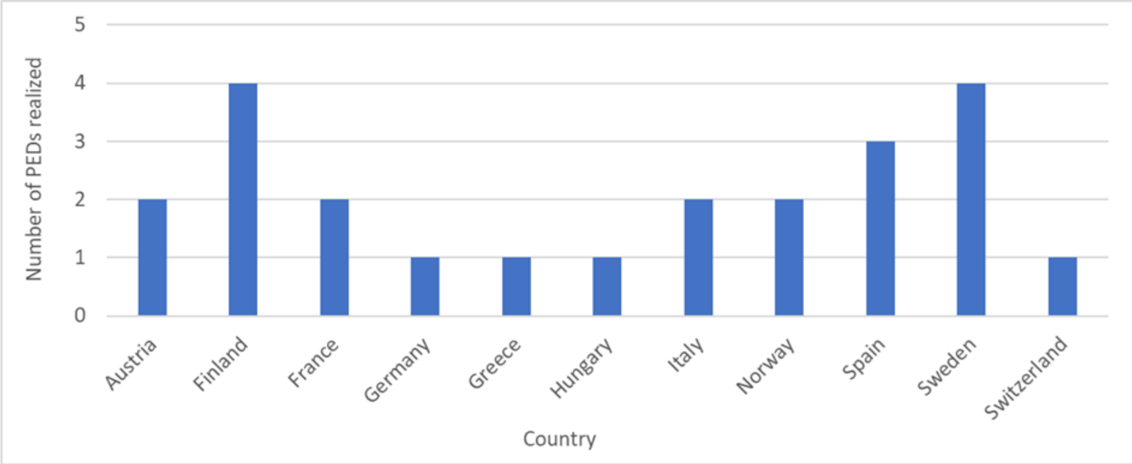

Figure 2 Geographical distribution of completed PEDs

This chart highlights that Finland and Sweden lead with the highest number of completed PEDs, each having 4 projects. Spain follows with 3 realized PEDs, while Austria, France, Italy and Norway each have 2. Germany, Greece, Hungary and Switzerland are represented by 1 completed PED in each country.

Projections for PED completion by 2050

The accompanying chart illustrates the projected number of completed PEDs from 2012 to 2049, highlighting the expected acceleration in the implementation of PEDs over the coming decades.

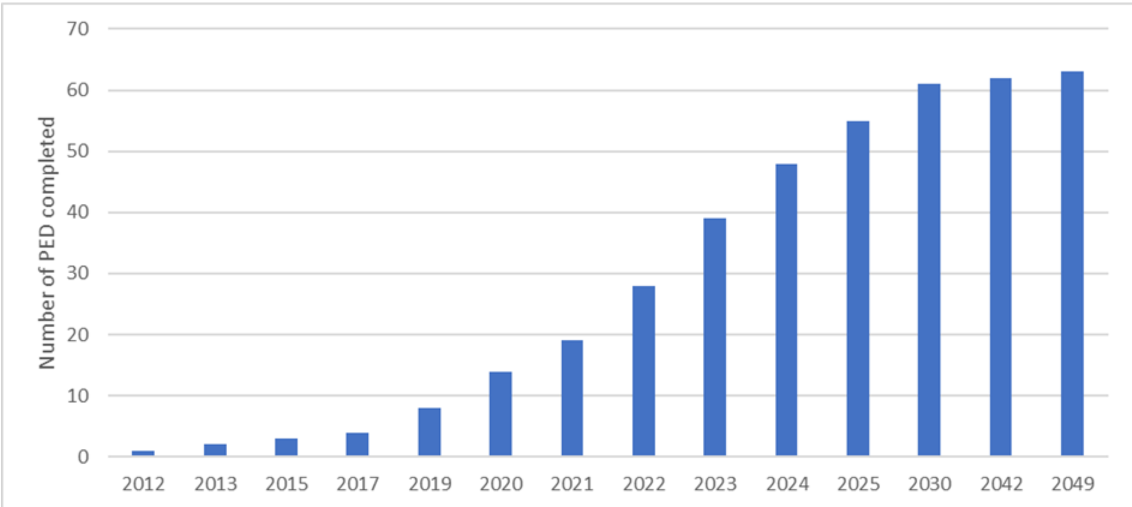

Figure 3 Cumulative PED completed (2012-2049)

Based on current trends and planned initiatives, it is projected that a significant number of PEDs will be completed by 2050. It is projected that nearly all planned and currently conceptual PEDs will be completed, amounting to a potential 90-95% realization of all proposed projects. This optimistic forecast assumes continued support from both public and private sectors, as well as ongoing advancements in renewable energy technologies and sustainable urban planning practices.

However, it is important to note that the SET-Plan ACTION n°3.2 has set an ambitious target of achieving 100 PEDs by 2050. This plan underscores the need for accelerated efforts and enhanced collaboration among stakeholders to meet this goal.

2.1.2.3 PEDs through the Köppen Climate Classification

The analysis of PEDs can be further enriched by examining their distribution and performance across different climate zones as classified by the Köppen Climate Classification system. This approach provides insights into how varying climatic conditions influence the implementation and efficiency of PEDs.

Each climate type presents unique opportunities and challenges for renewable energy production and energy efficiency. For instance, Mediterranean climates have abundant solar energy potential, while cold climates offer significant opportunities for geothermal energy.

The Köppen Climate Classification system categorizes global climates into five main types, denoted by a single letter (A, B, C, D, E). These primary categories are further subdivided based on seasonal precipitation and temperature patterns, indicated by second and third letters. Here is an overview:

A - Tropical Climates: Characterized by high temperatures year-round (average monthly temperature always above 18°C).

- Af: Tropical rainforest climate (no dry season)
- Am: Tropical monsoon climate (short dry season)
- As/Aw: Tropical savannah climate (distinct wet and dry seasons)

B - Arid Climates: Defined by arid conditions, with low precipitation and high evaporation rates.

- BWh/BWk: Desert climate (h indicates hot deserts, k indicates cold deserts)
- BSh/BSk: Steppe climate (h indicates hot steppe, k indicates cold steppe)

C - Temperate Climates: Have warm summers and cool winters.

- Cfa/Cfb/Cfc: Without dry season (a indicates hot summer, b indicates warm summer, c indicates cool summer)
- Cwa/Cwb/Cwc: Dry winter (a indicates hot summer, b indicates warm summer, c indicates cool summer)

- Csa/Csb/Csc: Dry summer (a indicates hot summer, b indicates warm summer, c indicates cool summer)

D - Cold Climates: Continental climates with hot summers and very cold winters, often experiencing significant snowfall.

- Dfa/Dfb/Dfc: Without dry season
- Dwa/Dwb/Dwc: Dry winter
- Dsa/Dsb/Dsc: Dry summer

E - Polar Climates: Characterized by extremely cold temperatures.

- ET: Tundra climate (the air temperature of the warmest month is always above 0°C)
- EF: Frost climate (the air temperature of the warmest month is always below 0°C)

By correlating PEDs with the Köppen climate types, the aim is to uncover patterns and extract lessons on how PEDs can be optimized according to various climate conditions. This analysis will contribute to a more nuanced understanding of PEDs, enabling more effective planning and implementation in diverse climatic contexts.

In Figure 4, 75 PEDs analysed are classified according to their respective climate zones. This categorization provides essential context that significantly impacts the feasibility and design of these districts, influencing both the availability of renewable energy sources (such as solar or wind power) and the energy demands of buildings.

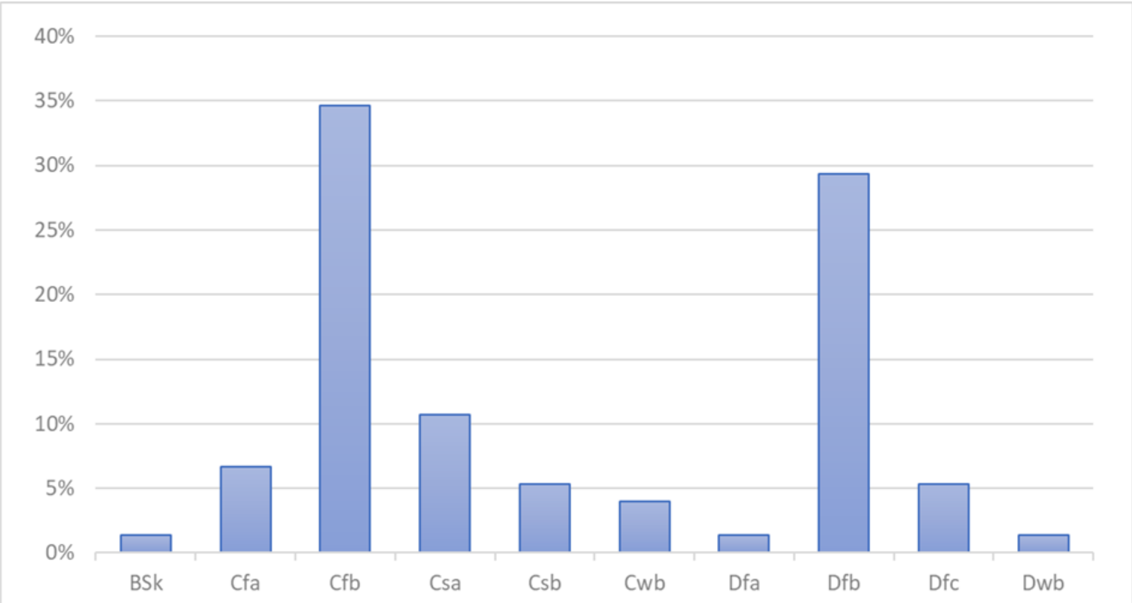

Figure 4 PEDs classified by Köppen climate zones

A significant number of PEDs are located in regions classified under the Cfb and Dfb climates in the Köppen Climate Classification system. Specifically, 35% of PEDs fall under the Cfb classification, while 29% are in the Dfb category. This indicates that certain climates are more conducive to the establishment of PEDs. Other climate zones, such as Csa (11%), Cfa (7%), Csb and Dfc (5% each), Cwb (4%), and BSk, Dsa, and Dwb (1% each), have a smaller representation.

Regions with a Cfb climate, characterized by temperate oceanic conditions with mild summers and winters, offer advantages for renewable energy utilization and energy-efficient building designs. The stable climate conditions are favourable for a variety of renewable energy sources, including solar and wind, and facilitate the integration of energy-efficient HVAC systems and building designs that require less thermal regulation. Conversely, regions with a Dfb climate, known for their humid continental conditions with warm summers and cold, snowy winters, present different opportunities. The substantial solar irradiance during summer months can be effectively harnessed for solar energy production. Additionally, the climatic conditions in these regions are favourable for wind and geothermal energy, particularly given the significant temperature differentials throughout the year.

While these climates present different challenges and opportunities, their prevalence suggests a flexibility and adaptability in the design and implementation of PEDs. This, underscores the potential for PEDs to thrive in various climates, leveraging unique local resources for energy generation and consumption. It also highlights the crucial role local climate plays in shaping the strategies and technologies used in PEDs.

In climates with extreme temperature variations or less predictable weather, technical and economic challenges may arise in implementing renewable energy solutions and energy-efficient designs. In some of these less-represented climatic zones, energy technologies suitable for PED development might be less mature or more costly to implement and maintain. Additionally, the variability in renewable energy production in arid or extremely cold climates could be a deterrent. However, climate is likely not the sole factor influencing the lower number of PEDs in these categories. Other factors such as policy incentives, infrastructure limitations, and availability of funding also play a significant role.

2.1.2.4 Spatial extent of PEDs

The spatial extent of PEDs is a critical factor influencing their design, implementation and overall efficiency. Understanding the area extension of PEDs helps evaluate their scalability and the feasibility of integrating various renewable energy technologies and sustainable practices.

The following chart illustrates the distribution of PEDs by their area extension:

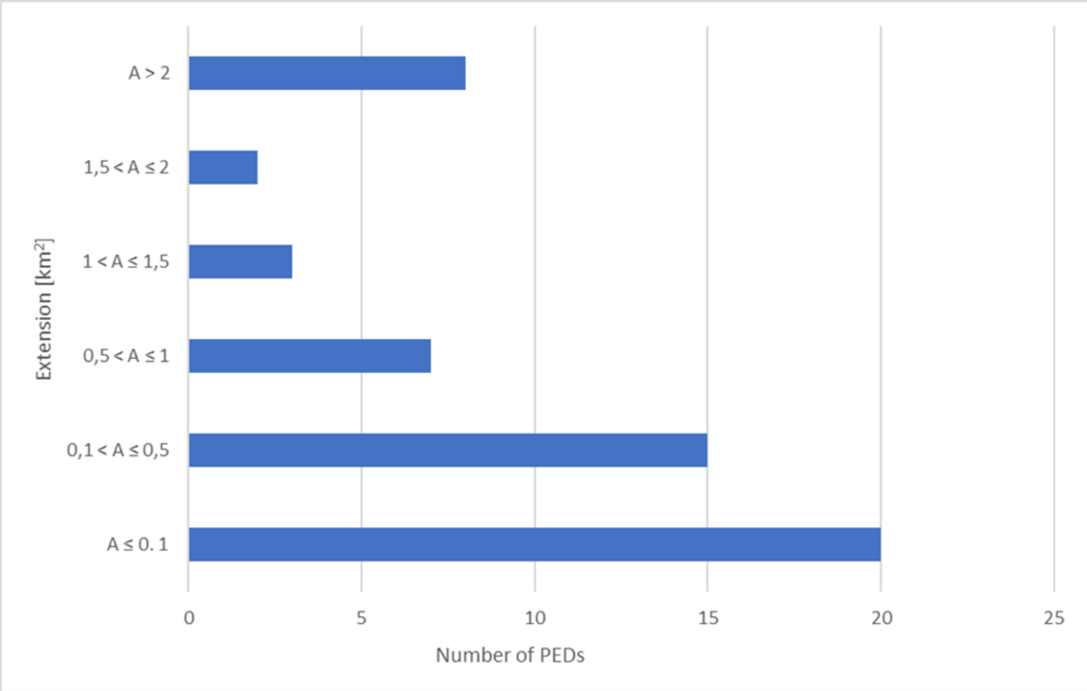

Figure 5 Distribution of PEDs by area extension

PEDs vary significantly in size, ranging from small, compact neighbourhoods to larger urban districts. The size of a PED affects several aspects, including energy generation potential, infrastructure requirements, and community engagement.

- PEDs with area ≤ 0.1 km²: These are the most common, accounting for approximately 20 PEDs. Small-scale PEDs benefit from higher density and closer proximity of resources, enhancing energy efficiency and facilitating community-based renewable energy projects. However, limited space can constrain the installation of renewable energy systems, such as large solar panels or wind turbines.
- PEDs with area between 0.1 and 0.5 km²: This category includes a significant number of PEDs, with around 15 projects. These districts balance density and available space, allowing for a mix of renewable energy sources and energy-efficient infrastructure. Coordination and integration across the area are manageable, making them suitable for various energy solutions.
- PEDs with area between 0.5 and 1 km²: This category includes around 7 PEDs. Medium-scale PEDs can integrate a wider variety of renewable energy sources, such as solar, wind, and geothermal, due to the availability of more space. They also offer greater potential for district heating and cooling systems, although coordination becomes more complex.

- PEDs with area between 1 and 1.5 km²: There are fewer PEDs in this category, around 3 projects. These larger areas allow for substantial renewable energy installations and can support diverse energy infrastructure, though they require more extensive planning and investment.
- PEDs with area between > 1.5 km²: This category includes 8 PED. Such districts can implement large-scale renewable energy projects and extensive infrastructure, benefiting from economies of scale but also facing higher complexity in management.

2.1.2.5 Land use of PEDs

The analysis of land use involves investigating whether these districts are predominantly residential, commercial, industrial, or of other types. The land use can significantly influence the energy consumption, infrastructure needs and community engagement strategies in a PED. Understanding the land use context of PEDs can contribute to the development of tailored strategies for different types of districts. However, it is important to acknowledge that some districts within the analysed dataset lack explicit information concerning their land use types. The omission of these specifics introduces a degree of uncertainty into the analysis, requiring a more nuanced approach to strategy formulation and planning.

The following Figure provides an additional layer of analysis by categorizing the 34 PEDs according to their primary land use: Residential, Commercial, Industrial and Other.

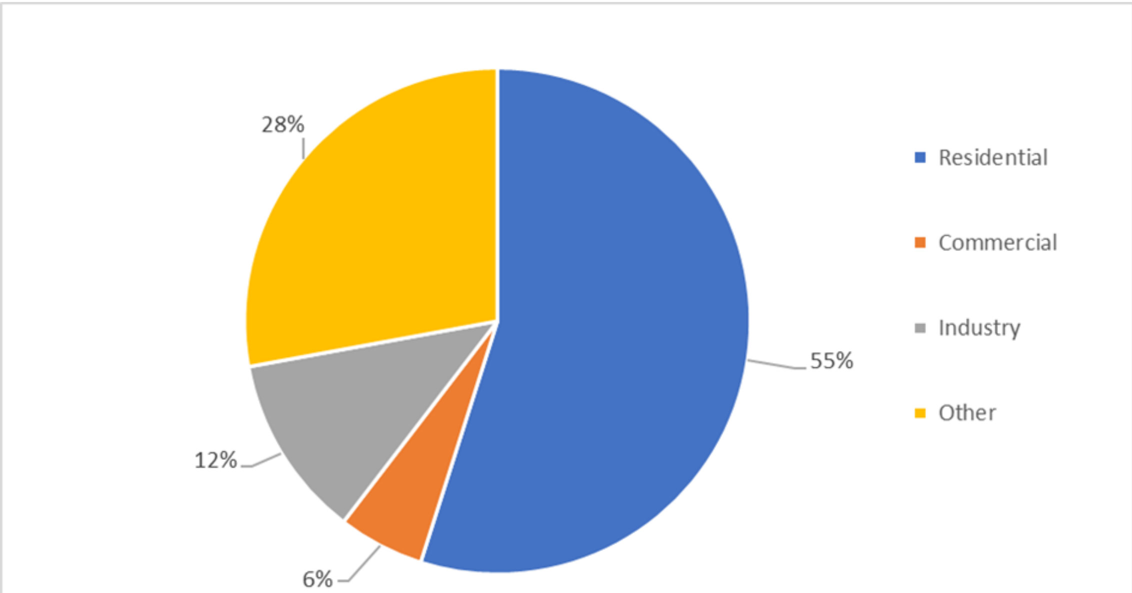

Figure 6 Land use types in PEDs

Residential districts, which make up the majority of PEDs (55%), are particularly suitable for the PED approach due to their typically lower energy consumption per square meter compared to other types of buildings. This lower energy demand makes it easier to achieve a positive energy balance, positioning residential areas as strategic focal points for sustainable urban development.

However, the remaining 45% of PEDs encompass a variety of other land uses, demonstrating the flexibility and adaptability of the PED concept, indicating that PEDs can be successfully implemented in diverse urban environments.

Commercial PEDs, which constitute only 6% of the total, face distinct challenges. The energy consumption in commercial districts may require more sophisticated solutions to achieve energy positivity. This lower representation might also reflect an initial focus on residential and industrial sectors, possibly due to more readily available subsidies or political support for these types of projects.

The industrial PEDs, making up 12%, highlight the integration of energy-intensive processes within the PED framework. These districts require specialized energy solutions to manage their higher energy demands effectively.

2.1.2.6 Analysis of renewable technologies in PEDs

Understanding the successful realization of PEDs requires a thorough examination of the renewable technologies employed.

Patterns, trends and preferences in the choice of renewable technologies for 70 PEDs are investigated in the next Figure. This analysis provides insights into the technological strategies that have proven most effective in achieving PED goals. Additionally, it helps identify the strengths and limitations of different technologies in the context of PEDs.

The next figure illustrates the prevalence of different renewable energy technologies used in PEDs.

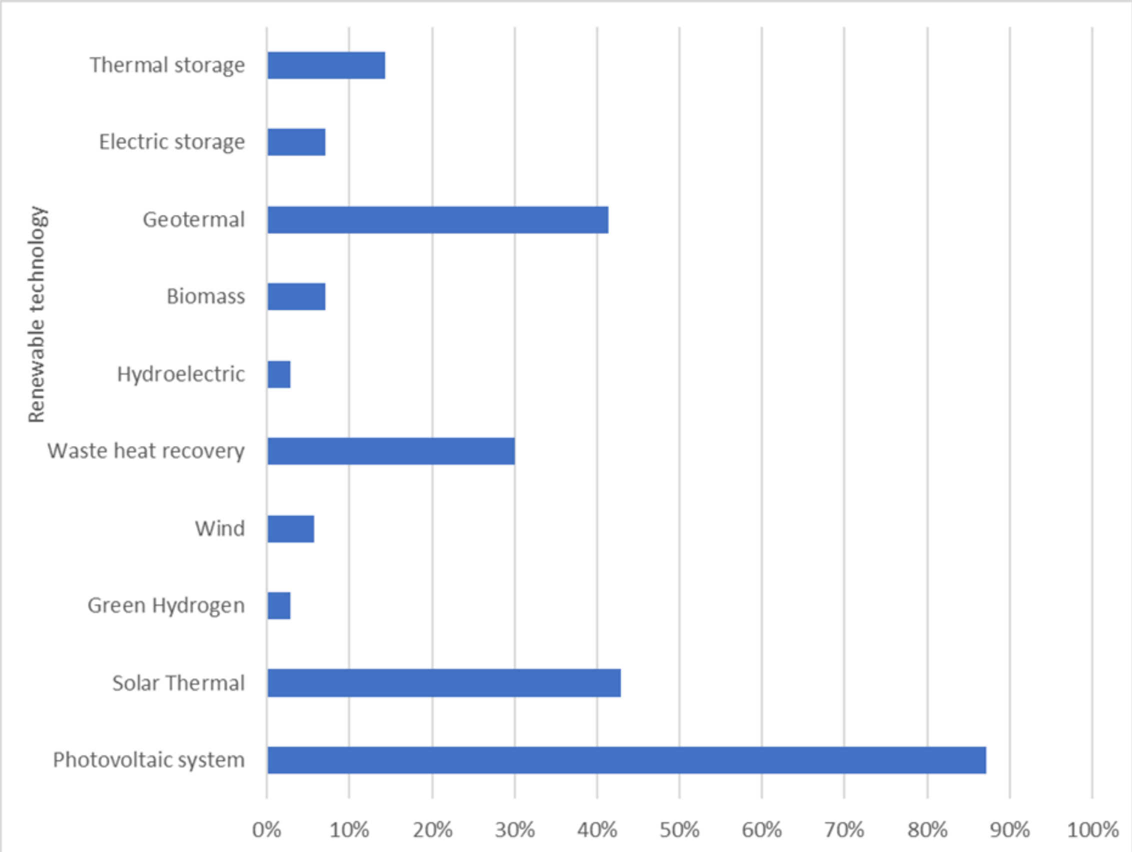

Figure 7 Prevalence of renewable technologies in PEDs

The data presents a revealing snapshot of renewable technology choices in PEDs. Photovoltaic systems are employed in 87% of districts, making them the most common technology, followed by solar thermal systems at 43% and geothermal technology at 41%. Less commonly used technologies include waste heat recovery at 30%, thermal storage at 14% and electric storage and biomass at 10%. Wind energy is used in 6% of districts, while hydroelectric and green hydrogen solutions are the least commonly employed, each at 3%.

The prominence of photovoltaic systems and solar thermal technologies is likely due to their relative simplicity, cost-effectiveness and adaptability to various climates and urban conditions. These technologies can significantly reduce energy costs in residential applications. Geothermal technology, utilized in 41% of PEDs, is valued for its efficiency and effectiveness in both heating and cooling applications, providing a consistent and reliable energy source, especially useful in climates with extreme seasonal variations.

Waste heat recovery, used in 30% of the districts, indicates a focus on energy efficiency and recycling otherwise lost energy, reflecting a comprehensive approach to sustainability. Thermal storage systems, present in 14% of districts, are used to balance heating and cooling loads in district heating, thereby increasing overall system efficiency.

Biomass, used in 10% of PEDs, is useful for both electricity generation and heating. However, its lower adoption rate compared to solar and geothermal options may be due to concerns about supply chain sustainability or air quality impacts. Similarly, electric storage solutions appear in a small percentage of PEDs, possibly due to the current costs of effective storage solutions or the complexity of integrating them into existing energy systems.

Wind energy, featured in 6% of PEDs, is influenced by the geographical and climatic suitability of locations, as well as the significant upfront costs and potential regulatory and social acceptance issues associated with wind turbine installations. Green hydrogen, found in 3% of districts, reflects its emerging status as a renewable technology. The initial costs and complexities of establishing a hydrogen infrastructure could explain its lower adoption rate.

Lastly, hydroelectric power is minimally represented, likely due to the specific geographical requirements for hydroelectric projects, making it less versatile than other renewable options. Hydroelectric power requires significant water bodies and often large dams, which are typically incompatible with the size and scope of PEDs. Additionally, the environmental impacts of constructing dams and reservoirs, along with the high costs, make technologies like solar, geothermal, and photovoltaic more attractive due to their scalability, decreasing costs, and ease of integration in urban settings.

This hierarchical distribution of technologies highlights current preferences and the perceived feasibility and effectiveness of these options in PEDs. The selection of technologies often depends on localized conditions, including the district's capacity for integrating advanced energy solutions. This distribution serves as an indicator of both current technological viability and the potential for adaptability to specific district characteristics.

2.1.2.7 Climate zone and renewable technology correlation in PEDs

The selection of renewable technologies in PEDs is significantly influenced by local climate conditions, which play a critical role in the effectiveness of these technologies.

This section analyses the correlation between Köppen climate zones and the types of renewable technologies utilized in 69 PEDs. The objective is to understand how climate conditions influence the choice of renewable technologies in the realization of PEDs.

The analysis addresses two key aspects of renewable technology adoption. First, it explores how the prevalence of various renewable technologies varies across different Köppen climate classifications, identifying the adaptability or limitations of each technology in specific climatic conditions. Second, it examines the portfolio of renewable technologies commonly employed within each climate zone, offering insights for optimizing renewable energy strategies tailored to distinct geographical and climatic conditions.

In the next Figure, the prevalence of various renewable technologies across different Köppen climate classifications is examined.

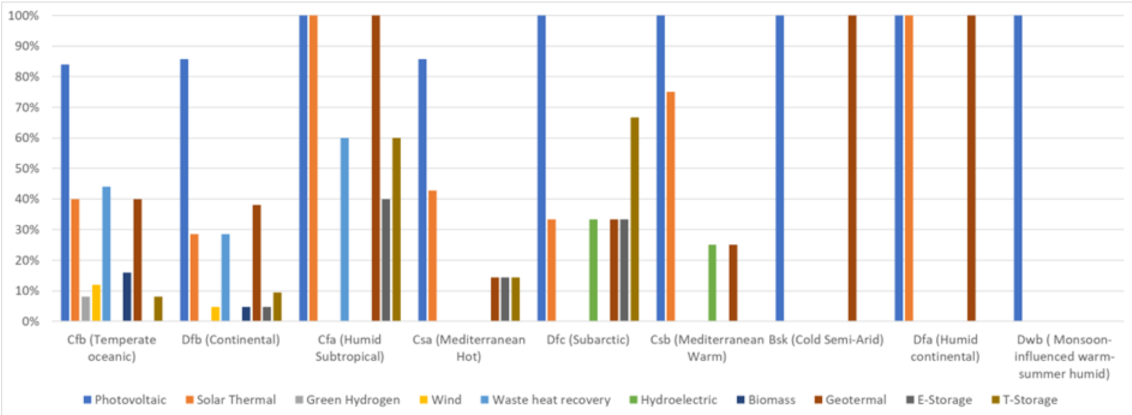

Figure 8 Analysis of various climate zones by the adoption of renewable technologies

The Figure offers a contrasting perspective by illustrating the adoption of various renewable technologies within each Köppen climate classification. Each cluster of bars represents a specific renewable technology, with individual bars denoting the percentage of PEDs utilizing that technology across different climate types.

In temperate oceanic (Cfb) climates, photovoltaic systems are highly prevalent, followed by solar thermal and waste heat recovery. Green hydrogen, although relatively new, shows a small presence.

Continental (Dfb) climates exhibit a strong preference for photovoltaic systems and geothermal energy, with solar thermal being less common.

Humid subtropical (Cfa) climates demonstrate full adoption of photovoltaic, solar thermal and geothermal technologies, indicating their strong alignment with these renewable sources.

Subarctic (Dfc) climates show universal adoption of photovoltaic systems but much lower adoption rates for other technologies such as solar thermal.

Cold semi-arid (Bsk) climates rely entirely on photovoltaic and geothermal systems.

Humid continental (Dfa) and monsoon-influenced warm-summer humid (Dwb) climates also show a strong preference for photovoltaic systems, with other technologies being minimally represented.

Photovoltaic systems are universally adopted across most climate types, highlighting their versatility and effectiveness. Other technologies, like solar thermal and waste heat recovery, are more prevalent in specific climates where they can be most effective. This analysis provides an understanding of how climate conditions shape renewable technology choices, essential for planning and deploying PEDs in various climatic settings.

The next figure examining the adoption of various renewable technologies within each Köppen climate classification.

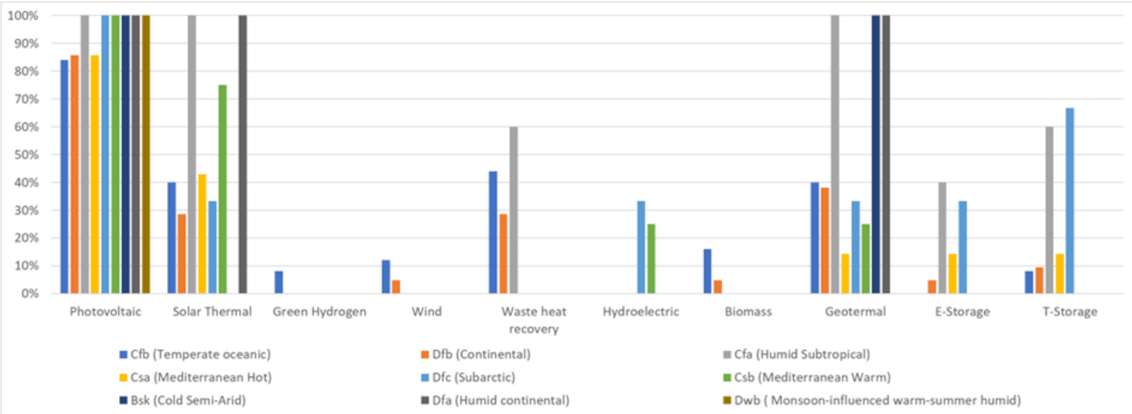

Figure 9 Analysis of renewable technologies adopted within each climate zone

The figure illustrates that photovoltaic systems are widely adopted across most climate zones, with 84% adoption in Cfb (Temperate oceanic), 86% adoption in Dfb (Continental), and 100% adoption in climates such as Dfa (Humid continental), Cfa (Humid Subtropical), Dfc (Subarctic), Csb (Mediterranean Warm), Bsk (Cold Semi-Arid) and Dwb (Monsoon-influenced warm-summer humid). This high rate of adoption indicates the versatility and adaptability of photovoltaic technology across various climatic conditions.

Solar thermal systems are predominantly utilized in climates such as Cfa (Humid Subtropical, 100%), Dfa (Humid Continental, 100%), and Csa (Mediterranean Hot, 43%). This pattern aligns well with the high solar irradiance characteristic of these regions, making solar thermal technology a practical and efficient choice.

Green hydrogen exhibits limited adoption, primarily in temperate oceanic climates (8%), suggesting that this technology may still be in an early stage of deployment or face specific environmental and economic constraints. Wind energy shows modest adoption, with higher prevalence in temperate oceanic climates (12%), likely due to favorable wind conditions.

Waste heat recovery is particularly adopted in temperate oceanic climates (44%) and in Cfa (Humid Subtropical, 60%), reflecting its applicability and potential in regions with established industrial activity and diverse energy needs. Hydroelectric technology, on the other hand, is minimally represented in Dfc (Subarctic, 33%), which is likely attributable to the geographical requirements of hydro installations rather than specific climatic factors.

Biomass technology has limited but focused adoption in temperate oceanic climates (16%), indicating its potential effectiveness in areas with suitable biomass resources, despite its emerging status compared to other renewable technologies.

Geothermal technology is most prevalent in humid subtropical climates (100%), as well as in Bsk (Cold Semi-Arid, 100%), Cfa (Humid Subtropical, 100%), and Dfa (Humid Continental, 100%), pointing to its suitability in regions with stable underground thermal conditions, which facilitate efficient energy extraction.

Electric storage solutions are more commonly utilized in humid subtropical climates (40%), highlighting the need for reliable energy storage in areas characterized by high energy demand and variable renewable energy production. Thermal storage, meanwhile, is present predominantly in Dfc (Subarctic, 67%), indicating the need for effective heat storage during colder periods to enhance energy efficiency.

2.1.2.8 Energy needs and area

Assessing the effectiveness and sustainability of PEDs requires a detailed analysis of their energy needs. With only 22 fully realized PEDs and many still under development, the dataset in this section is limited.

The relationship between the physical area of PEDs and their energy needs is a fundamental aspect of understanding their energy dynamics. Analysing how energy requirements scale with the size of these districts provides crucial insights into the planning and management of sustainable urban environments. This examination helps to identify whether larger districts inherently demand more energy or if other factors significantly influence energy consumption.

Figure 10 and Figure 11 offer a detailed look at this relationship by presenting scatter plots that compare thermal and electrical energy needs against the area of various PEDs. Figure 10 explores the thermal energy needs about the area, while Figure 11 examines the electrical energy needs. These visual representations reveal the complexity and variability in how energy needs correlate with the physical size of PEDs.

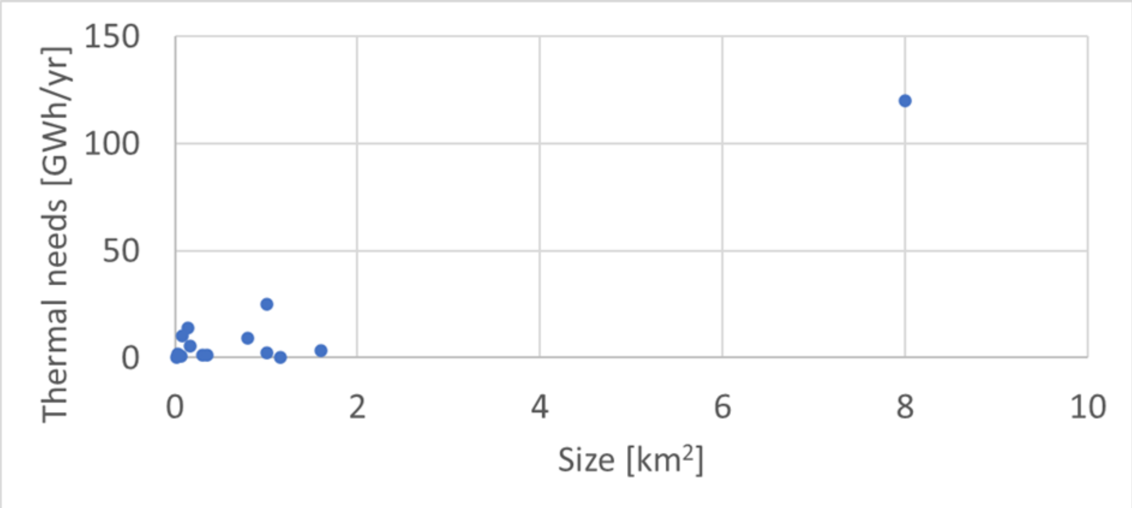

Figure 10 Correlation between PED area and thermal energy needs.

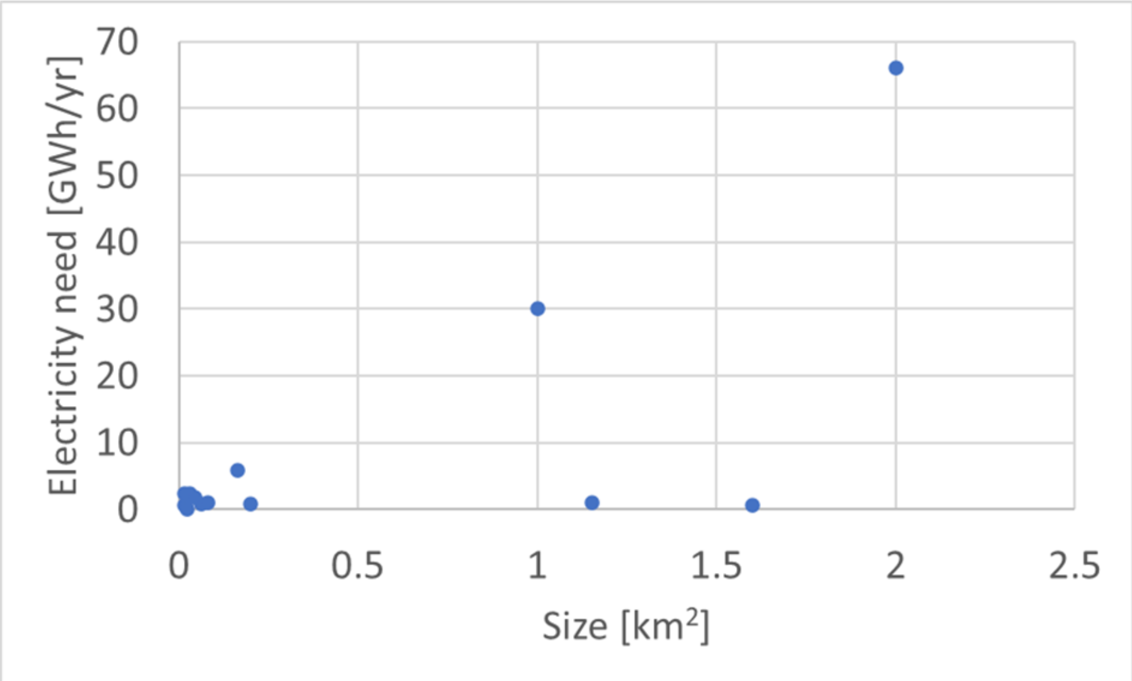

Figure 11 Correlation between PED area and electrical energy needs.

Both figures exhibit similar dispersed data points with no clear correlation between the area of the PED and its energy needs, whether thermal or electrical. This highlights several key points. First, both thermal and electrical energy needs in PEDs are influenced by a multitude of factors beyond just the physical size of the district. These factors could include the type of buildings, occupancy rates, efficiency of energy systems, climatic conditions and the specific energy strategies implemented within the district. The lack of a direct correlation in both figures suggests that simply increasing the area of a PED does not linearly increase its energy needs. This indicates that energy planning for PEDs must consider various aspects of urban design, energy infrastructure, and local conditions rather than relying on area as a primary determinant.

2.1.2.9 Relationship between generation and energy needs

Understanding the balance between energy generation and consumption is crucial for the successful implementation and sustainability of PEDs. Figure 12 and Figure 13 investigate into this balance by comparing the generated thermal and electricity against the respective energy needs in various PEDs. These figures provide a visual representation of how well the energy production within these districts aligns with their consumption demands, offering insights into the effectiveness of their energy management strategies.

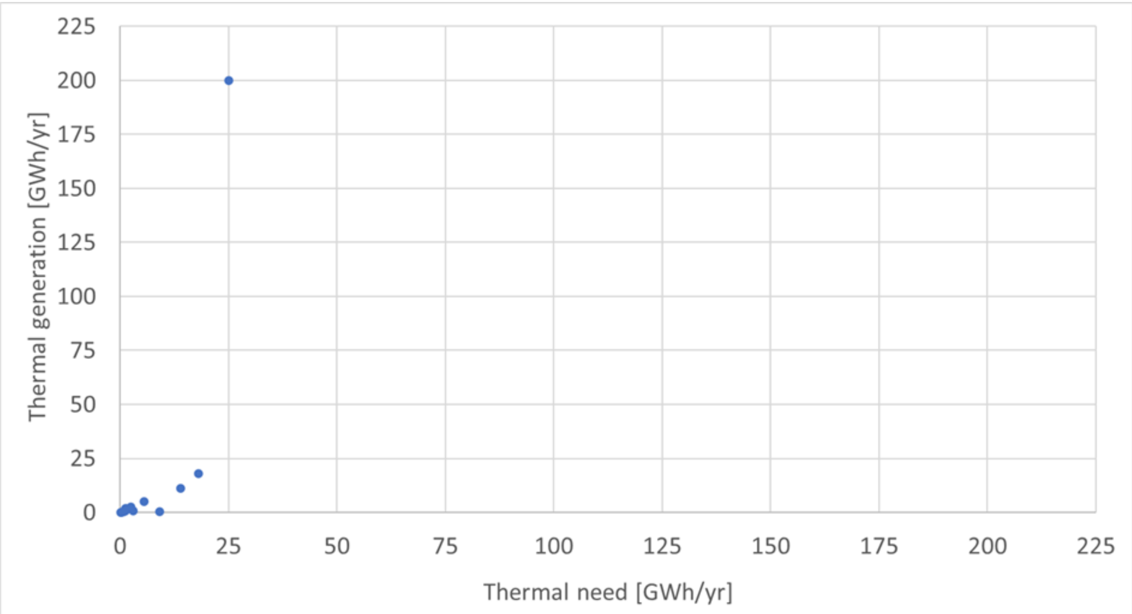

Figure 12 Balance between thermal energy generation and needs in PEDs.

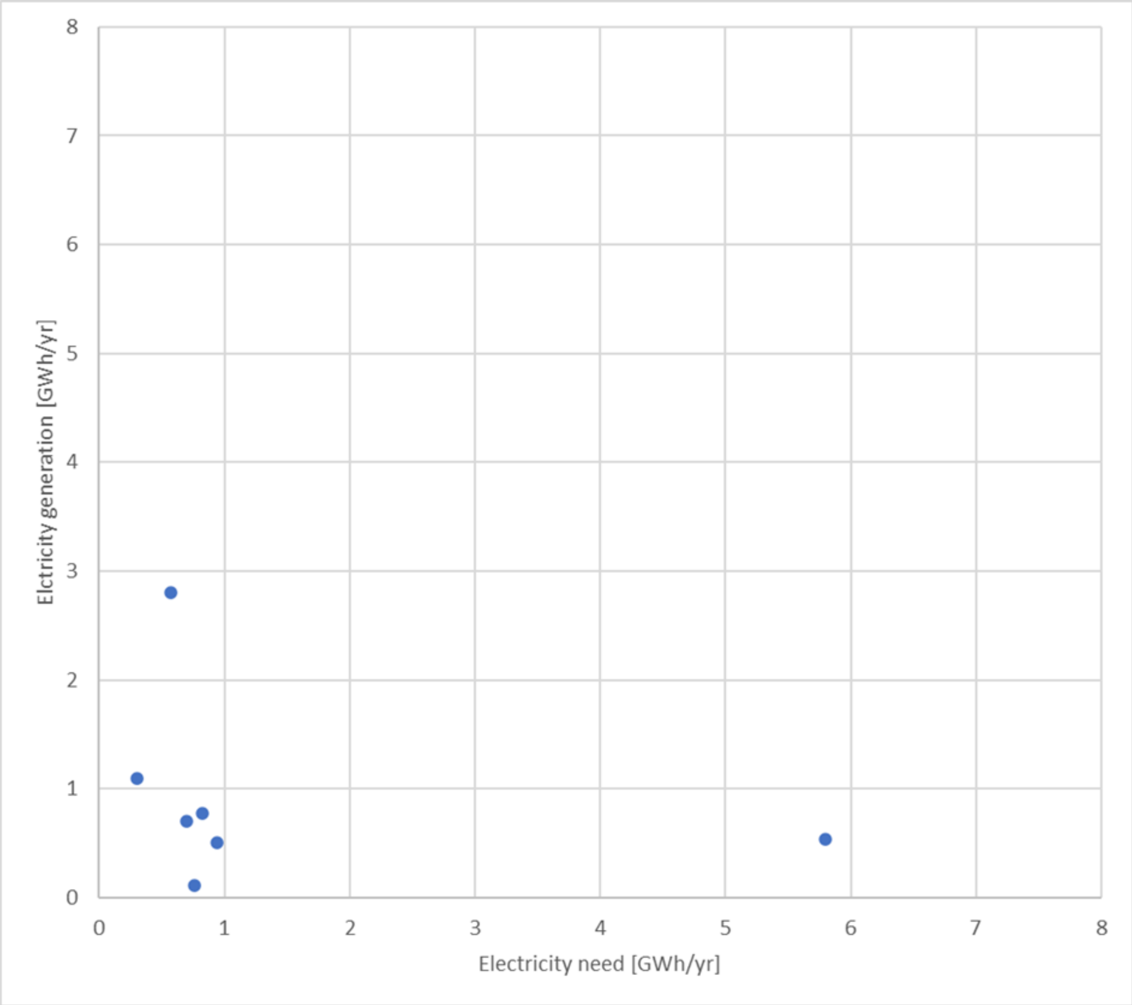

Figure 13 Balance between energy generation and needs in PEDs.

This comparison helps to identify whether the districts can produce sufficient thermal energy to meet their requirements or if there are gaps that need to be addressed. The dispersion of data points in this figure reflects the diversity in thermal energy strategies and the varying effectiveness of different approaches.

Similarly, Figure 13 examines the relationship between electricity energy generation and electricity energy needs. This scatter plot highlights how different PEDs manage their electrical energy balance and reveals any discrepancies between production and consumption. The distribution of data points indicates the complexity and variability of electricity management within these districts.

2.1.3 Lesson learned

The distribution analysis of PEDs reveals that these districts are more developed in countries with higher levels of social participation and engagement. The Köppen climate classification plays a crucial role in understanding where PEDs are located. PEDs are predominantly found in regions with favourable climatic conditions, such as temperate oceanic (Cfb) and continental (Dfb) climates, where the local environment supports the integration of diverse renewable technologies. This suggests that successful implementation and development of PEDs are closely linked to not only the socio-political context but also the specific climatic conditions that facilitate or hinder the adoption of energy solutions.

The analysis of development stages shows that while many PEDs are in advanced stages of planning or implementation, there are significant challenges that slow down their progress. Financial barriers and regulatory frameworks pose substantial obstacles. These challenges contribute to the difficulty in reaching the ambitious goal of achieving 100 PEDs by 2050, as set by current strategic initiatives. Despite these hurdles, the growing number of PEDs in operation underscores the potential for widespread adoption as these issues are addressed.

Examining the spatial extent of PEDs, it is observed that most effective PEDs are typically smaller than 1 km^2. This smaller scale allows for better management and coordination, making it easier to implement energy-efficient technologies and maintain a positive energy balance. The analysis suggests that smaller districts are more likely to succeed in becoming energy positive due to the reduced complexity in managing energy flows and infrastructure compared to larger areas.

Regarding land use, the primary type of PED is residential, but the inclusion of non-residential elements, such as commercial or industrial areas, highlights the flexibility of the PED concept. This flexibility allows for the adaptation of PEDs to different urban environments, making it possible to implement energy-positive strategies in diverse settings. However, the mixed-use nature of some PEDs introduces additional challenges in balancing energy demand and supply, particularly in areas with varying energy needs throughout the day.

The adoption of renewable technologies within PEDs is strongly influenced by the climatic context, as demonstrated by the analysis of existing districts. Photovoltaic systems are among the most widely used technologies, adaptable to various climates and urban settings. Solar thermal technologies are also commonly adopted, especially in regions with high solar irradiance. Geothermal systems, while highly efficient, are less widespread due to their dependence on specific geological conditions and the need for significant space, limiting their feasibility in densely populated urban areas.

The relationship between energy generation and consumption within PEDs remains a complex issue. The analysis reveals that there is no clear pattern between consumption and the area of the district, indicating that energy efficiency and renewable energy generation are influenced by multiple factors beyond just spatial considerations. This complexity underscores the need for tailored approaches in the design and implementation of PEDs, considering local conditions, available resources, and the specific energy needs of the district.

The analyses conducted are heavily dependent on the two primary sources utilized: the Booklet and the PED Database. These databases are continuously being updated and focus on different aspects of PEDs, each offering unique insights. Effective utilization of these resources requires careful consideration of their strengths and limitations, and integrating their insights through a pre-analysis process, essential to ensure a comprehensive and accurate assessment of PEDs in practice.

2.2 State of the art of existing tool and methods

Understanding the technological aspects and static data alone does not suffice for the effective design and implementation of PEDs. Advanced tools that enable dynamic and integrated modeling, simulation and optimization of the energy and environmental performance of districts are crucial. This chapter aims to explore the state of the art of these tools, examining how they contribute to the achievement of sustainability goals and addressing the challenges identified in the earlier sections. Building on the author's study[17], the analysis provides a comprehensive understanding of how these tools can be seamlessly integrated into the PED design process. This integration aims to facilitate the development of more sustainable and efficient energy solutions, ultimately supporting the realization of broader environmental and economic objectives.

Current tools are fragmented, significantly hindering their ability to support the complex design process required for PEDs. PEDs are known for their surplus renewable energy generation, but recent advancements in urban environmental science stress the importance of an integrated approach to achieve the key performance indicators of the United Nations' 17 Sustainable Development Goals (SDGs). Consequently, PED designs must dynamically incorporate input from multiple stakeholders. These complexities intersect with urban challenges such as heat islands, microclimates, nature-based solutions, future climate conditions.

Additionally, resource availability, social dynamics, connectivity, walkability, and economic activity must all be considered, making the design process even more intricate. This multifaceted approach is essential to ensure that PEDs are not only energy-positive but also sustainable, resilient, and responsive to the diverse demands of urban environments.

Rapid urbanization in the digital age, along with a changing climate, requires data-driven policies and tools to balance various environmental factors. These factors include energy consumption, carbon emissions and the quality of both indoor and outdoor environments, all while considering the interests of multiple stakeholders. Recent advancements in computational tools allow for more efficient and accurate assessments of these environmental criteria[18]. The integration of parametric workflows and artificial intelligence (AI) into evaluation processes is becoming more frequent[19]. This integration expands the scope and scale of environmental performance assessments from individual buildings to entire urban districts[20]. The limited number of available PED examples illustrate a fragmented design environment where disparate tools and performance criteria support different design objectives without continuity or a clear understanding of the mutual impacts of variables and environmental performance criteria.

The analysis of tools and methods for PEDs illustrated the multifaceted approach necessary to address contemporary challenges in optimizing environmental performance at the urban scale. The following sections examine various critical aspects:

1. Tools and methods in PEDs design;
2. Scales and evaluation boundaries in PEDs;
3. Available analytical approaches and methods for evaluating PED performance;
4. PED Tools and their classification;
5. Digital workflows to achieve advanced PED designs;
6. PED tools and future climate and urban resilience;
7. Integration of PED tools into design phases and interaction with stakeholders;
8. Gaps between existing tools and practical PED design;
9. Outlooks, future challenges and opportunities for PED tools.

2.2.1 The role of tools and methods in PEDs design

The role of tools and methods in PED design within the larger performative framework is directly influenced by four key factors:

1. shift in scale from single buildings to urban ecosystems;
2. transition from singular environmental objectives to multifaceted analyses;
3. growing involvement of multiple stakeholders in the design process;
4. increasing adoption of data-driven design processes.

2.2.1.1 From single buildings to urban ecosystems

In recent years, the emphasis in sustainable building design has shifted from nearly (net) zero energy buildings (nZEBs or NZEBs) to PEDs. This transition signifies a move from focusing on the energy efficiency of individual buildings to achieving surplus energy generation and management across entire urban districts.

Both nZEBs and PEDs prioritize the energy balance between supply and demand, promoting on-site renewable energy generation. Research efforts in pursuit of nZEB and ZEB (Zero Energy Building) goals have led to studies focusing on:

- Energy performance prediction tools [21];
- Renewable energy integration[22]
- Life cycle assessment (LCA)[23];
- Grid integration [24]
- Energy monitoring and verification [25]
- Understanding occupant behaviour and user experience [26]

These efforts have also underscored the necessity of extending the nZEB concept to an urban scale, considering both environmental quality and energy performance aspects within the design process[27].

The PED concept follows similar principles and includes additional elements such as urban energy systems, energy mutualization and interactions between building energy systems. This broader scale requires the adaptation of existing tools and methods developed for individual nZEB strategies to address trade-offs between individual buildings and the district.

2.2.1.2 From singular environmental objectives to multifaceted analyses

Since 2010, along with the discussions focused on Zero Energy Buildings (ZEBs), the introduction of the 17 SDGs in 2015 and standards like WELL Community [28] and the Living Community Challenge [29] have brought forth various frameworks related to carbon and climate KPIs. These include aspects such as outdoor thermal comfort, wind comfort, urban heat islands, urban energy systems and other ecological factors. This broader ecological category encompasses indicators like biodiversity, habitat preservation, green infrastructure, and water management, emphasizing the preservation and enhancement of the natural environment within urban districts.

This wider environmental performance perspective presents the challenge of simultaneously addressing multiple interrelated indicators during the design process. This involves balancing conflicting KPIs, such as solar shading versus exposure analyses, visual versus thermal comfort, tree canopy versus building density, and community versus building scale energy storage and supply systems. Additionally, integrating different tools that measure these indices using various simulation engines with distinct input parameters and computational loads poses further difficulties.

Presenting and weighting these results to optimize multiple performance objectives at the district scale remains a significant challenge.

2.2.1.3 Involvement of multiple stakeholders in the design process

Planning at the district level requires the collaboration of a wide range of stakeholders [30], including design professionals, homeowners, local communities, policymakers, urban ecologists, and energy service providers. Effective cooperation among these groups is crucial to developing a strategy that aligns the diverse objectives of such a complex project, covering social, economic, and environmental aspects. In the PED design, tools that facilitate this collaborative process are vital. These tools should support iterative, multi-criteria decision-making through an integrated platform that consolidates the insights and contributions of all stakeholders. They should not only enable the integration of various areas of expertise but also foster a broadly participatory design process. To fill a critical gap in PED design practices, these tools should provide a continuous conceptual framework that guides stakeholders through the different stages of the design process. This framework ensures that design decisions are interconnected and part of a comprehensive and inclusive strategy for developing sustainable and resilient urban districts.

2.2.1.4 Adoption of data-driven design processes

The significance of tools in PED design should be understood within the broader shift toward data-driven architectural processes [31]. This transformative change is driven by innovative methods and technologies such as smart controls, digital twinning and Building Information Modeling (BIM). These technologies create connections between the physical and digital aspects of design, potentially revolutionizing the entire design process by providing multifaceted benefits, including prediction, evaluation, collaboration, optimization and operation phases. BIM, for example, has already proven its value in enhancing performance-based decision-making at the building scale.

A key trend within data-driven design is the move toward parametric and generative workflows. Platforms like Grasshopper allow designers to rapidly and interactively explore a vast design space, drawing insights from various data sources and simulation engines. These workflows offer remarkable flexibility in adapting to different KPIs and scales. Additionally, their effectiveness is increasingly enhanced through AI integration, which improves designers' ability to make well-informed decisions.

2.2.2 Scales and evaluation boundaries in PEDs

Researchers involved in various projects and initiatives are working to define the scales and boundaries of PEDs to assist municipalities, planners and other stakeholders in realizing their potential [32] [33]. There is a broad consensus that scaling up from individual buildings to the district level involves more than just aggregating single building methods and requirements. Aggregating buildings can lead to more efficient energy supply and demand management; however, it also introduces additional complexities related to boundary definitions and a higher number of interdependent design factors. Therefore, new analytical tools and methods, as well as domains such as infrastructural and environmental, become relevant. This, includes four categories of methods and tools for PED design, each related to different operational scales:

- the spatial scale;
- the system scale;
- the microclimate scale;
- the hybrid scale.

The spatial scale

Analysing the energy performance of hundreds or thousands of buildings within a district requires different methods and tools than those used for individual buildings, for two primary reasons.

Firstly, there are uncertainties stemming from limited cadastral information and the lack of available energy use data for existing buildings, coupled with minimal information about new buildings during early design stages. In this context, planning for PEDs can benefit from urban building energy modeling (UBEM) tools that utilize functional building archetypes to speed up the energy modeling process for entire districts[34]. These tools can also automatically divide floors into schematic core and perimeter zones[35].

Secondly, the extended time required for energy simulations at the urban scale poses a challenge. To mitigate this, methods have been developed to use a few thermal zones assigned to building façades, grouped by insolation levels[36], within district energy analysis tools[37]. Additionally, researchers have validated the reliability of simplified metrics based on solar radiation and shading, building form, and urban density to predict energy usage without the need for detailed simulations[38].

The system scale

Planning for PEDs can be enhanced by integrating the building domain with other urban analysis domains, such as district systems, to improve the efficiency of managing energy demand and supply. This integration optimizes the heating system network topology by considering various thermal plant options, heating distribution scenarios and simulated building energy use, which helps to reduce overall energy consumption, greenhouse gas emissions, and utility costs[39]. Additionally, selecting different building clusters based on decentralized or centralized systems and on-site PV energy generation allows for exploring district scenarios that achieve lower CO_2 emissions and heating costs while identifying KPI relationships [40].

The microclimate scale

A comprehensive approach to planning PEDs involves considering the accessibility of open areas, which is significantly influenced by various urban climate phenomena characteristic of environments with different densities, fabrics, urban surface materials and the energy use of buildings. Therefore, the evaluation boundaries for PEDs must consider the microclimate scale of the outdoor domain and environmental design objectives. At the block scale, the impact of trees and grass patches with varying building cluster forms on wind comfort in public areas was examined [41]. At the neighbourhood scale, the effect of dense historic urban fabric with high thermal mass surfaces on the mean radiant temperature of the outdoor environment and the perceived temperatures by residents was analysed [42]. At the district and city scales, the effects of the composition, spatial pattern and type of urban green spaces on land surface temperature were studied to assess the potential urban heat island effect [43].

The hybrid scale

The integration of building and spatial scales, along with the consideration of the outdoor domain in the planning of PEDs, can benefit from newly developed digital methods and tools that operate at the hybrid scale. These methods integrate various simulation workflows to evaluate the combined achievement of multiple KPIs for the design solution. Some studies have analysed energy use and generation load match, indoor daylight availability, and year-round outdoor thermal comfort for building clusters with different typologies[44], densities, and envelope characteristics[45]. Other research has focused on layout variations of the same office building cluster in different urban environments to reduce cooling energy use and improve outdoor thermal comfort during the hot season[46]. Additionally, studies have examined pattern variations of residential building clusters in existing urban environments to ensure facade sunlight exposure as recommended by local regulations and outdoor wind comfort according to established metrics[47].

2.2.3 Analytical approaches and methods for evaluating PED performance

Currently, there are numerous UBEM tools designed for analytically assessing energy efficiency and flexibility in buildings through multi-scale measures and systems. These tools exhibit variability in their spatial-scale models and computational approaches, enabling simulations with diverse outputs and temporal resolutions. A recent study [48] categorized UBEM tools into three groups:

1. Physics-based models;
2. Reduced-order models;
3. Data-driven models.

According to their modeling approaches. Building on this classification, there is a fourth category—metadata-driven models.

The following discussion elaborates on the methodologies utilized by these four modeling approaches and provides a comprehensive examination of their challenges and opportunities in evaluating PEDs.

2.2.3.1 Physics-based models

The physics-based modeling approach involves conducting transient simulations of heat transfer and energy trade-offs within buildings. Tools employing this approach consider building geometry, thermal and optical properties, as well as appliances and equipment. This detailed level of analysis enables PED designers to identify measures that enhance energy efficiency and promote renewable energy generation in buildings [49].

In addition to buildings, these tools can also size and evaluate district thermal and energy systems, providing a means for buildings to offset their energy demand [20].

Furthermore, this category of tools assists utilities and energy service providers in making informed decisions regarding demand-response initiatives, energy efficiency programs, and related technologies [49].

Despite their comprehensive capabilities for evaluating energy efficiency and flexibility in PED design, physics-based modeling tools have notable limitations. The detailed simulation methodology these tools utilize is computationally intensive, particularly for city-scale PED simulations. Computational constraints further complicate multi-objective optimization attempts using these UBEM tools. Although archetypes and floor multiplication techniques exist to mitigate computational issues, they often reduce the accuracy of outcomes, making them unsuitable for certain energy efficiency and flexibility evaluations.

2.2.3.2 Reduced order models

Unlike physics-based models, reduced-order modeling approaches do not face computational limitations. UBEM tools in this category evaluate the performance of PEDs using normative calculation methods established by organizations such as the European Committee for Standardization (CEN) and the International Organization for Standardization (ISO) [48]. However, reduced-order models cannot perform extensive simulations, resulting in coarse output resolutions that offer a general overview of PEDs' performance. These models incorporate only a limited number of design details for normative calculations, which restricts their ability to conduct multi-objective optimization. Furthermore, the applicability of normative calculation methods across different climates and contexts is questionable.

2.2.3.3 Data-driven models

Data-driven modeling approaches utilize simple regression or machine learning (ML) models based on measured data to evaluate PEDs. Simulating PED designs with data-driven models is computationally less demanding, and the results are reliable. However, because the measured data represent existing conditions, assessing multi-scale retrofit measures becomes impractical. Furthermore, the adaptability of mathematical or ML models to different climates and contexts may be limited[48].

2.2.3.4 Metadata-driven models

Similar to data-driven modeling approaches, the metadata-driven modeling approach also utilizes simple regression or machine learning (ML) models, but these are developed from simulated data, known as metadata. Initially, the physics-based modeling approach is used to simulate several parametric PED design iterations and generate metadata. Subsequently, simple or advanced statistical methods are employed to test and train models using this metadata. Ultimately, the model enables the determination of multi-objective optimized PED designs with reduced computational power.

Since these regression or ML models are created from metadata derived through physics-based modeling, the results are generally reliable. It is important to note that metadata-driven modeling approaches for simulating PED performance are still evolving, with very few studies available in the current literature [50] [27].

2.2.4 PED Tools and their classification

Tools designed for energy modeling of PEDs vary in scope, resolution, objectives, and modeling techniques. Some tools incorporate aspects of the social domain, such as Intelligent Community Design (iCD)[51], [52] and address mobility issues, like City Energy Analyst[52]. However, the majority primarily focus on building energy demand and supply. Certain tools employ simplified dynamic modeling approaches for calculating thermal loads, such as City Energy Analyst[53] and TEASER[54], while most utilize physics-based dynamic simulations to assess thermal loads, exemplified by EnergyPlus [55].

Providing a comprehensive and exhaustive classification of these tools is an extremely complex task. Nevertheless, certain specific aspects will be considered. These aspects can be summarized by the following questions:

- What domains does the tool investigate? (e.g., can it model energy use in buildings? does it calculate CO_2 emissions for transportation?)
- What is the tool based on? Which mathematical models does it implement?
- What outputs can the tool provide?

A total of 43 tools were analysed, with 70% deemed suitable for research purposes, 58% appropriate for practitioners, and 28% usable by both researchers and practitioners.

2.2.4.1 Domains covered by the tools

Many tools primarily focus on:

Energy-related aspects:

- Energy generation (67%)
- Energy consumption (77%) at the building or district level

Other considerations include:

- Mobility issues: 9% of the tools (e.g., LakeSIM[56])
- Environmental aspects: 40% of the tools
    - Full life cycle assessment for CO_{2eq} emissions: 7% of the tools
- Indoor environmental aspects: 33% of the tools, including:

    - Daylight
    - Indoor air quality (IAQ)
    - Thermal comfort
- Outdoor environmental aspects: 16% of the tools, addressing:
    - Outdoor thermal comfort
    - Urban heat islands
- Economic aspects: 51% of the PED tools
    - Payback time (PBT) or net present value (NPV): 12% of the tools

Among the reviewed PED tools, decision support tools are included, although not all of them compute building thermal loads. Specifically:

Single- or multi-objective optimization tools focusing on energy supply technologies within geographical boundaries:

- Calliope [57]
- EnergyPRO [58], [59]
- Oemof [59], [60]
- MANGO [60]

Energy demand parameters:

- Exogenous: Calliope, energyPRO, MANGO
- Endogenous: oemof

Tools focusing on network topology and urban planning:

- DecodingSpaces Toolbox [61], [62]
- Urbano [62]
- DigiWo [63]

Interfaces for visualizing key modeling results:

- Colibri [64]
- Thread/DesignExplorer[65]

Optimization tools for Rhino and Grasshopper:

- Opossum [66]
- Octopus [67]

The specific fields covered by each tool are detailed in Table 4. The table groups various applications, including those related to the 'environmental boundary' category, which includes climate change, carbon emissions, acidification, eutrophication, land use, ecological footprints, particulate matter emissions and human toxicological effects (not an exhaustive list).

Table 4 covers only broad areas of categorization. This implies that all tools may provide further elaboration of the simple outputs, such as:

- Composition of temperature outputs within adaptive comfort outputs;
- Connection of indoor environment variables and generation/consumption into flexibility or load match indicators.

This elaboration can be achieved either explicitly by the tools or through user elaboration. Additionally, the table indicates the tool's capacity to calculate aspects of both renewable energy-based systems (e.g., PV or wind turbines) and non-renewable energy-based systems (e.g., gas boilers). The landscape for PED modeling predominantly emphasizes energy demand (77%) and supply (67%), with limited consideration given to mobility (9%) and social issues (7%).

Table 4 PED modeling tools and domains of interest

DOMAIN OF APPLICATION								
Tool	Energy			Environmental boundary	Indoor environment	Outdoor environment	Economic	Social
	Energy demand	Energy supply	Mobility					
Intelligent Community Design (iCD) [68]	H&C, DHW, EL	REN, NO-REN		CO_{2eq}-UP			O&M	other[1]
Insight [69]	H&C, EL	REN, NO-REN			DL		IC, PBT, O&M	
Urban Modeling Interface (UMI) [70]	H&C, DHW, EL	REN, NO-REN		CO_{2eq}-LC, EE-LC	DL			other[2]
Sefaira [71]	H&C, DHW, EL	REN, NO-REN		CO_2-UP	DL, TC		O&M	
ClimateStudio [72]	H&C, DHW, EL	REN		CO_2-UP	DL, TC		O&M	
Ladybug [73]						TC		
Honeybee [74]	H&C, DHW, EL	NO-REN		CO_2-UP	DL, TC			
Dragonfly [75]	H&C, DHW, EL	REN, NO-REN	X	CO_2-UP		UHI	IC	
Butterfly [76]					TC	TC		

Pollination [77]	H&C, DHW, EL	NO-REN			DL, TC			
Eddy3D [78]						TC		
Morpho [79]						TC		
Envimet [80]						TC		
CityBES [81]	H&C, DHW, EL	REN, NO-REN		CO_{2eq}-LC		TC, UHI	IC, PBT, O&M	
URBANopt [82]	H&C, DHW, EL	REN, NO-REN		CO_{2eq}-UP				
COFFEE [83]	H&C, DHW, EL	NO-REN						
CitySim [84]	H&C, DHW, EL	REN, NO-REN						
SEMANCO [85]	H&C, EL	REN, NO-REN		CO_2-UP			O&M	
SimStadt [86]	H&C, DHW, EL	REN, NO-REN		PE-UP, CO_2-UP			IC, O&M	
LakeSIM [56]	H&C, DHW, EL		X					
City Energy Analyst [87]	H&C, DHW, EL	REN, NO-REN	X	CO_{2eq}-CUPM, PED-CUPM			IC, O&M	
Tool For Energy Analysis and Simulation For Efficient Retrofit (TEASER) [88]	H&C	REN, NO-REN						
Calliope [89]	H&C, DHW, EL	REN, NO-REN					O&M	
energyPRO [58]	H&C, EL	REN, NO-REN					IC, PBT, NPV, O&M	
oemof (Open Energy Modeling Framework) [59]	H&C, EL	REN, NO-REN					IC	
MANGO [60]	H&C, DHW, EL	REN, NO-REN		CO_2-UP			IC, O&M	
ICL (Intelligent Communit	H&C, DHW, EL	REN, NO-REN	X	CO_2-UP			IC, PBT, O&M	

ies Life Cycle) [90]								
DER-CAM [91]	H&C, DHW, EL	REN, NO-REN		CO_2-UP			IC, PBT, O&M	
Making City (ENERKAD®) [92]	H&C, DHW, EL	REN		CO_2-UP			O&M	
DeCoding Spaces Toolbox [61]	Not applicable[1]							
Urbano [62]								other[3]
DigiWo [63]	Not applicable[2]							
Design Explorer/ Thread[3][93], [94]	H&C, EL				DL			
Colibri[3] [64]	H&C, EL							
Opossum [66]	Not applicable[4]							
Octopus [67]	Not applicable[4]							
EnergyPlus [55]	H&C, DHW, EL	REN, NO-REN		CO_{2eq}-UP	DL, IAQ, TC		IC, O&M	
trnsys [95]	H&C, DHW, EL	REN, NO-REN			TC		IC, O&M	
DOE-2 [96]	H&C, DHW, EL	REN, NO-REN			DL		O&M	
eQUEST [97]	H&C, DHW, EL	REN, NO-REN			DL		O&M	
ESP-r [98]	H&C, DHW, EL				DL, TC			
OpenIDEAS [99]	H&C, DHW, EL	NO-REN					O&M	
DesignBuilder [100]	H&C, DHW, EL	REN, NO-REN		CO_{2eq}-LC	DL, IAQ, TC		IC, O&M	

Table 5 Legend of the table four

H&C	heating and cooling	**NO-REN**	non-renewable energy	**CO_{2eq}-CUPM**	CO_{2eq} emissions (construction, use phase, mobility)	**DL**	daylight	**IC**	investment cost
EL	electricity	**CO_{2eq}-UP**	CO_{2eq} emissions (use-phase)	**PE-UP**	primary energy (use phase)	**IAQ**	indoor air quality	**PBT**	payback time
DHW	domestic hot water	**CO_{2eq}-LC**	CO_{2eq} emissions (life cycle)	**CO_2-UP**	CO_2 emissions (use-phase)	**TC**	thermal comfort	**NPV**	net present value
REN	renewable energy	**EE-LC**	embodied energy (life cycle)	**PED-CUPM**	primary energy demand (construction, use phase, mobility)	**UHI**	urban heat island	**O&M**	operation and maintenance costs

[1] Collection of components for algorithmic architectural and urban planning, including street network generation and analysis, visibility, and statistical data analysis, building blocks generation

[2] The tool has the target to generate buildings starting from pre-defined blocks, to maximize some targets, such as the building density.

[3] The tool does not perform energy simulations; it is an interface that collects previous simulation results.

[4] The tool does not perform energy simulations; it can be exploited as a support optimization tool in Grasshopper.

Other[1]: Jobs created, disposable income, fuel poverty, property value, derelict development, Walkability, Accessibility, energy consumption reduction

Other[2]: Jobs created, walkability

Other[3]: Amenity demand profile, streetscore, amenityscore, walkscore

2.2.4.2 Modeling approaches

Over half of the analysed PED tools rely on building energy dynamic simulation (55.8%), with only a few conducting static analyses (7%). Tools utilizing static-based simulation, like SimStadt [101], provide outputs with a monthly timeframe resolution. Among dynamic simulation tools, there are further distinctions between simplified and physics-based dynamic simulation models:

Simplified dynamic models:

Tools such as oemof [102] adhere to calculation standards based on technical norms, regulations, or national guidelines, making up 8.3% of the dynamic-based tools.

Other simplified dynamic tools, like City Energy Analyst and TEASER, use reduced-order models from Modelica libraries [103], representing 12.5% of the dynamic-based tools.

These simplified approaches are typically focused on the early stages of PED design.

Such tools provide crucial insights during the initial phases of planning and design, ensuring that key parameters are considered efficiently.

Physics-based simulation models:

Physics-based simulation models offer detailed results and are utilized for more advanced stages of PED design, including energy flexibility considerations. These tools typically rely on the EnergyPlus engine, as seen in tools like Sefaira [71], [104] ,UMI [105], ClimateStudio [72] and Honeybee [74]. Additionally, Intelligent Community Design (iCD) [51] and Intelligent Communities Life Cycle (ICL)[106] deploy the 'Digital Twin' modeling approach, incorporating real-time operational data alongside physics-based simulations.

The modeling approaches employed by the analysed tools are detailed in Table 6.

Key findings include:

- Physics-based simulation models:
  - Utilized by about 39.5% of the analysed tools to simulate building behaviour.
- Simplified dynamic or static models:
  - Employed by 18.6% of the tools.
- Data-driven approaches:
  - Combine physics-based simulation models with real-time operational data, representing 4.7% of the tools.
  - These approaches offer further refinement in modeling building behaviour but remain relatively scarce.

Such detailed simulation models are critical for later stages of PED design, providing comprehensive insights and supporting advanced energy flexibility strategies.

Table 6 Main modeling features of the PED tools (not applicable means that tools do not perform building thermal energy simulation)

MAIN CHARACTERISTICS				
tool	design phase	scale (city, district, building)	time-resolution (dynamic/static)	modeling approach
Intelligent Community Design (iCD) [51]	Detailed design	District	Dynamic	Data-driven
Insight [107]	From early concept to detailed design	Building	Dynamic	Physics-based
Urban Modeling Interface (UMI) [105]	Early phase	District, city	Dynamic	Physics-based
Sefaira [104]	Early phase	Building	Dynamic	Physics-based
ClimateStudio [72]	From early concept to detailed design	Building, district	Dynamic	Physics-based
Ladybug [73]	Early phase	Building, district	Not applicable	Not applicable
Honeybee [74]	From mid concept to detailed design	Building	Dynamic	Physics-based
Dragonfly [75]	From early concept to detailed design	District	Dynamic	Physics-based
Butterfly [76]	Not applicable	Building, district	Not applicable	Not applicable
Pollination [108]	From early concept to detailed design	Building	Dynamic	Physics-based
Eddy3D [78]	Not applicable	district	Not applicable	Not applicable
Morpho [79]	Not applicable	District	Not applicable	Not applicable
Envimet [80]	Not applicable	District	Not applicable	Not applicable
CityBES [81]	Early phase	District, city	Dynamic	Physics-based
URBANopt [82]	From early to mid-concept	District	Dynamic	Physics-based
COFFEE [83]	Early phase	Building, district	Dynamic	Physics-based
CitySim [109]	Early phase	District, city	Dynamic	Reduced order calculation method

SEMANCO [110]	Early phase	District	Static	Standards-based
SimStadt [101]	Early phase	Building, district, city	Static	Standards-based
LakeSIM [56]	Early phase	District, city	Static	Reduced order calculation method
City Energy Analyst [53]	Early phase	District	Dynamic	Reduced order calculation method
Tool For Energy Analysis and Simulation For Efficient Retrofit (TEASER) [88]	Early phase	Building, District	Dynamic	Reduced order calculation method
Calliope [89]	Not applicable	From district to national scale	Not applicable	Not applicable
EnergyPRO [58]	Not applicable	From district to regional scale	Not applicable	Not applicable
oemof (Open Energy Modeling Framework) [102]	Early phase	District	Dynamic	Standards-based
MANGO [60]	Not applicable	District, city	Not applicable	Not applicable
ICL (Intelligent Communities Life Cycle) [106]	Detailed design	District	Dynamic	Data-driven
DER-CAM [91]	Not applicable	Building, district	Not applicable	Not applicable
Making City (ENERKAD®) [111]	Early phase	Building, district, city	Dynamic	Standards-based
DeCodingSpaces Toolbox [61]	Not applicable	District, city	Not applicable	Not applicable
Urbano [62]	Not applicable	District, city	Not applicable	Not applicable
DigiWo [63]	Not applicable	Building, district	Not applicable	Not applicable
Design Explorer/ Thread [93], [94]	Not applicable	Building, district	Not applicable	Not applicable
Colibri [64]	Not applicable	Building, district	Not applicable	Not applicable
Opossum [66]	Not applicable	Not applicable	Not applicable	Not applicable
Octopus [67]	Not applicable	Not applicable	Not applicable	Not applicable
EnergyPlus [55]	From early concept to detailed design	Building, district	Dynamic	Physics-based
trnsys [95]	From early concept to detailed design	Building, district	Dynamic	Physics-based
DOE-2[96]	From early	Building, district	Dynamic	Physics-based

	concept to detailed design			
eQUEST [112]	Early concept	Building, district	Dynamic	Physics-based
ESP-r [113]	Early phase	District	Dynamic	Physics-based
OpenIDEAS [114]	Early phase	Building, district	Dynamic	Physics-based
DesignBuilder [100], [115]	From early concept to detailed design	Building, district	Dynamic	Physics-based

2.2.5 Digital workflows to achieve advanced PED designs

Recent developments in digital workflows have significantly enhanced the capabilities of existing tools in the design of PEDs. These workflows allow for greater integration and interoperability among various software platforms, enabling more precise and efficient design processes. By automating certain aspects of the design, such as energy simulations and spatial planning, digital workflows contribute to the creation of more advanced and optimized PED designs.

For instance, tools like Grasshopper for Rhino,[116] demonstrate considerable transformative potential in PED design. These tools support the development of advanced PEDs that not only achieve a net positive energy balance but also prioritize ecological sustainability and public health [117]. This dynamic and multifaceted approach is essential in addressing the challenges posed by rapidly evolving urban climates[118] [119].

Advanced PEDs should address this complexity by integrating comprehensive digital workflows for dynamic energy management. These workflows should employ predictive analytics to optimize energy consumption and incorporate responsive systems that adapt to climate variations. PED designs should harmonize with urban aspects, such as ecological systems, all supported by sophisticated digital frameworks that enhance health and sustainability.

In contrast, less advanced PEDs often consider energy in isolation from broader sustainability aspects. The distinction between isolated tool use and integrated digital workflows is essential in PED design. Digital tools like Modelica, City Energy Analyst (CEA), TRNSYS, and others play key roles in tasks such as energy modeling, simulation, and data analysis.

While no single tool perfectly combines all PED elements [20], current PEDs might struggle to effectively respond to climate change, environmental shifts and community needs. However, employing digital workflows enables the integration of these tools into a cohesive, unified approach.

Shifting from singular tools to integrated digital workflows in advanced PEDs opens new possibilities, allowing them to better adapt to environmental changes and embrace a more sustainable, resilient urban living approach.

Operating in a digital environment where multiple tools can be combined is critical. This approach mitigates the complexity of disparate systems by offering a unified platform for data exchange and tool interoperability.

For example, Grasshopper enables the integration of various plugins and external data sources, simplifying complex analyses and design tasks.

Combining tools, as outlined in Table 7 in a unified workflow allows for cross-referencing of data and insights. In this advanced design context, parametric platforms facilitate seamless data transfer between different tools and computational methods via plugins (Table 8).

Modules handling numerical and geometric data can connect for diverse assessment objectives. Integrated workflows streamline the capture and relay of simulation input parameters across various platforms, refining results without direct linkage [120].

For instance, digital tools for energy evaluation can be coupled with ecological tools like Meerkat for GIS data integration and Ladybug for climate data visualization [73] . Similarly, Morpho (an ENVI-met interface) for climate modeling data integration enables PED adaptation to local microclimates [121], [122].

District-level adaptation can reduce energy demand [123], [124] . The Elk plugin processes biodiversity-focused GIS data, enriching designs with ecological metrics such as habitat patches.

The Mosquito plugin integrates public health data, assessing design impacts on health to support urban designs.

Additionally, the DeCodingSpaces Toolbox promotes healthier PEDs by facilitating walkability and enhancing contact with nature, empowering PED planners to craft health-enhancing spaces.

At the core of these workflows is the ability of tools to seamlessly transfer data.

For instance, Grasshopper, with its robust data management and interoperability via plugins like TT Toolbox (for data streaming), ensures consistent data flow (Table 8). This fosters an integrative, data-driven design approach that addresses energy, ecology, and health comprehensively.

Table 7 PED Digital Workflow: Overview of key tools and plugins compatible with Grasshopper for design optimization across energy, ecology, and health domains.

Category	Tool/Plugin Name	Functionality (Based on Existing Knowledge)	Data Received	Data Provided	PED Affected Design Variable
Energy	City Energy Analyst (CEA)	High-resolution urban energy demand simulations, integrating building physics & energy systems.	GIS data, Climate Data.	Building physics, energy systems, energy demand.	Building energy efficiency, HVAC systems optimization.
	TRNSYS	Specialized in district heating and cooling; traces energy sources, storage, and consumption.	District System designs, Solar installations.	Energy consumption, heating/cooling data.	District-level energy consumption, Storage & distribution optimization.
	CitySim	Simulates urban energy and environmental dynamics (assumed).	Building designs, Climate Data.	Energy consumption patterns, environmental interactions.	Urban energy balance, Interactions between buildings and environment.
	Honeybee	Dynamic building energy simulations.	Building designs, Weather data.	Energy consumption patterns, thermal properties.	Building-level energy consumption, Facade design optimization.
	Dragonfly	Urban-scale energy and environmental simulation.	Urban layouts, Climate data.	Energy and environmental performance data.	Urban form and fabric energy efficiency.
	UMI	Integrates various urban planning and design tools for comprehensive sustainability analysis.	Urban layouts, Climate data	Sustainability metrics, urban design impacts.	Urban sustainability strategies, holistic urban planning.
Ecology	Meerkat	GIS data integration tool within Grasshopper.	Site designs, Urban layouts.	GIS data, including topography, land use, etc.	Land use optimization, Site-specific design interventions.
	Ladybug	Integrates and visualizes climate-related data for design purposes.	Building designs, Urban layouts.	Climate data, weather patterns.	Climate adaptation strategies, Sunlight/shade optimization.
	Morpho	Interface to ENVI-met; focused on microclimate modeling.	Building designs, Urban layouts.	Climate data, microclimate interactions.	Microclimate management, green infrastructure design.
	Elk	Biodiversity-focused GIS data processing tool.	Site designs, Urban layouts.	GIS data, including habitat patches,	Biodiversity enhancement, Habitat

				biodiversity metrics.	preservation & creation.
	Pando	Modeling of vegetation systems	Greenery Design	Vegetation types	Behaviour of Vegetation, Microclimatic analysis
	Green Scenario	Environmental impact assessment of urban designs	Urban designs, ecological data	Environmental impact analysis, green infrastructure strategies	Ecological impact assessment, green infrastructure planning.
Health	Mosquito	Integrates public health data for design evaluation.	Urban designs, Building layouts.	Public health metrics, population data.	Public health promotion, Design for well-being & comfort.
	DeCoding Spaces Toolbox	Urban and architectural analysis tools enhancing spatial understanding.	Building designs, Urban layouts.	Topological, network, and spatial data.	Enhanced Walkability, and Vision of Natural Features

Table 8 PED Digital Workflow: Overview of Grasshopper plugins categorized by functionality: interoperability, optimization, machine learning and visualization

Category	Name of Plugin	Function & Data Interaction	Relevance to PED design
Interoperability & Integration	TT Toolbox	Ensures data streaming between Grasshopper and other platforms using multiple design data to provide streamlined data for other tools.	Data integration & seamless design workflows.
Optimization	Galapagos/Octopus/Opossum	Optimization tools refine design parameters using design data and environmental parameters to yield optimized design parameters.	Enhanced energy efficiency, Ecological balance, and Health promotion.
Machine Learning	Owl/Dodo/Lunchbox	Learning paradigms supplant traditional simulations, using design data and previous simulations to offer predictive designs and simulations.	Proactive designs based on learning from data.
Visualization	Design Explorer	Tool that visualizes complex design spaces, employing design variations and simulated outcomes to present a visual representation of design spaces.	Design clarity, Decision-making support.

Optimization tools like Galapagos, Octopus, and Opossum refine design workflows.

Integrating emerging technologies—AI, the internet of things (IoT), and blockchain—is crucial to augmenting PED capabilities, particularly for climate change adaptation and managing energy and ecological systems. These technologies offer new avenues for dynamic adaptation, efficient resource use, and predictive modeling within digital workflows, aligning environmental parameters with design needs. The role of machine learning in PED design, as demonstrated by plugins like Owl, Dodo, and Lunchbox, leverages learning paradigms that may surpass traditional simulations.

This synergy is crucial for the effective integration of digital workflows, particularly in advancing PED design and implementation. Platforms like Grasshopper streamline tool integration and data management, yet they are not universal solutions. A balanced approach blending technical proficiency with an understanding of local context and community needs is essential.

However, integrating multiple sophisticated tools presents challenges, especially for teams lacking technical expertise. Grasshopper, as an example of an integrated digital environment, mitigates complexities by providing a unified platform for simplifying analyses through plugin integration and external data sources. Nevertheless, successful integration demands more than mere data aggregation; it requires nuanced understanding for optimizing PED designs.

Implementing a holistic digital workflow necessitates robust IT infrastructure and technical expertise, which are crucial for reliable simulations. While platforms like Grasshopper streamline data processes, robust data collection and validation, along with stakeholder capacity building, remain vital. Balancing digital reliance with real-world contexts is paramount, ensuring that over-reliance on digital tools does not overshadow on-ground realities.

Adapting digital workflows to local contexts and incorporating qualitative insights ensures designs resonate with local environments and community needs.

The effective use of digital workflows in designing advanced PEDs hinges on integrating diverse tools within platforms like Grasshopper. While these platforms offer significant potential for optimizing PED designs across energy, ecology, and health parameters, they also present challenges in complexity, data management, and balancing digital capabilities with real-world contexts. Success in this endeavour requires technical proficiency and adaptability, considering local environmental and community dynamics.

Moreover, the growing urgency of addressing climate change adds another layer of complexity to PED design. As urban areas face increasingly severe weather events, rising temperatures, and shifting climate patterns, the ability of PEDs to adapt to these changes becomes critical. Digital workflows must, therefore, incorporate predictive climate models and resilience strategies to ensure that PEDs can withstand and respond to the impacts of climate change. This includes integrating tools that can model future climate scenarios, assess the vulnerability of energy systems, and plan for sustainable urban development that mitigates climate risks. By embedding these considerations into the design process, digital workflows can help create PEDs that are not only energy efficient but also resilient to the long-term effects of climate change.

2.2.6 PED tools and future climate and urban resilience

Considering future weather conditions in PED design is crucial due to the escalating impacts of climate change. The resilience and long-term sustainability of PEDs rely on adapting to shifting climate patterns and extreme weather events. Neglecting future climate scenarios may result in suboptimal energy performance, overestimation of heating or cooling demands and potential mismatches in energy generation and consumption, risking the overall energy balance and environmental goals of PEDs. To ensure the effectiveness of PEDs amid climate change, it is vital to use high-resolution future weather data and advanced modeling for evolving urban microclimates.

Like buildings, the energy systems in PEDs can be categorized into base load and variable load systems based on their reliance on climatic conditions [125].

- Base load systems, such as street lighting, exhibit energy consumption tied to usage;
- Variable load systems like district cooling depend on ambient climate conditions.

UBEM tools evaluate the energy performance of these systems using representative weather files [126] , available in formats like "typical meteorological year," "test reference year," or "design summer year."

Typically, statistical methods generate these files to eliminate infrequent extremities from historical weather datasets[127].

However, relying on present-day representative weather files for PED assessment offers insights into past climate conditions but overlooks future climate changes.

Several studies [128] [129] have highlighted potential overestimations of heating and underestimations of cooling demands in buildings when simulated with present-day representative weather files. These concerns raise questions about the energy efficiency and adaptability of PEDs in future climate change scenarios.

Currently, future weather file generators produce climate-specific files worldwide, aligning with climate change scenarios from the Intergovernmental Panel on Climate Change (IPCC). These files derive from global or regional climate models (GCMs or RCMs) validated by the IPCC's Working Groups.

GCMs offer broader spatial resolutions, typically a few hundred kilometres, while RCMs provide finer resolutions, ranging from a few tens of kilometres to meters. To enhance spatial accuracy, future weather file generators employ static and dynamic downscaling methods, especially where RCM outputs are not available for every geolocation[130].

Although GCM and RCM outputs mostly offer daily or monthly data, weather files require hourly resolution. To address this, generators use static and dynamic temporal downscaling models, providing the necessary hourly climate data [131]. It is crucial to note that the high-resolution data used for downscaling captures a location's boundary layer climate.

Historical data used for present-day weather files or downscaling is collected from weather monitoring stations near airports or building rooftops, capturing the boundary layer climate[127] . However, in densely built areas like cities, this boundary layer climate might not accurately represent PEDs' energy systems. Buildings exhibit notable deviations in cooling and energy performance due to overlooking microclimatic influences from urban form and materiality [132].

Errors in building energy performance arise from neglecting microclimatic influences induced by nature-based solutions [133]. Hence, integrating urban climate modeling (UCM) with building energy modeling (BEM) tools becomes essential for accurately simulating building energy performance [134]. Some researchers have devised chaining and coupling techniques to integrate microclimatic data into building energy simulations [135]. The chaining approach involves one-way data exchange between UCM tools and BEM tools for the same timestep, while the coupling approach engages in two-way data exchange either in parallel or in sequence. UCM tools, like urban weather file generators, modify present-day or future representative weather files, considering urban form and materiality, and are utilized for chaining with UBEM. The coupling approach effectively exchanges transient heat flux information between UBEM and UCM tools at each step. However, these coupling methods, although available, entail high computational expenses, especially for conducting annual simulations [136]

2.2.7 Integration of PED tools into design phases and interaction with stakeholders

The development of PEDs is a complex process that requires the integration of diverse tools and the input of various stakeholders across different scales and stages of the project lifecycle. Understanding how these tools are utilized throughout the PED process necessitates a simultaneous evaluation of design phases, scales, and stakeholder involvement. The PED design landscape includes several methodologies for identifying key phases, as highlighted by the PED-EU-NET team [16].

Examples include:

- The MakingCity project's six-phase approach [137]
- The Atelier project's seven-step strategy [138]
- Project RESPONSE's four phases [139]

Cheng et al. [140] identify crucial phases—master planning, energy planning, construction, implementation, monitoring, and post-occupancy evaluation (POE)— that are instrumental in aligning goals, tools, and stakeholders, providing a structured framework for categorization.

Multidisciplinary collaboration among stakeholders is essential throughout the PED design process. Li et al. [141] emphasize the need for spatially-tiered stakeholder categorization, highlighting the importance of multi-level decision-making. Relevant planning scales, ranging from regional to building levels, are outlined in resources such as the Louisiana Planning Assembly Kit [142]and the Positive Energy Districts Solution Booklet [143].

However, harmonizing design phases, stakeholder interests and scales can be challenging due to their frequent intersections. In practice, these elements are interconnected by critical decision-making junctures known as 'intervention points.' Stakeholders navigate challenges during these intervention points using various tools.

Given the evolving roles of stakeholders in PED development, it is crucial to analyse the relevant stakeholders and tools employed at each intervention point.

Table 9 illustrates the connection between intervention points and design phases[140], while Table 10 identifies key stakeholders[137] [144] [140] [141] [143] [145] associated with each point. These tables use intervention points as a common thread, visually clarifying the complexity and hierarchy within the PED design process.

A review of PED design tools used in real-world demonstrations reveals that, [16] during early phases like master planning and energy planning, tools focused on developing a sustainable energy vision—along with methods for rapid, iterative energy demand assessment like ENERKAD—are prevalent.

As the process progresses into intermediate phases, including energy planning and construction/refurbishment planning, the emphasis shifts towards multi-scale energy assessment tools, such as ENERKAD, CEA, and Ladybug as well as tools addressing specific intervention points, such as SpineOPT for flexibility issues. In the later stages, particularly during Construction/Refurbishment Planning at the building scale, the focus shifts to energy and comfort assessment tools like EnergyPlus, IDA ICE, and TRNSYS. In the final phases, such as monitoring and post-occupancy evaluation (POE), the use of more experimental tools, including digital twins and model predictive control algorithms, becomes evident.

Table 6 presents a comprehensive overview of PED tools, showing that the majority (25 tools) are designed for the early phases, with 11 extending into detailed design. However, there is a notable scarcity of tools for the later stages, particularly for post-implementation tasks such as POE and monitoring. This observation is consistent with the insights derived from the intervention points detailed in Table 9 and Table 10.

Of the 17 identified intervention points, 13 are associated with the pre-implementation design phases, while only 4 are linked to post-implementation stages. This trend also extends to stakeholder involvement, with all 30 identified stakeholders being actively engaged in the pre-implementation phases, underscoring their critical role throughout the design process.

Despite an apparent balance in tool distribution the lack of tools for later stages, especially for monitoring, energy and flexibility management, and energy accounting, remains significant.

Currently, only a few experimental tools, such as model predictive control algorithms and digital twins, address these crucial aspects.

Table 9 PED design phases, and corresponding intervention points

design phases / intervention points	Master planning	Energy planning	Construction /renovation planning	Implementation	Monitoring	POE
energy vision	X					
renewable potential	X	X	X			
building placement/ insolation	X					
outdoor comfort	X					
energy and flexibility design	X	X				
user mix	X	X				
integration with wider infrastructure		X	X			
integrating EVs		X	X			
passive design		X	X			
indoor comfort		X	X			
energy storage		X	X			
microgrids		X	X			
active design system efficiency		X	X			
energy and flexibility management			X	X	X	
occupant behaviour		X	X	X	X	X
accounting of energy				X	X	X
decision support	X	X	X	X	X	X

Table 10 Key stakeholders in each intervention point during the PED design process

scales / Intervention points	City scale	District scale	Building scale
energy vision	Local authorities, Enterprises, Knowledge institutes, Citizens		
renewable potential	Energy suppliers, TSOs, DSOs, Flexibility/Energy market operators, Local authorities, City energy engineers, Developers	Energy engineers, Architects, Local authorities	Architects, Electrical/Mechanical engineers, Manufacturers, Installation companies, Facility management, Local authorities
building placement/ insolation	City planners, Local authorities, Designers, Developers	District planners, Architects, Local authorities	

Outdoor comfort		District planner, Local authorities, Designers, Developers	
energy and flexibility design	Energy suppliers, TSOs, DSOs, Flexibility/Energy market operators, Local authorities, City energy engineers, Developers	Energy suppliers, TSOs, DSOs, Flexibility/Energy market operators, Local authorities, City energy engineers, Developers	Energy engineers, Mechanical/Electrical engineers
user mix		Social planners, Energy engineers, Energy manager, DSO, Flexibility market operator, Energy communities	
integration with wider infrastructure	Energy suppliers, TSOs, DSOs, Regional/local authorities, Developers		
integrating EVs		Energy suppliers, TSOs, DSOs, Flexibility/Energy market operators, Local authorities, City energy engineers, Developers	Energy suppliers, TSOs, DSOs, Flexibility/Energy market operators, Local authorities, City energy engineers, Developers
passive design			Architects, Manufacturers, Construction company
indoor comfort			Architects, Mechanical/Electrical engineers, Occupants
energy storage			Architects, Electrical/Mechanical engineers, Manufacturers, Installation companies, Facility management, Local authorities
microgrids		Energy manager, Energy providers, DSO, Asset manager, Energy engineers, Local authorities	
active design system efficiency			Architects, Electrical/Mechanical engineers, Manufacturers, Installation companies, Facility management
energy and flexibility management		Energy suppliers, TSOs, DSOs, Flexibility/Energy market operators, Local authorities, City energy engineers, Developers	Flexibility market operator, Energy manager, Energy providers, DSO, Asset manager, Energy engineers, Local authorities, Energy communities
occupant behaviour			Occupants, Facility management
accounting of energy		Energy manager, Energy providers, DSO, Energy manager, Asset manager, Energy engineers, Local authorities	
decision support	All	All	All

While optimization and energy analysis tools are available, their usage is less widespread compared to tools used for defining the project's vision. Tools tailored for the intermediate-to-final design stages, covering both district and building scales, are increasingly being integrated into the planning process with greater effectiveness. However, despite the importance of post-occupancy evaluation (POE) and monitoring in the later stages, these areas still require better tool integration and more advanced utilization. Consequently, a persistent gap remains in meeting the diverse tool needs of city, district, and building planners. Bridging this gap necessitates the integration of missing tools and the adoption of a unified, comprehensive design approach aligned with the Integrated Energy Design[146] philosophy. This alignment is crucial for unlocking the full potential of PEDs.

2.2.8 Gaps between existing tools and practical PED design

There is a significant gap in unified PED design frameworks, largely attributed to the field's novelty and the diversity of local contexts. Factors including varying regulations, types of renewables, energy storage, consumption patterns, and local economic opportunities require a tailored approach, necessitating distinct tools for different scenarios [147].

Examining case studies from PED-EU-NET [16] provided insights into the tools currently utilized in PED design. These tools predominantly include energy modeling software, either at the building level (TRNSYS, EnergyPlus, IDA-ICE [148]) or the neighbourhood scale (CEA, ENERKAD). Additionally, methods for flexibility assessment (grey-box modeling [149]) and technology selection (web-based decision tree module [12]) are utilized. In some case studies, virtual twins (GRIDS energyCity [150]platform, SPARCS Virtual Twin [151]) play a role during operational phases. However, the incompleteness of these tools reveals a spectrum of challenges, some of which are tool-addressable (energy and optimization) and others that are beyond tool capabilities (policy or political changes). This analysis specifically targets tool-addressable challenges, striving to identify necessary tools and connections by analysing the barriers outlined in Table 7 from PED-EU-NET.

While the absence of certain tools is one reason for existing gaps, based on experience, there are other factors at play. Use cases from industry show that even tools with potential advantages might be underused because of various performance gaps, such as industry reluctance towards modern technologies, organizational and technical challenges, and lack of tool integration [152], [153], [154]. Under the umbrella of Annex 83 [155], aspects were identified based on five existing case studies, including a range of tools such as TRNSYS [156], CEA [157], EnergyPLAN [158], and EnergyPlus [159], where current energy modeling software must improve for better adoption, along with the associated challenges and potential paths for improvement [160].

From a design practice perspective, PED tools are categorized based on usage into three groups:

- Tools widely used and integrated into PED design;
- Tools available but underutilized due to challenges with integration, usability, user interface and user experience (UI/UX), and accuracy, as detailed in Table 12**.**
- Absent tools, which include emergent behaviour simulation and blockchain, along with necessary capabilities like fast, iterative scenario analysis and essential links between cost and renewable modeling.

The current fragmented toolkit for PED design complicates essential tasks like calibration, sensitivity analysis, and validation, rendering them resource intensive. Although AI and ML solutions are still in their infancy and have not yet been fully integrated, they hold the potential to streamline these processes, promising a future of enhanced design efficiency. By fostering interdisciplinary collaboration, we can harness these technologies to streamline design processes and navigate the complexities of urban development. Advancing this synergy of tools and expertise is imperative for the realization of PEDs, ensuring sustainable and adaptive urban environments for future generations.

These gaps and their implications are further discussed in Table 11**.**

Table 11 Mapping barriers in PED design practice and potential tool solutions

Barriers	Challenge	Capability needed	Tool Gap
Regulatory	Missing cross-sectoral collaborations	Interoperability	Cross-sectoral tool connections
Economic	High initial investment for renewable transition	Econometric-renewable modeling connection	Econometric-renewable modeling link
	Energy-inefficient buildings or low-income tenants	Quick cost-benefit and impact assessment	Renovation scenario and impact analysis tool
	Optimizing energy flows cost-effectively	Low-data resolution cost-benefit optimization	Optimization for energy generation, storage, and consumption
	Identifying and monetizing multiple benefits	Easy-benefit monetization methods	Multiple benefits calculation
	Lack of models assessing local energy sharing	Multiple scenario calculation and energy sharing optimization	Tool modeling local energy sharing
Technical	Selecting energy-saving measures	Customizable multi-scale energy modeling	Adaptable energy modeling software

	Maximize renewable uses, local-regional network connections	Renewable potential analysis with broader system connection	Regional electricity and renewable modeling software
	Enabling sector coupling and exchange of energy	Multiple scenario calculations, connecting energy flows, energy sharing optimization	Software module capable of analysing energy flow and sharing.
	Cost-effective energy storage exploration	Energy storage optimization linked to energy systems	Integrated energy storage modeling
	Integrating EVs in energy system design	Integrated or composable EV model	EV and energy modeling
	Exploring blockchain for local power management	Blockchain emulation, emergent behaviour modeling	Integrated blockchain module analysing costs and effects of blockchain implementation
	Demand response	Integrated or composable demand response (DR) model	DR optimization module
	Monodirectional infrastructure	Low-voltage microgrid scenario analysis	Integrated microgrid scenario analysis module
	Nature based solutions (NBS) integration	Coupling NBS with energy modeling	Integration of NBS analysis with energy modeling
Social	Passive users	Emergent behaviour scenario analysis	Agent-based PED performance tool
	Limited energy flexibility	Emergent behaviour scenario analysis	Agent-based PED performance tool

Table 12 Current practical challenges and improvement paths based on Belda et al [161]

Area	Challenge Description	Improvement Path
Input Data	Challenges in data accuracy, collection, ownership, and protection.	Standardize data protocols, enhance sharing, create comprehensive databases
Meteorological Data	Limited weather profile integration hinders micro-climate considerations	Expand weather profiles, enhance integration with external meteorological files.
Geometrical Data	Complex building geometries are challenging to model.	Advance geometrical capabilities of tools, automate reading of building attributes.
Energy System Parameters	Limitations in defining building services and renewable systems.	Enhance customization, allow multiple supply systems at the building level.
Building Energy Modeling	Building definition, and customization issues	Improve space identification, intuitive interfaces for manual inspection, modifications
User Interface and Complexity	Inconvenient interfaces limit adoption.	Design intuitive interfaces, provide comprehensive training.
Modeling Process and Accuracy	Balance between technology-driven processes and accuracy.	Introduce adaptive simplifications without compromising accuracy.
Data Integration	Lack of integration between various data types.	Develop purpose-defined routines and code for seamless integration.

2.2.9 Outlooks, future challenges, and opportunities for PED tools

While most PED tools consider the energy supply and demand of the PED itself, there is comparatively less focus on environmental aspects.

Climate change is addressed as an impact category in all PED tools dealing with environmental issues (40%). Around 33% of PED tools evaluate carbon dioxide emissions during the operational phase, while only a few account for the entire life cycle, such as UMI, CityBES, and DesignBuilder. Only 7% of the tools assess primary energy demand throughout the operational phase, with examples including UMI, SimStadt, and City Energy Analyst. Embodied energy is considered by 5% of the tools, notably UMI and City Energy Analyst.

Concerning economic aspects:

- Investment costs are assessed by 30% of the tools;
- Operational costs are evaluated by 49% of the tools.

Only 12% estimate the payback time or net present value (PBT or NPV), with tools such as Insight, CityBES, energyPRO, ICL, and DER-CAM addressing these metrics.

Social aspects are largely neglected by most PED tools (93%), with exceptions like iCD, UMI, and Urbano, which address social indicators such as job creation and walkability. Table 4 details the main results obtainable from each tool.

There is a notable lack of emphasis on environmental and social issues, with only 40% and 7% of the tools, respectively, accounting for them. Moreover, additional environmental impact stages beyond operational phases should be considered. Furthermore, there is a deficiency in implementing metrics for assessing the financial viability of investments, such as payback time and net present value, in 88% of the analysed tools.

The analysis highlights varied approaches to PED modeling potential, with diverse classifications based on investigated items and mathematical modeling. The current focus largely centres on energy balances and computing energy requirements for heating, cooling, and electricity consumption in buildings. However, true integration of modeling domains should be pursued for under-represented elements such as mobility modeling, social aspects, economic factors, life cycle environmental sustainability, and outdoor thermal comfort.

The concept of PEDs is poised for global expansion as urban sustainability initiatives expand. To assess their potential, is possible to learn from the 15-year history of ZEB implementation, which has taught us that the gap between ZEB conceptualization and realization remains significant and that the majority of ZEBs have remained demonstration projects [162].

In contrast, PEDs have set clear policy-level implementation goals, with Europe aiming for 100 PEDs by 2050. Yet, bridging the high aspirations of PEDs with practical urban design realities poses significant challenges. To facilitate PED implementation, a set of tools supporting PED design will be essential for city planners, designers, and developers to align with regulations and policies.

Considering the broader context, the future of PED design tools appears transformative. This transformation will be driven by technological advancements, a heightened focus on high-energy-performance urban design, and environmental quality. These tools will optimize energy efficiency, integrate nature-based solutions (NBS), renewable energy sources, and urban storage and supply systems, including advanced energy storage and water management. They will also prioritize environmental quality, addressing aspects like visual and thermal comfort, air and water quality, green and blue infrastructures, and biodiversity, fostering holistic, eco-friendly, and liveable districts.

In the context of these aspects and the scopes, metrics, and toolsets discussed, key future challenges and opportunities for PED tools are identified. These challenges and opportunities are categorized using the same framework introduced earlier (2.2.1), providing insights into the evolving landscape of PED implementation.

2.2.9.1 Transitioning from individual buildings to districts

- Opportunities: Beyond BEM, UBEM tools gradually unlock the ability of tools to predict, optimize and communicate energy-related aspects of district building interactions, such as district energy load balance, combined storage systems, mixed-use energy mutualization, district heating and cooling, and renewable energy interactions. Beyond operational energy, the district-scale engagement expands the analytical life cycle analysis perspective and opens new horizons for exploring the mutual impacts of buildings, green systems, and the environmental quality of outdoor semiprivate and public spaces (e.g., outdoor thermal comfort).
- Challenges: Upscaling the analysis boundary from the building to the district is computationally complex due to the datasets needed to perform a reliable analysis,

the integration of several KPIs, and the computational loads needed to allow for such a comprehensive integration.

2.2.9.2 Multi-objective Environmental Analysis

- Opportunities: The need in PED design to perform fast and large-scale calculations while accounting for several environmental performance KPIs at the district scale and generate optimized scenarios based on those KPIs necessitates the aid of artificial intelligence. The evolution of AI- and ML-enhanced workflows for architectural design optimization is accelerating, and their incorporation into the PED design process is a natural next step. This is particularly important when considering the need for real-time analyses or when involving multiple stakeholders in a collaborative PED design process.
- Challenges: (1) lack of established methods for appropriately weighing different KPIs during PED optimization in the design phase; (2) the integration of quantitative and qualitative indicators; (3) the harmonization of fragmented tools and metrics, each requiring distinct input data and evaluation protocols, resulting in potential inefficiencies in PED design; and (4) the constraint of computation time impedes effective and timely communication.

2.2.9.3 Multi-stakeholders' Engagement

- Opportunities: Collaborative design platforms facilitating the participation of multiple stakeholders in PED projects promise enhanced decision-making and consensus-building. Virtual reality (VR) and augmented reality (AR) technologies offer immersive visualization of PED designs, aiding stakeholders and the public in comprehending and engaging with proposed projects. Co-simulation and collaborative platforms are being developed to allow interactive exploration of PED design criteria or multiple design scenarios. Visual aids such as interactive screens help these tools communicate spatial and numerical results to diverse audiences.
- Challenges: (1) cost considerations, as smaller municipalities and design firms may encounter difficulties in affording advanced immersive PED design tools; (2) the need to develop tailored software-hardware interfaces for each type of project; and (3) the current limitations of available immersive technologies in terms of usability, response time, and user comfort (e.g., field of view in AR platforms).

2.2.9.4 Data-driven Design

- Opportunities: Rapid advances in IoT and GIS technologies link smart city and urban digital twinning initiatives. These advancements will create new middleware like urban geospatial workflows, dashboards, web-based applications, and GIS-driven tools for PED design. These tools enable interactive, data-driven, multi-disciplinary PED design using data from various sources.
- Challenges: (1) securing accurate and up-to-date energy consumption, microclimatic, and other data repositories necessary for coherent and precise performative prediction and analysis; (2) addressing privacy concerns that limit data use for design; and (3) overcoming the lack of standardized protocols and data formats.

Despite the challenges, the field of PED tools offers many opportunities for innovation, collaboration, and integration into urban development initiatives.

As PEDs become increasingly prevalent, these tools will emerge as indispensable instruments in advancing the objectives of establishing an effective collaborative and holistic data-driven environment for PED designs. The complexities associated with PED designs, transcending mere energy balance by exploring the interplay of governance, technology, stakeholders, and urban dynamics. From the shift in scale to multifaceted analyses and the integration of diverse stakeholders, tools serve as essential conduits in navigating the contemporary landscape of PED design.

The examination of existing PED tools has revealed several critical insights into the technical complexities and methodological challenges inherent in their application. The analysis highlights the role of these tools within a performative framework that seeks to balance multiple sustainable design goals. Central to this discussion is the integration of simulations for holistic assessments, particularly in the context of high-density urban areas, where the absence of standardized metrics and the need for improved databases and methodologies are most acutely felt.

The analysis underscores the limitations of traditional energy balance metrics, advocating for a more comprehensive approach that includes considerations of outdoor microclimates, social dynamics, economic factors, future climatic scenarios, microclimatic conditions, and life cycle sustainability. The integration of tools such as Urban Building Energy Modeling (UBEM) and microclimate simulations, alongside the convergence of various analytical perspectives—from energy evaluations to broader social, economic, and environmental assessments—emerges as a crucial aspect of PED design.

The complexity of achieving a truly integrated assessment framework, which transcends conventional energy modeling, is evident. The need for tools that can encompass the full range of factors influencing PED performance is increasingly recognized. This comprehensive approach is essential for advancing PED design and ensuring that such districts contribute meaningfully to sustainable urban development.

It is evident that the field of PED tools is poised at a critical juncture, where the potential for innovation is vast but accompanied by substantial challenges. The promise of AI-driven solutions, which have the capacity to address data complexities, scale analyses to district-level precision, and streamline multi-objective optimizations, is particularly noteworthy. However, these possibilities are tempered by the challenges of computational complexity, the prioritization of key performance indicators, tool integration, affordability, data accuracy, privacy concerns, and standardization.

The subsequent analysis will focus on a specific tool that aims to address some of the identified challenges. This tool, which will be examined in detail, represents an effort to integrate the diverse elements required for comprehensive PED design, offering a pathway towards more resilient and sustainable urban environments. The analysis will explore its capabilities, limitations, and potential applications within the broader context of PED development, providing a foundation for future advancements in this critical area.

2.3 Aims and contribution of the thesis

An in-depth analysis of existing tools for the design and management PEDs has highlighted a series of significant limitations that reduce their effectiveness, especially during the preliminary design phases.

These limitations become even more evident when such tools are applied to large urban districts, where the complexity and amount of required data increase exponentially. Many of the currently available tools demand a high quantity of detailed data and complex inputs, making them difficult to use in the early stages of design when the available information is often limited or uncertain. This hinders designers' ability to perform quick assessments and efficiently explore different design options.

Moreover, these tools are not always designed to effectively manage large-scale analyses, which further complicates their application in large urban district contexts. The lack of scalability and flexibility can lead to inaccurate results or ones that do not represent the real energy dynamics of the district, negatively influencing strategic decisions. This situation is particularly problematic given the urgent need to develop sustainable energy solutions at the urban level to address the challenges of climate change and environmental sustainability.

Some existing tools lack the necessary flexibility to adapt to different spatial and temporal scales of PED projects. They are unable to provide meaningful results with a reduced number of inputs, instead requiring detailed data that may not be available in the initial stages. This often results in an investment of time and resources not justified by the needs of a preliminary analysis, especially when working with large urban districts that require quick and efficient evaluations to guide strategic decisions. The need to simplify and accelerate the preliminary design process is therefore evident.

Research Questions

To address the identified limitations and bridge the gaps in current PED design practices, this thesis is guided by the following research questions:

1. How can a simplified tool enable accurate energy modeling in large urban districts during the preliminary design phase, despite limited or uncertain input data?
2. How can the proposed tool ensure scalability and flexibility across different spatial and temporal contexts?
3. How can the proposed tool enhance usability for a diverse range of stakeholders, including urban planners, engineers and policymakers?
4. How can a dynamic PED design tool be developed to improving strategic planning in large urban districts?
5. What methodologies can integrate energy modeling with environmental analysis to evaluate the long-term environmental impacts of retrofit strategies?

These questions aim to guide the development of a new tool that simplifies the design process for PEDs, making it adaptable and accessible to various contexts.

Proposed objectives and contributions

Building upon these questions, this study proposes the development of a simplified tool specifically designed to support the initial design phases of PEDs. The tool addresses the identified gaps by offering:

1. Simplified energy modeling: Utilizing energy archetypes and an optimized set of parameters to enable the evaluation of complex energy scenarios with minimal data. This addresses challenges related to data accuracy and availability, as well as the need for quick cost-benefit analyses.

2. Interoperability and adaptability: Capable of integrating with various data types and models, and adaptable to different spatial and temporal scales. This facilitates cross-sectoral collaborations and addresses regulatory and technical barriers by connecting different sectors and disciplines.

3. User-friendly interface: Addressing usability issues by providing an intuitive user interface and experience, encouraging wider adoption and overcoming challenges related to UI/UX. This aligns with the improvement paths identified for enhancing user interfaces and complexity management.

4. Rapid iterative analysis: Allowing for fast scenario analysis and iterative design processes to refine strategies efficiently. This meets the need for tools that support multiple scenario calculations and low-data resolution optimization.

5. Life Cycle Perspective: Supporting the analysis of intervention phases from a life cycle perspective to understand the long-term impact of retrofit strategies. This contributes to environmental sustainability, addressing the need for tools that link econometric models with renewable energy modeling.

The key element of the proposed tool is its ability to provide an accurate overview of a district's energy dynamics with minimal input data. By simplifying the modeling process and focusing on essential parameters, the tool empowers decision-makers to quickly explore different design options, identify potential challenges and opportunities, and make informed decisions early in the design process. This addresses the need for tools that can handle low-data resolution cost-benefit optimization and provide multiple scenario analyses.

The tool's ease of use and adaptability make it ideal for large-scale projects where managing the complexities of interactions between buildings, infrastructures and users is crucial. By integrating capabilities such as energy storage modeling, EV integration, and the potential for incorporating emergent technologies like blockchain, the tool addresses several technical barriers identified in current PED design practice.

To validate the effectiveness and applicability of the developed tool, studies were conducted on four distinct case studies representing a variety of urban contexts, district sizes and building typologies. These case studies allowed for testing the tool's versatility in different real-world situations. The results demonstrated that the tool offers accurate evaluations for districts of various sizes and characteristics, confirming its utility for both designing new districts and implementing large-scale retrofit interventions. The case studies also highlighted the tool's ability to support customized energy strategies tailored to the specific needs of each context, addressing the need for adaptability to local conditions.

The goal of this tool is to bridge the gap between theory and practice in the preliminary design phase, addressing the challenges identified in current PED design practices and the specific gaps outlined in the analyses. By offering a robust and simple solution, it aims to facilitate collaboration among various stakeholders involved in the design process, integrating energy, environmental, economic, and social considerations.

In conclusion, this thesis aims to make a significant contribution to the field of sustainable urban design by providing a practical and accessible tool that can be used by designers, urban planners, and decision-makers to promote the development of effective and sustainable PEDs. It is hoped that the developed tool will facilitate the adoption of more informed and sustainability-oriented design practices, supporting global efforts for the transition towards more resilient and low-carbon cities. The proposed innovation represents a step forward in integrating simplified and scalable approaches in urban design, helping to overcome current limitations and opening the way to new opportunities for research and practical application.

3. Methodology

3.1 Overview of the methodology and functional framework

The methodology outlined here is designed to assess and compare the energy consumption and environmental impacts of building archetypes at both baseline and renovated scenarios within a district. The process is structured into several key phases:

1. Data Collection: The first phase involves gathering data from Energy Performance Certificates (EPC) and Geographic Information Systems (GIS). This data is critical for understanding the characteristics of existing buildings and for segmenting them into distinct archetypes.
2. Supplementary data from standardized databases and building codes: when EPCs lack certain details, ensuring a comprehensive dataset that accurately reflects the building stock.
3. Development of Archetypes: Based on the collected data, archetypes are developed through a detailed process of segmentation and characterization. These archetypes serve as representative models for different types of buildings within the district;
4. Reference building: Following the development of archetypes, reference buildings are created for each;
5. Calibration: The models are calibrated with actual energy consumption data where available, ensuring their accuracy in representing real-world conditions;
6. Renovation scenarios are then defined by identifying potential energy efficiency measures;
7. Pre-Calculated energy demand: The energy demand for each archetype is pre-calculated for two scenarios:
    - Baseline Buildings: Energy demand is calculated based on current conditions without any interventions.
    - Renovated Buildings: Energy demand is calculated for buildings after proposed retrofit interventions, ensuring compliance with national norms (according to national norms).
8. Transition to district-level analysis: The analysis shifts from individual archetypes to the district level. This transition is based on the number of buildings per archetype within the district;

9. User Inputs: Users provide additional details about the existing systems and renewable energy sources for both baseline and renovated scenarios:

- Baseline Scenario: Details on existing heating, cooling, and renewable systems.
- Renovated Scenario: Information on post-retrofit systems and updated renewable energy sources.

10. Energy comparison: An energy consumption analysis is performed to compare the baseline scenario with the renovated scenario. This step quantifies the energy savings achieved through the proposed renovations;

11. Environmental impacts for baseline and renovated scenario:

- Baseline Scenario: Focuses on the current environmental impact during the building's operational phase.
- Renovated Scenario: Considers both the operational impacts and the embedded impacts from the retrofit interventions.

12. Environmental impact comparison: Finally, a comprehensive comparison of the environmental impacts is conducted, contrasting the operational phase impacts of the baseline scenario with the combined operational and embedded impacts of the renovated scenario. This analysis helps to evaluate the overall effectiveness and sustainability of the retrofit interventions.

The following figure illustrates the comprehensive methodology developed and implemented.

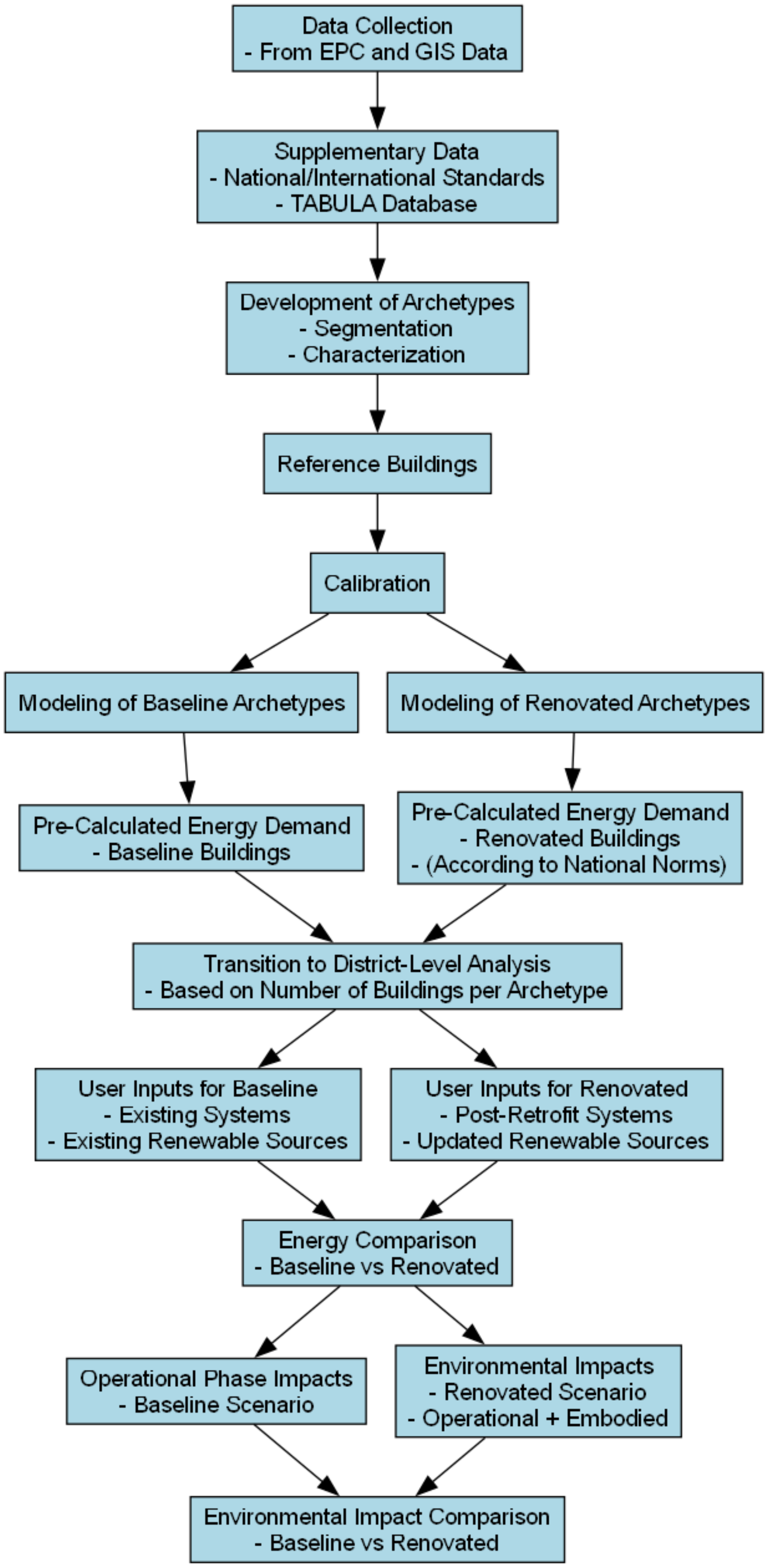

Figure 14 Methodology Flow chart

The methodology presented in this study is centred on the use of building archetypes as a tool to describe urban districts and to evaluate their potential to achieve the target of becoming PEDs. This study seeks to determine whether the districts, as represented by their respective archetypes, can meet this ambitious target. The approach begins with a comprehensive analysis of individual building archetypes within the district, using detailed data from EPC and GIS. These data sources allow for precise segmentation and characterization of the buildings, enabling the creation of representative archetypes that reflect the diversity of the district's building stock.

Once these archetypes are established, the study moves to assess the energy demand of the district. This is done by aggregating the energy performance of the individual archetypes, both in their current state (baseline) and after proposed retrofit interventions (renovated scenario). The methodology specifically examines whether these retrofit measures, designed in accordance with national norms, can transform the district into a PED.

However, the study goes beyond merely evaluating energy performance. It also considers the environmental impacts associated with the retrofit measures required to achieve the PED target. By conducting a comprehensive lifecycle analysis of these environmental impacts, the study ensures that the drive for energy efficiency is balanced with environmental sustainability.

3.1.1 Temporal resolution of output

The outputs generated by the simulations are originally produced with an hourly resolution, ensuring a high level of detail suitable for dynamic analysis. For purposes of synthesis and broader interpretation, these outputs are often aggregated to monthly or annual timescales. Monthly and annual aggregation facilitates the visualization of long-term trends, such as the overall energy balance or seasonal variations in energy demand and production.

3.2 Case study descriptions

The case studies analysed in this chapter provide the empirical foundation for the development of building archetypes, which will be used as pre-calculated data within the energy simulation tool. The analysis of Pamplona, Bucharest, Copenhagen and Parma districts has allowed for the collection of detailed data on energy demands for heating, cooling, and electricity. These data, organized by archetype, offer a representative view of the different building types within the studied districts, considering their construction characteristics and corresponding energy consumption profiles.

The archetypes derived from the case study analysis will be integrated into the tool described in the chapter 3.5, serving as pre-calculated inputs for energy demand. This approach enables efficient and reliable assessment of energy performance within the considered districts, facilitating the simulation and optimization processes within the tool, and supporting the identification of intervention scenarios and strategies for improving energy efficiency at the district level.

Pamplona

This research was also developed in the framework of a collaboration with researchers from the OPENLAB project and the National Renewable Energy Centre (CENER), focusing on field evaluations to assess how a real district could transition into a PED. This collaboration provided practical insights into the feasibility of implementing PED concepts in real-world urban environments. One of the case studies analysed was the San Pedro district in Pamplona, consisting of a total of 10 residential buildings constructed around the 1950s. These buildings, which are part of a social housing project, use methane-fuelled boilers for heating during the winter, while in the summer, they benefit from Pamplona's favourable climate by relying on natural ventilation. The analysis was conducted in the field, and photographs of each building were included in the chapter

Annexes. Given that all buildings are residential, constructed in the same period and homogeneous in terms typology, a single archetype was adopted to represent the entire district.

Below is a table that summarizes the characteristics of the archetype used to represent the district:

Table 13 Segmentation of existing buildings in the Pamplona district

Building Type	Number of Buildings	Construction Period
Residential Type	10	1940-1950

Bucharest

The district analysed in Bucharest is in Sector 6 (BS6) and comprises a total of 443 residential buildings.

The prevalent system for heating is district heating and for cooling is a centralized fan coil system, supported by heat pumps also employs electric heating systems for DHW.

From the analysis of the EPC, the buildings can be segmented by years of construction as follows:

- 48 buildings were constructed between 1960 and 1969;
- 376 buildings were constructed between 1970 and 1980;
- 19 buildings were constructed between 1980 and 1985.

All buildings within the district are residential and constructed in different historical periods. The EPC analysis reveals that some buildings have undergone a retrofit process. Consequently, these buildings can be divided into six archetypes: three original and three retrofitted.

Consequently, six archetypes were considered:

Constructed in the 1960s:

1. Archetype 1: Low-rise residential buildings with 5 floors, characterized by a compact and elongated rectangular shape.
2. Archetype 2: Mid-rise residential buildings with 11 floors, characterized by a compact rectangular shape.
3. Archetype 3: Mid-rise (West-East Oriented) residential buildings with 11 floors, characterized by a more elongated rectangular form.

Retrofitted counterparts:

4. Retrofitted Archetype 1: Maintains the same compact and elongated rectangular shape but incorporates additional insulation and energy efficiency measures.
5. Retrofitted Archetype 2: Maintains the same compact rectangular shape but incorporates additional insulation and energy efficiency measures.
6. Retrofitted Archetype 3: Maintains the same elongated rectangular form but incorporates additional insulation and energy efficiency measures.

To provide a visual representation of the common building types in the district, the following images illustrate the most prevalent typologies.

Figure 17 Low-rise residential buildings

Figure 15 Mid-rise residential buildings

Figure 16 Mid-rise (West-East oriented) residential buildings

Copenhagen

The district analysed in Copenhagen consists of 85 buildings, both residential and non-residential structures. The prevalent heating system in this district is district heating, which distributes heat to the buildings via a network of insulated pipes and provides domestic hot water, while the cooling system is primarily decentralized, with many buildings relying on individual air conditioning units or local cooling solutions such as heat pumps and chillers. Among the non-residential buildings, there are gyms, prisons and various other types of facilities. The residential buildings in the district vary in shape and have been constructed across different historical periods. The following table provides a detailed overview of the segmentation of these buildings within the district:

Table 14 Segmentation of existing buildings in the Copenhagen district

Building Type	Number of buildings	Construction period	Characteristics
Residential Type 1	24	1970s	Compact rectangular shape, brick construction
Residential Type 2	2	2011s	Elongated shape, concrete panels
Prisons	20	1990s	High-security features, reinforced concrete
Gyms	2	2011s	Large open spaces, steel frame
Other non-residential buildings *	37	2007	Combination of commercial and office spaces

*Most of the buildings in the fifth archetype are non-residential, with most of them being constructed predominantly in 2007.

To provide a visual representation of the common building types in the district, the following images illustrate the most prevalent typologies.

Figure 19 Archetype 1: Residential building 1

Figure 18 Archetype 2: Residential building 2

Figure 21 Archetype 3: Prison

Figure 20 Archetype 4: Gym

Parma

The district analysed in Parma consists of a total of 1259 buildings, both residential and non-residential structures. However, 12 of these buildings were not included in the analysis due to a lack of reference for their construction period or because they were identified as fuel stations.

The heating demand is covered by a gas boiler while cooling demand is served by local heat pump-based. In residential buildings, the DHW is provided by electric heating systems.

The next figure illustrates the 3D GIS model of Parma, where buildings are represented using GIS technology. This approach was necessary due to the large number of buildings concentrated in a specific area and their diversity in terms of typology and characteristics. By utilizing GIS, it was possible to manage and visualize the complexity of the urban environment effectively, providing a clear and organized representation of the district's structures.

Figure 22 3D GIS visualization of Parma

The segmentation process for the building stock in Parma involves categorizing the buildings according to their usage and the period in which they were constructed. Based on this segmentation, several archetypes have been identified for the Parma district:

Table 15 Segmentation of existing buildings in the Parma district

Building Type	Number of Buildings	Construction Period
Residential Type 1	917	Before 1991
Residential Type 2	65	Post-1991
Cinemas	23	Post-1991
Hospitals	7	1962-1971
Schools	14	1972-1981
University Campus	94	Post-1991
Productive buildings	127	1982-1991

3.3 Data collection for case studies

The analysis begins with a comprehensive data collection process aimed at accurately describing each district. This involves integrating Geographic Information System (GIS) data with Energy Performance Certificates (EPCs) to create a detailed and cohesive dataset that represents the unique characteristics of each district.

- EPC: provide a standardized assessment of building energy performance, including information such as energy consumption and energy efficiency.
- GIS: allow for spatial analysis and visualization of geographic and spatial data related to buildings and their environments.

The data collection process involves associating each building in the district with its corresponding EPC. This ensures that both energy performance data and spatial characteristics are accurately linked for each building. To maintain data quality and integrity, procedures such as removing duplicates, correcting inconsistencies and validating records against official databases are implemented. Incomplete or missing data is addressed by applying national or international building standards.

3.4 Archetype development

The development of building archetypes is a fundamental step in analysing and modeling the energy performance of a district's building stock. This section outlines the systematic approach taken to create representative models—referred to as archetypes—that encapsulate the diverse characteristics of buildings within the district.

The process of developing archetypes follows these steps:

1. Segmentation of the building stock;
2. Characterization of the building stock;
3. Creation of reference buildings;
4. Development of archetype descriptive table.

3.4.1 Segmentation of the building stock

Each building in the district is associated with an EPC and initially segmented based on its usage, such as residential or commercial. Further segmentation is performed by considering the construction period of each building, and data is filtered to remove any anomalies that could reduce the quality of the results. The segmentation relies heavily on the information provided by the EPCs.
If there are many buildings of the same type and constructed in the same period, the shape of the building is used as an additional segmentation criterion. This ensures a more precise classification and allows for a detailed analysis of buildings with similar characteristics.

3.4.2 Characterization of the building stock

The characterization process focuses on the non-geometric characteristics of each archetype. It involves detailed analysis of the data from the EPCs to capture aspects such as energy consumption, efficiency, and other relevant non-geometric attributes.

A critical element of this characterization are thermal properties and the internal loads, which include lighting, equipment usage, and occupancy patterns. These internal load parameters are often fundamental for the calibration process but are not typically provided by EPCs.

When EPCs lack detailed information necessary for accurate energy modelling appropriate standards and databases are utilized to supplement the missing data. The selection of these resources depends on whether the buildings are residential or non-residential.

For residential buildings:

- Thermal Properties: If EPCs do not provide explicit U-values (thermal transmittance) for the building envelope, standardized databases like the TABULA [163] Database are used. This database offers detailed thermal properties for walls, windows, and floors based on building typologies and construction periods.

- Occupancy profiles and internal loads: Since EPCs often lack detailed information on occupancy and internal loads, standards such as EN 16798-1:2019[164] are applied. This standard provides input parameters for indoor environmental conditions, including occupancy density (m^2/person), occupancy schedules, and internal heat gains from occupants and equipment. However, EN 16798-1:2019 does not provide specific values for lighting loads (W/m^2). This is addressed by using EN 15193-2[165], which focuses on energy performance in buildings and provides typical values for lighting load estimations (W/m^2).

For non-residential buildings:

- Internal load profiles: EPCs may provide thermal consumption data but often omit detailed internal load profiles for lighting and equipment. In such cases, ISO 18523-1[166] is utilized. This standard is specifically designed for non-residential buildings and defines schedules and internal loads, including lighting and appliance use, for various building types.

By employing these standards and databases, the following data can be obtained:

- From EN 16798-1:2019:
    - Occupancy density (m^2/person) and schedules;
    - Internal heat gains from occupants, equipment and lighting;
    - Parameters for indoor environmental quality, including temperature and ventilation rates.
- From EN 15193-2:
    - Typical lighting power densities (W/m^2) for residential buildings.
- From ISO 18523-1:
    - Detailed occupancy schedules for various types of non-residential spaces;

  - Internal loads from equipment and lighting specific to non-residential buildings;
  - Standardized profiles for heating, cooling, and ventilation needs.
- From the TABULA Database:
  - U-values and thermal properties of building envelope components based on building type and age;
  - Standardized building typologies for residential buildings in different countries;
  - Data on typical construction materials and methods used during specific periods.

This approach ensures that missing or incomplete data in EPCs are supplemented with reliable and standardized information, leading to a consistent and accurate dataset for energy analysis. By selecting appropriate standards based on the building type, the analysis can more precisely model energy consumption and efficiency, ultimately facilitating a more accurate evaluation of the overall energy demands within the district.

3.4.3 Creation of reference buildings

For creating reference buildings, both GIS and EPC data are utilized. GIS helps in understanding the geometric form of the buildings, while EPCs provide information on surface areas and other physical and thermal properties. For each segmented typology, reference buildings are created with averaged physical and thermal characteristics.

3.4.4 Development of archetype descriptive table

Following the creation of reference buildings, descriptive table for each archetype is developed. This table summarize the typology, geometric and thermal characteristics, providing a comprehensive overview of the archetype.

The following table summarizes the parameters considered in the case study analysis process:

Table 16 Summary of parameters considered in the case study analysis process

Characteristics	Unit	Case study
Country	-	
City	-	
Construction year	-	
Typology	-	
Number of heated floors	-	
S/V ratio	[m^{-1}]	
Area of S façade	[m^2]	
Area of E façade	[m^2]	
Area of N façade	[m^2]	
Area of W façade	[m^2]	
Area of Roof	[m^2]	
Area of Basement	[m^2]	
Net floor area of heated zones	[m^2]	
Height	[m]	
Window area on S façade	[%]	
Window area on E façade	[%]	
Window area on N façade	[%]	
Window area on W façade	[%]	
People design level	[m^2/person]	
Lighting design level	[W/ m^2]	
Appliances design level	[W/ m^2]	
Construction materials		
Ext walls	-	
Ext walls 2		
Floor	-	
Roof	-	
Ventilation rate (residential)	[l/s m^2]	
Ventilation rate (non residential)	[m^3/h-m^2]	
Infiltration rate	[h^{-1}]	
U value of wall	[W/m^2-K]	
U value of wall 2	[W/m^2-K]	
U value of roof	[W/m^2-K]	
U value of basement	[W/m^2-K]	
U value of glass	[W/m^2-K]	
g value of glass		

The initial information serves to provide a general overview of the archetype, which is useful for its identification and segmentation. This includes details such as the country, city, construction year and typology.

All geometric parameters are aimed at ensuring the reproducibility and graphical representation of the reference building. These include the number of heated floors, surface-to-volume (S/V) ratio, areas of the south (S), east (E), north (N), and west (W) façades, as well as the areas of the roof and basement. The net floor area of heated zones and the height of the building contribute to the understanding of its vertical dimension and potential stack effect on air movement. The percentage of window area on each façade is included to assess the building's daylighting potential and thermal performance.

The design levels for people, lighting, and appliances indicate the expected internal heat gains from occupants, lighting systems, and equipment. This information is crucial for accurately modeling the building's energy performance.

The construction materials for the exterior walls, floor and roof are identified to understand their thermal properties and impact on energy performance. The infiltration rate indicates the rate at which outdoor air infiltrates the building, affecting heating and cooling loads.

The U-values (thermal transmittance) of the wall, roof, basement and glass measure the thermal performance of the building envelope components. The g-value of the glass indicates its solar heat gain coefficient, which affects the building's cooling load and daylighting.

3.4.5 Modeling, calibration, and validation

The buildings are modelled in SketchUp that represents the physical structure of each building. These models are then imported into OpenStudio, an open-source software platform designed for detailed building energy analysis. Within OpenStudio, comprehensive energy models are developed to simulate the thermal performance of the buildings.

The calibration process is a critical step to ensure that these models reflect real-world conditions as closely as possible. Calibration is performed using data from the EPC and focuses on several key energy demands: thermal energy demand (for heating and cooling), electricity demand and in the case of residential buildings, the demand for domestic hot water (DHW).

The energy models are then calibrated by comparing the simulated energy consumption against the actual data provided by the EPCs, with the goal of achieving a maximum discrepancy of no more than 10%.

For the simulation itself, an analysis using ideal loads was chosen. This approach simplifies the simulation by assuming that the heating and cooling systems can perfectly meet the building’s energy demands without the constraints of specific HVAC equipment. This ideal load analysis allows for a better comparison between different retrofit scenarios and energy-saving measures, focusing on the building's demand rather than the performance of specific systems.

Once the models are calibrated, there is a validation process to confirm their robustness. This involves testing the models against additional data sets or simulating energy performance under varying conditions to ensure consistent accuracy.

3.5 Tool development

The TREE PED tool is a comprehensive solution designed to assist municipalities, urban planners and sustainable energy professionals (at an early design stage) in transforming urban districts into PEDs or planning new ones. This tool embodies an innovative approach to urban energy planning, emphasizing environmental sustainability and efficiency. A brief summary of the core ideas within the tool is following.

Key Functionalities:

1. Energy demand assessment: evaluates energy requirements for existing and retrofitted districts;
2. Final energy consumption analysis: analyses various energy consumption scenarios;
3. District energy balancing: assesses whether a district can meet the criteria of a PED, focusing on balancing local energy production and consumption;
4. Renovation strategy planning: offers strategic insights for improving energy efficiency in urban districts, crucial for sustainable development;
5. Life cycle environmental impact: considers the environmental impact throughout the life cycle of district development, from material production to end of life.

Objective:

The primary objective of the TREE PED tool is to facilitate the transition of urban districts into PEDs. By integrating comprehensive energy analysis and environmental assessment, the tool provides actionable insights for sustainable urban development.

Target Stakeholders:

1. Municipalities seeking to implement sustainable energy policies;
2. Urban planners involved in district-level energy planning;
3. Sustainable energy professionals focusing on urban energy efficiency and environmental impact.

Practical Application:

The TREE PED tool can be applied in various urban contexts, from small communities to large metropolitan areas. Its versatility allows for a tailored approach to each unique district, making it an asset in urban sustainability initiatives.

The tool utilizes building archetypes with pre-calculated energy demand values for both existing and retrofitted districts, based on the analysis of the case studies. These values are derived from a comprehensive database that includes a wide range of building types and retrofit measures specific to the districts of Bucharest, Copenhagen, Parma and Pamplona. The inclusion of archetypes from these diverse locations ensures accurate modeling of energy performance, allowing for a detailed analysis and comparison of various retrofit scenarios within the tool, as described in the case study analysis.

In addition to evaluating existing districts, TREE PED also addresses new construction predicting energy demands using its database of building archetypes.

Furthermore, TREE PED expands its analysis to include detailed assessments of environmental impacts for each scenario, as will be detailed further in the documentation.

Upon receiving user-provided "Building Data" and specific "User Decisions" related to potential retrofit scenarios, the tool references these precalculated values.

It then generates energy demand results for:

1. The current state of the district (or the planned results for the new construction district);

2. The potential state of the district renovated.

The tool then computes the "Final Energy Consumption" for both scenarios, offering a comparative view of energy utilization before and after the proposed retrofit.

Subsequently, the tool evaluates the environmental implications:

1. Environmental impact (Use stage): this is based on the energy consumption values for both the existing and retrofitted scenarios;
2. Environmental impact (Production stage for the renovated district): this component assesses the environmental impact associated with the materials and processes chosen for the retrofit;
3. End-of-Life Impacts: Additionally, it evaluates the environmental impact associated with the disposal or recycling of building materials at the end of their life;
4. Environmental indicators: Energy Payback Time (EPT), Global Warming Potential (GWP-PT) Payback Time and Energy Return Ratio (ERR).

The tool provides a comparative analysis between the existing and retrofitted district, allowing users to estimate the environmental and energy efficiency benefits of potential retrofit measures.

Building simulation is performed in Energy Plus environment in non-steady state, thus the tool manages hourly results of the following variables: thermal energy consumption required for heating and cooling and the use of electrical energy for lighting and electrical appliances.

The proposed tool serves as a comprehensive platform for assessing, planning and optimizing PEDs. It employs a multi-faceted approach that integrates customizable building archetypes, renovation planning at the district level and embodied impact calculations across various life cycle stages.

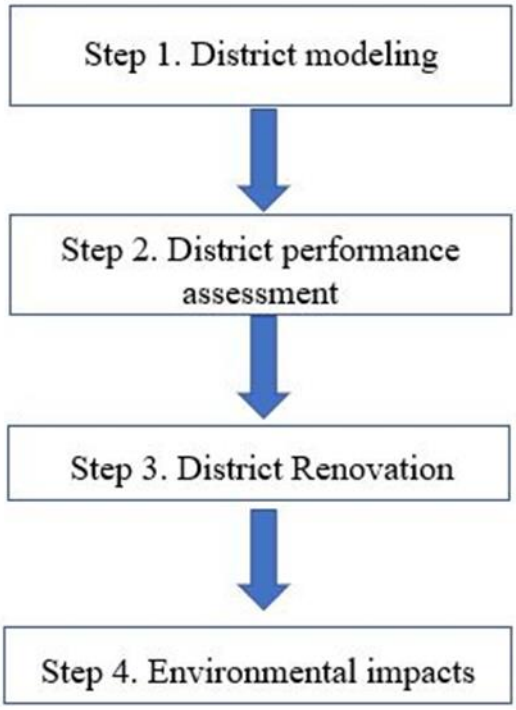

Figure 23 Concept stages of the tool operation

3.5.1 District modeling

The district modeling process unfolds in three main phases, initially focusing on the building modeling. The building modeling is carried out through the application of the previously developed archetypes, which serve as the foundational reference for accurately representing the structures within the district. These archetypes facilitate the integration of existing systems and ensure consistency in the building descriptions throughout the modeling process.

The proposed model follows an explicit methodology where outcomes are directly based on user-defined inputs and assumptions. This approach ensures transparency, allowing users to easily understand and replicate the calculations.

Designed for flexibility, the model lets users manually adjust input parameters after the initial simulation. For instance, after running the first scenario, users can change variables like the type and capacity of renewable energy sources or the level of building insulation. This enables users to iteratively explore different configurations and evaluate their effectiveness in achieving the PED target provides insights into the environmental implications of their choices, facilitating more informed and sustainable decision-making.

Although the model does not feature automated optimization, its manual iteration process offers considerable adaptability. This allows decision-makers to quickly and efficiently refine scenarios based on key performance indicators and environmental impacts.

3.5.1.1 Building modelling

Archetypes serve as representative models for groups of buildings that share similar characteristics, significantly simplifying the modeling and evaluation of energy consumption at the district level. This approach is particularly advantageous when dealing with many buildings, as it streamlines the analysis by reducing the complexity associated with individually assessing each building's energy performance.

The analysis of archetypes facilitates the output of critical data such as the energy demand for heating, cooling and domestic hot water, which are essential for calculating the energy consumption in districts and their corresponding environmental impacts. Additionally, the characteristic features of the reference building allow for an appropriate evaluation of the opaque and glazed parts of each building, which are necessary for the subsequent environmental assessment.

The tool integrates archetypes as fundamental components, which are accessible through the building description function. These archetypes are distinctly delineated via a segmentation process. The segmentation of buildings is user-driven, relying on three critical parameters: the construction period, the building type, and the geographical location. Notably, segmentation is paired with characterization; once archetypes are selected in this step, all their characteristics are automatically predefined. This ensures that, upon selection, each archetype comes with a comprehensive set of predefined attributes.

Following the segmentation and characterization of building archetypes, the tool uses statistical methods to embed standardized hourly load profiles within each archetype. These profiles are designed to reflect the typical energy usage patterns for each archetype.

However, these embedded profiles are activated and utilized only if the user provides annual consumption data. Upon selecting an archetype, the tool automatically applies these statistically derived load profiles, effectively translating the annual data into an approximate hourly energy usage.

3.5.1.2 Energy generation

Solar thermal systems

In the systems description, it is fundamental to underline that the selection of a solar thermal system has a direct impact on the thermal energy demand necessary for heating and domestic hot water. The choice of this system significantly influences the amount of energy consumed.

In the analysis of the thermal energy generation from solar thermal systems, the methodology involves integrating distinct parameters, some of which are calculated using the ASHRAE Fundamentals Handbook [167] and irradiation data sourced from PVWatts[168] .

The parameters for the solar thermal system are divided in:

1. User-Input Parameters:

- Latitude and Longitude: To determine solar irradiance levels specific to the location.
- Solar thermal collector typology: Options could include flat plate, evacuated tube and compound parabolic;
- Collector's area (in square meters): The total area covered by solar thermal collectors;
- Efficiency of the solar systems.

2. Background data:

- Tilt angle: Ideally set to optimize solar absorption based on the location's latitude.

3. Data from PVWatts:

- Direct beam irradiance;
- Diffuse irradiance.

Parameters, calculated using methodologies from the ASHRAE:

- Beam component;
- Diffuse component;
- Ground-Reflected component.

This combination of all these parameters is useful for the estimation of thermal energy of solar panel.

The equation 1 evaluates the direct radiation on a panel $I_{t,direct}$ from direct beam irradiance I_{beam} and the incident angle θ which is the angle between the incoming sunlight and the normal (perpendicular) to the panel's surface

$$I_{t,direct} = I_{beam} \times \cos\theta$$

Eq 1

Where:

I_{beam} is the direct beam irradiance obtained from PVWatts [W/m^2];

$I_{t,direct}$ is the direct radiation on a panel [W/m^2];

Θ is the incident angle [°].

Equation 2 evaluates the total diffuse solar irradiance $It_{,d}$ from I_d the diffuse horizontal irradiance and a parameter Y which represents the ratio of clear-sky diffuse irradiance on a vertical surface to that on a horizontal surface.

It is important to note that this equation is valid for tilt angles less than 90 degrees, implying that is assumed that the tilt angle will never be equal to 90 degrees:

$$I_{t,d} = I_d \times (Y \times \sin\Sigma + \cos\Sigma)$$

Eq 2

Where:

$I_{t,d}$ is the total diffuse solar irradiance by a tilted surface[W/m^2];

I_d is the diffuse horizontal irradiance from PVWatts [W/m^2];

Y is the diffuse irradiance coefficient;

Σ represents the tilt angle of the surface [°].

Y depends on the incidence angle θ, as seen in equation 3:

$$Y = \max(0.45, 0{,}55 + 0.437 \times \cos\theta + 0.313 \times \cos^2\theta)$$

Eq 3

The Ground-Reflected Component of irradiance for surfaces of all orientations can be calculated using the equation 4:

$$I_{t,r} = \left(I_{t,direct} \times \sin\beta + I_{t,d}\right) \times \rho_g \frac{1 - \cos\Sigma}{2}$$

Eq 4

Where:

$I_{t,r}$ is the ground-reflected irradiance on the tilted surface [W/m^2];

$I_{t,direct}$ is the direct radiation on a panel [W/m^2];

β is the solar altitude [°];

$I_{t,d}$ is the diffuse horizontal irradiance [W/m^2];

ρg is the ground reflectance assumed to be 0.2 for a typical mixture of ground surfaces;

Σ represents the tilt angle of the surface [°].

With the three components—direct, diffuse, and reflected irradiance is possible to calculate the global irradiance on a tilted surface.

The global irradiance $I_{t,g}$ is the sum of the direct beam irradiance on the tilted surface. $I_{t,direct}$, the diffuse irradiance on the tilted surface $I_{t,d}$ and the ground-reflected irradiance on the tilted surface $I_{t,r}$.

The equation to calculate the global irradiance on a tilted surface is given by:

$$I_{t,g} = I_{t,direct} + I_{t,d} + I_{t,r}$$

Eq 5

From the global irradiance and the area of each kind of solar panel and the efficiency of the panel provided by users is possible to evaluate the thermal energy production from solar thermal panels.

The equation 6 calculate the output energy from solar panel:

$$Q_{out} = I_{t,g} \times \sum_{i=1}^{3} A_i \times \eta_i$$

Eq 6

Where:

Q_{out} is the thermal energy output from the solar panel [W];

$I_{t,g}$ is the global irradiance [W/m^2];

A_i represents the surface area of each panel (flat plate, evacuated tube and compound parabolic) [m^2];

η_i represents the efficiency of each panel (flat plate, evacuated tube and compound parabolic).

The thermal energy output calculated is subtracted from the total thermal energy demand for heating and domestic hot water of each archetype.

Photovoltaic systems

The incorporation of photovoltaic systems and energy storage units holds a key role in regulating the electrical energy dynamics within the district. This includes the total energy generated, as well as the amounts imported to or exported from the district.

The tool integrates with PVWATTS V8 [168] to calculate the amount of electricity generated by the photovoltaic system converting from direct current (DC) to alternating current (AC) via an inverter (see chapter 3.6.1). It utilizes detailed irradiance data, including direct and diffuse components, which are essential for evaluating the energy production potential of solar panels.

Like the description of the solar thermal system for the description of the photovoltaic system there are: user input parameter, background data and data from PVWATT (chapter 3.6.1.1).

The system capacity is automatically evaluated based on the panel's efficiency parameter (a background data) and the square meters of the photovoltaic system provided by the user. Moreover, this parameter is utilized by PVWatts to calculate the energy generated by the photovoltaic system (chapter 3.6.1.1).

The battery capacity is a parameter that users can freely choose, while the interaction between the battery and the photovoltaic system, including the associated parameters of imported or exported energy, is automatically calculated by the tool (chapter 3.5.2.1).

3.5.1.3 Energy use within buildings

Energy systems can also be clarified for each building within the district based on their ability to cover heating, cooling, or domestic hot water needs:

- Heating

For heating, options include heat pumps (such as air-to-air, air-to-water, ground-to-water, and water-to-water), boilers that use energy carriers (like gas, biomass, and diesel), or district heating systems, which typically utilize centralized boilers using gas or biomass, or heat pump systems.

- Cooling

For cooling, options include heat pumps and district cooling systems.

- Domestic hot water

For domestic hot water in residential buildings, options include electric water heaters, heat pumps and boilers with user-defined efficiencies.

In the next step, users can view energy results of the existing district that are influenced by their selections and the background operations of the tool. The same logic is applied to the renovated district. The difference is that, also there is also a comparison of energy performance between the existing and renovated district.

3.5.2 District assessment

The choices made in the previous step have enabled the estimation of several critical aspects of the district's energy performance, including but not limited to:

Energy Demand (ED): Selecting a specific architectural archetype determined the energy demand of the district, encompassing requirements for heating, cooling, and domestic hot water.

Thermal production of solar thermal systems (Q_{out}): Integrating solar thermal systems within the district made it possible to compare the district's heating demand with and without these systems, highlighting their potential to reduce thermal energy demand.

Final energy consumption (FEC): The choice of efficiency for each system affected the final energy consumption, which is the actual energy used to meet the district's energy demand.

Electricity generation (G_t): The selection of the area and type of solar panel enabled the calculation of the energy produced by the district.

These parameters are crucial for the primary energy balances of the system. This analysis determined whether the district, in its baseline configuration, has achieved the status of a PED or how far it is from reaching this goal.

The final energy consumption (FEC) depends on several precalculated factors: the energy demand for heating (ED_H), cooling (ED_C), and domestic hot water (ED_{DHW}) alongside the production of thermal energy by solar thermal systems and the efficiency of these systems as specified by the user. Furthermore, given that multiple buildings may adhere to the same architectural archetype, it is important for users to delineate the proportion of buildings within each archetype that are serviced by each energy system.

The thermal energy generated by solar panels directly offsets the demand for heating (ED_H) and domestic hot water (ED_{DHW}) Conversely, the total area undergoing conditioning impacts the scaling of energy demands across all categories—heating, cooling, and domestic hot water—ensuring a comprehensive and accurate calculation of final energy consumption.

It is important to note that the logic governing solar thermal energy prioritizes the demand for domestic hot water (DHW) before covering the energy demand for heating. This prioritization is justified by the consistent year-round need for domestic hot water, as opposed to the seasonal demand for heating. Consequently, when both DHW and heating demands are present simultaneously, the solar thermal system first allocates energy to meet the DHW requirements, with any remaining energy then being directed towards fulfilling the heating demand.

Henceforth, when referring to "energy demand for heating and for domestic hot water," it refers to the energy demand reduced by the contribution of solar thermal energy.

Additionally, considering that not all systems are present simultaneously, the energy demand is scaled according to the proportion of buildings within each archetype that are serviced by each energy system. The total area undergoing conditioning impacts the scaling of energy demands across all categories—heating, cooling, and domestic hot water—ensuring a comprehensive and accurate calculation of final energy consumption.

The final energy consumption (FEC) is divided into electrical and thermal components:

Electric Component:

- FEC_{H-El}: Final energy consumption for heating;
- FEC_{C-El}: Final energy consumption for cooling;
- FEC_{DHW-El}: Final energy consumption for domestic hot water.

Thermal Component:

- FEC_{H-Th}: Final energy consumption for heating;
- FEC_{DHW-Th}: Final energy consumption for domestic hot water.

The energy demand (ED) for each archetype is covered by different systems:

Heating demand covered by (ED_H):

- Heat pumps (ED_{H-HP});
- District heating systems (ED_{H-DH});
- Boilers (ED_{H-B}).

Cooling covered by (ED_C):

- Heat pumps (ED_{C-HP});
- District cooling systems (ED_{C-DC}).

Domestic Hot Water covered by (ED_{DHW}):

- Air-to-water heat pumps (ED_{DHW-HP});
- Electric water heaters (ED_{DHW-WH});
- Boilers (ED_{DHW-B}).

Equation 7 estimates the final energy consumption for cooling (FEC_{C-El}) for a single archetype, considering heat pumps:

$$FEC_{C-Elj} = ED_{C-HP}/SEER + (ED_{C-DC}/\varepsilon_{C-DC})$$

Eq 7

Where:

- FEC_{C-Elj}: is the electrical FEC used to cover the ED_C for a single j^{th} archetype[kWh];
- ED_{C-HP}: is the energy demand for cooling covered by heat pumps [kWh];

- $SEER_i$: is Seasonal Energy Efficiency Ratio of the ith heat pump;
- ED_{C-DC}: is the energy demand for cooling covered by the district cooling [kWh];
- ε_{C-DC}: is the district cooling system efficiency for cooling considering the central heat pump and the distribution.

Equation 8 evaluates the electric final energy consumption for domestic hot water $FEC_{DHW-ELj}$ for a single residential archetype considering air-to-water heat pumps and electric water heaters.

$$FEC_{DHW-Elj} = \frac{ED_{DHW-HP}}{SCOP_{DHW}} + ED_{DHW-WH}$$

Eq 8

Where:

- $FEC_{DHW\ Elj}$: is the electrical FEC used to cover the ED_{DHW} for a single jth archetype [kWh];
- ED_{DHW-HP}: is the energy demand for domestic hot water covered by the air to water heat pump[kWh];
- $SCOP_{DHW}$: is Seasonal Coefficient of Performance;
- ED_{DHW-WH}: is the energy demand for domestic hot water covered by the electric water heaters [kWh].

Equation 9 assesses the thermal final energy consumption for domestic hot water FEC_{DHW-Th} for a single archetype considering boilers.

$$FEC_{DHW-Th} = \frac{ED_{DHW-B}}{\eta_B}$$

Eq 9

Where:

- FEC_{DHW-Th}: is the thermal FEC used to cover the ED_{DHW} for a single jth archetype [kWh];
- ED_{DHW-B}: is the energy demand for domestic hot water covered by boilers[kWh];

- η_B: average efficiency of the boiler.

The FEC_H, such as FED_{DHW}, includes both thermal and electrical energy sources. This dual-source nature arises from the use of both heat pumps (FEC_{H-El}) Eq 10 and boilers and district cooling (FEC_{H-Th}) Eq 11.

Equation 10 calculates the electric final energy consumption for heating FEC_{H-El} for a single archetype, considering four types of heat pumps:

$$FEC_{H-El} = \frac{ED_{H-HP}}{SCOP} + (\frac{ED_{H-DH}}{\varepsilon_{H-DH}})$$

Eq 10

Where:

- FEC_{H-El}: is the electrical FEC used to cover the ED_H for a single j^{th} archetype [kWh];
- ED_{H-HPi}: is the energy demand for heating covered by heat pumps[kWh];
- $SCOP_i$: is Seasonal Coefficient of Performance of heat pumps;
- ED_{H-DH}: is the energy demand for heating covered by district heating[kWh];
- ε_{H-DH}: is the district heating system efficiency for heating considering the central heat pump and the distribution.

Equation 11 evaluates the thermal final energy consumption for heating FEC_{H-Th} for a single archetype.

$$FEC_{H-Th} = \frac{ED_{H-B}}{\eta_b} + (\frac{ED_{H-DH}}{\eta_{H-DH}})$$

Eq 11

Where:

- $FEC_{H\ Th}$: is the thermal FEC used to cover the ED_H for a single j^{th} archetype [kWh];
- ED_{H-B}: is the energy demand for heating covered by boilers[kWh];
- η_B: average efficiency of the boiler;

- ED_{H-DH}: is the energy demand for heating covered by district heating[kWh];
- η_{H--DH}: is the district heating system efficiency for heating considering the central boiler and the distribution.

Assessing the thermal final energy consumption for heating (FEC_{H-Th}) and the thermal final energy consumption for domestic hot water FEC_{DHW-Th} area the key component of the calculation of fuel consumption Eq 12.

Equation 12 assesses the consumption of fuel for boilers for every archetype:

$$I_{kj} = \frac{FEC_{H-Th}}{PCS_k} + \frac{FEC_{DHW-Th}}{PCS_k}$$

Eq 12

Where:

- I_{kj}: is the fuel consumption of the k^{th} energy carrier for a single j^{th} archetype;
- FEC_{H-T}: is the thermal FEC used to cover the ED_H covered for a single j^{th} archetype [kWh];
- FEC_{DHW-Th}: is the thermal FEC used to cover the ED_{DHW} for a single j^{th} archetype [kWh];
- PCS_k: the lower heating value of the k^{th} energy carrier.

The electricity consumption is important for the electricity balance of the district and depends on different parameters:

- FEC_{C-El};
- FEC_{DHW-El};
- FEC_{H-El};
- Lighting;
- Appliances.

Eq 13 describes the methodology for calculating electricity consumption within the district.

The following equation estimates the electricity consumption of the district:

$$E_C = \sum_{j=1}^{n} (FEC_{C-Elj} + FEC_{DHW-Elj} + FEC_{H-Elj} + +E_{Coj})$$

Eq 13

Where:

- E_c: electricity consumption for district[kWh];
- FEC_{C-Elj}: is the electrical FEC used to cover the ED_C provide by heat pumps or district cooling for a single j archetype[kWh];
- $FEC_{DHW-Elj}$: is the electric FEC used to cover the ED_{DHW} provide by air to water heat pump and electric water heater for a single j residential archetype [kWh];
- FEC_{H-Elj}: is the electric FEC used to cover the ED_H provide by heat pump and district heating for a single j residential archetype [kWh];
- E_{Coj}: electricity consumption for other electricity loads for a single j residential archetype (lighting, appliances) [kWh].

3.5.2.1 District generation

The estimation of PV energy generation depends on different parameters (see chapter 3.6.1.1).

The electricity generated by photovoltaic can be used for three purposes: to compensate electricity consumption, to recharge batteries and to export energy outside the district. The electricity produced from the battery system is modelled following the procedure described in [169]in which it is assumed that:

- the PV system always feeds first the load and then, if a surplus is available, the battery system and at the end the grid;
- the battery storage system cannot be used to feed the grid and vice versa.

The following equations explain the energy flows between photovoltaic systems, buildings and batteries. Estimates the electricity delivered from the battery system to feed the electricity consumption.

$$El_{BS-EC} = \delta_{SOC} \cdot C$$

Eq 14

Where:

- El_{BS-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].

For a comprehensive understanding of the analysis of the SoC, it becomes essential to explicitly incorporate the temporal variable.

If the energy from the photovoltaic system at time (t-1) is less than the electricity consumption (E_C) and the state of charge of the battery (SoC) at time (t-1) is sufficient to provide an energy flow ($El_{BS \rightarrow EC}$) to meet the building load fully or partially, then the state of charge (SoC) is calculated using the Eq 15:

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

Eq 15

Where:

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

Alternatively, if the energy from the photovoltaic system (G) at time (t-1) is greater than the electricity consumption , indicating that there is excess energy available to charge the battery system (El_{PV-BS}), and if the state of charge (SoC) at time (t-1) is less than the maximum state of charge, then the state of charge (SoC) is calculated using the following equation:

$$SoC(t) = SoC(t-1) + \frac{El_{PV-BS}\,(t-1) \cdot \varepsilon(t)}{C(t)}$$

Eq 16

Where:

- SoC represents the state of charge;
- $El_{PV-BS}(t)$ represents the electricity delivered from the photovoltaic system to feed the battery system[kWh];

- ε(t) represents the battery efficiency corresponding at the time step (t).

Eq 17 assesses the electricity imported or exported in the district.

$$E(t) = G(t) - E_C(t) + E_{BS-EC}(t)$$

Eq 17

Where:

- E(t) represents the electricity exported (E_e) or imported (E_i) at hour t [kWh];
- G(t) represents the electricity generated at hour t [kWh];
- E_c(t) represents the total electricity consumption at hour t [kWh];
- E_{BS-EC}(t) represents the electricity delivered from the battery system to feed the electricity consumption at hour t [kWh].

3.5.2.2 Energy Storage and flexibility

The presence of the storage system reduces the energy exported by the district Eq 17, but on the other hand improve the dynamic management of energy supply and demand.

By accumulating excess energy during low-demand periods and dispensing it during high-demand times, the storage systems contribute to the 'Load Cover Factor ' (Eq 18), which measures the percentage of the electrical demand covered by on-site electricity generation [170] and the 'Grid Interaction Index’ (Eq 19), [171] that represents a standard deviation of the difference between exported and delivered energy within a given time interval within a year, normalized on the highest absolute value.

Eq 18 evaluate the Load cover factor:

$$\gamma load = \frac{\int_{t1}^{t2} min[G(t) - S(t) - \delta(t), E_C(t)]dt}{\int_{t1}^{t2} E_C(t)dt}$$

Eq 18

Where:

- γ_{load} is the load cover factor;
- G(t) is the on-site energy generation [kWh];
- S(t) is the energy storage system's energy balance [kWh];

- $\delta(t)$ represents the energy losses in the system [kWh];
- $E_c(t)$ represents the instantaneous energy consumption [kWh].

Eq 19 evaluate the Grid interaction index:

$$F_{grid} = STD \frac{net\ grid}{\max \mid net\ grid \mid} \times 100$$

Eq 19

Where:

- F_{grid} is the Grid interaction index;
- net grid is defined as the difference between exported and delivered energy [kWh];

A lower Grid Interaction Index indicates a higher degree of self-sufficiency, as the district relies less on external energy sources. This underscores the importance of flexible storage strategies for effective energy balancing and the long-term sustainability of the district. Once the electricity consumption and locally generated energy within the district are thoroughly understood, it becomes possible to evaluate the district's overall energy balance.

The balance between energy consumed and energy generated locally is a critical factor for identifying the renovation strategies needed to drive the district toward its PED goals. This balance serves as an indicator of the district's current state, revealing whether the emphasis should be on increasing local energy production, reduce consumption or a combination of both.

Eq 20 represent the energy balance of the district, if the balance is greater than zero the district achieves the target PED in terms of primary energy. The balance evaluates the generation of renewable energy, the consumption and their respective primary energy factors.

The primary energy factors are evaluated according to ISO52000[172].

$$B = \sum_{k=1}^{n} G_k \times TPEF_K - \sum_{s=1}^{n} C_s \times TPEF_s$$

Eq 20

Where:

- B refers to the balance results of the district;

- G_k refers to the energy generated of a k^{th} renewable energy (such as photovoltaic system, solar);
- $TPEF_K$ refers to the total primary energy factors of k^{th} renewable energy;
- C_s refers to the energy consumed of a s^{th} energy source such as electricity (E_c), methane, biomass, oil, etc.);
- $TPEF_s$ refers to the total primary energy factors of s^{th} energy source.

3.5.3 District-Renovation

The tool enables 3 renovation solution at the district level, allowing for coordinated and large-scale interventions. This feature is critical for districts aiming to improve their overall energy efficiency and sustainability profile.

To assess whether a district can achieve the target of becoming a PED, there are 4 solutions proposed:

1. **Reducing energy demand through building envelope improvements:**

This includes measures like enhanced insulation and window upgrades in compliance with each country's standards, significantly reducing the heating and cooling needs of the buildings.

To enhance the performance of buildings, there are various insulating materials available in the market. However, there is a growing trend towards the use of insulators that have lower environmental impacts and in particular regulatory trends are increasingly leaning towards the promotion of natural insulators in construction practices.

2. **Reducing energy demand with solar thermal heating solutions**:

By utilizing solar energy for heating purposes, these systems substantially lower the thermal energy requirements. The installation capacity for solar thermal systems is deliberately not limited, allowing for maximum utilization of renewable energy sources.

3. **Reducing final energy consumption through system efficiency upgrades:**

This involves implementing advanced, more efficient heating, cooling and electrical systems to minimize the energy input required for the district.

4. **Increasing renewable electric energy share:**

This approach considers the potential to increase the square meters of installed solar panels. Like the solar thermal installations, the expansion of photovoltaic systems is uncapped, promoting the maximal use of renewable energy sources.

These solutions correspond to respective simulations and are critical for districts aiming to improve their ensuring a sustainable, energy-efficient and environmentally friendly urban environment.

Primary energy and electricity balances evaluate in this step follow the same logic as in the previous step.

3.5.4 Energy and environmental impacts

3.5.4.1 Introduction to Life Cycle Assessment (LCA)

The LCA is a fundamental methodology for analysing and quantifying the environmental impacts associated with the entire life cycle of a product, process, or system. This approach allows for the evaluation of environmental impacts from the extraction of raw materials, through production, use, and end-of-life disposal.

The adoption of renewable energy sources and the optimization of energy efficiency are essential components of the global energy transition. However, it is crucial to understand not only the immediate benefits but also the overall environmental impacts associated with these transitions. LCA provides detailed insights into these impacts, offering essential data for informed and sustainable decisions.

The LCA methodology follows several well-defined phases, including:

- Goal and scope definition: identifying the specific objectives of the analysis and the scope of the study.
- Life Cycle Inventory (LCI) analysis: collecting detailed data on material and energy flows within the system under study.
- Life Cycle Impact Assessment (LCIA): quantifying environmental impacts based on the collected data.
- Interpretation of results: analysing and interpreting the results to draw useful conclusions and make recommendations.

In the tool, LCA is applied to evaluate the environmental impacts associated with the energy retrofit of an urban district. This includes analysing the production, the use phases and the end of life considering various energy efficiency improvements and the adoption of renewable energy systems.

Implementing LCA allows for the identification of major sources of environmental impact and the assessment of the effectiveness of mitigation strategies. The production phase and end of life may involve a temporary increase in impacts due to the materials used for retrofitting.

Overall, LCA provides a balanced evaluation of the benefits and challenges associated with transforming the district into a PED.

As a scoping choice of the tool, the production phase and end of life is analysed only for the renovated district and not for the existing one. This allows for a focused assessment of the environmental impacts associated with the renovation activities, providing a clear comparison of the benefits brought by the energy efficiency improvements and the use of new materials and technologies.

The tool evaluates two environmental midpoint impact categories Global Warming Potential and Cumulative Energy demand using the following methodologies:

- The Cumulative Energy Demand (CED) method [173], which is utilized for calculating the consumption of non-renewable primary energy.
- The EF 3.0 methodology [174] is applied for evaluate the Global Warming Potential impact.

3.5.4.2 The production phase

In the production phase, the analysis focuses on the impacts related to the consumption of insulation materials, replacement of windows for the retrofitting of buildings, as well as the impact stemming from the installation of new energy systems. This includes all solutions mentioned in chapter 1143.5.2.

The analysis of the production phase must consider that a single year of the district's life cycle is being evaluated. Therefore, the impact of the production phase should account for the total lifespan of the materials and systems used. The impacts will be divided by the number of years in the life cycle to provide an annualized impact assessment.

The considered lifespans are:

- 30 years for insulation and 20 years for windows— [175];
- 30 years for photovoltaics system [176];
- 20 years for the battery system [177];
- 25 years for the flat plate and 20 for evacuated tube solar thermal panel[178];
- 20 years for the heat pumps and boilers [176].

The tool amortizes the calculated annual environmental impacts over these periods.
To estimate the necessary amount of insulation it is assumed that insulation can be installed on external walls, floors and roofs. The user provides information on the conditioned floor area and the number of floors, allowing the calculation of the area where the insulation will be installed on the floor and roof. For the external walls, the areas depend on the vertical surfaces provided by the user and the window-to-wall ratio (WWR) typical for each building archetype. This allows for distinguishing between opaque and glazed surfaces. This calculation determines the square meters of insulation needed, but the objective is to evaluate the insulation in kg. The next step involves determining the thickness of the insulation.

This parameter depends on the thermal transmittance values, or U-values, of the exterior walls, roof and floor that are characteristic of each building archetype. This method involves using these U-values to ascertain the necessary thickness of insulation material to achieve desired energy efficiency levels.

Once the insulation thickness is established, the mass of the insulation can be calculated, considering the density of the insulation material.

Subsequently, Eq 21 is used to evaluate the total impact of the insulation.

$$EI_i = \mathrm{M_i} \times \mathrm{FC_i}/\mathrm{UL_i}$$

Eq 21

Where:

- EI_i is the environmental impact of the production phase of the insulation;
- M_i are the kg of insulation used to renovate buildings in the district [Kg];
- FC_i is the insulation characterization factor [$KgCO_{2eq}$/Kg] for the GWP and [MJ/Kg] for the cumulative energy demand;
- UL_i is the insulation useful life.

To assess the environmental impact of windows, it's essential to analyse the total glazed area Eq 22, which can be determined from the area of total walls and the Window-to-Wall Ratio (WWR).

$$A_w = A_{TW} \times WWR$$

Eq 22

Where:

A_w is the area of windows [m^2];

A_{TW} is the total vertical wall [m^2];

WWR is the window to wall ratio.

The Frame Ratio further allows for the separation of the window into its constituent parts: the frame Eq 23 and the glazed surface Eq 24.

$$A_f = A_w \times f$$

Eq 23

Where:

A_f is the m^2 of frame area [m^2];

A_w is the total window area [m^2];

f is the frame ratio.

$$A_g = A_w - A_f$$

Eq 24

Where:

A_g are the m^2 of windows glass [m^2];

A_w is the total window area [m^2];

A_f is the frame area [m^2].

The impact of the replacement of windows is described in Eq 25.

Eq 25 assess the environmental impact of windows.

$$EI_W = [(A_f \times FC_f) + (A_g \times FC_g)]/UL_w$$

Eq 25

Where:

- EI_w is the environmental impact of windows;
- A_f are the m^2 of windows frame [m^2];
- A_g are the m^2 of windows glass [m^2];
- FC_f window frame characterization factor [$KgCO_{2eq}/m^2$] for the GWP and [MJ/m^2] for the cumulative energy demand;
- FC_g window glass characterization factor [$KgCO_{2eq}/m^2$] for the GWP and [MJ/m^2] for the cumulative energy demand;
- UL_w is the windows useful life.

The following equations are used to assess the impact of the production phase of the energy systems included in the tool:

1. Photovoltaic system:

$$EI_p = (P_p \times FC_P)/UL_p$$

Eq 26

Where:

- EI_p is the environmental impact of the production phase of the photovoltaic system;
- P_p are the installed capacity of photovoltaic system installed [kW];
- FC_p is the characterization factor of the photovoltaic system [$KgCO_{2eq}/kW$] for the GWP and [MJ/kW] for the cumulative energy demand;
- UL_p is the photovoltaic system useful life.

2. Battery storage systems:

$$EI_{bs} = (C \times FC_{bs})/\mathrm{UL}_{bs}$$

Eq 27

Where:

- EI_{bs} is the environmental impact of the production phase of the battery system;
- C is the capacity of battery system installed [kWh];
- FC_{bs} is the characterization factor of the battery system [$KgCO_{2eq}$/kWh] for the GWP and [MJ/kWh] for the cumulative energy demand;
- UL_{bs} is the battery system useful life.

3. Solar thermal units:

$$EI_{st} = \mathrm{sm_{st}} \times \mathrm{FC_{st}}/\mathrm{UL_{st}}$$

Eq 28

Where:

- EI_{st} is the environmental impact of the production phase of the solar thermal system;
- sm_{st} is the area of installed solar thermal systems in the district [m^2];
- FC_{st} is the insulation characterization factor [$KgCO_{2eq}/m^2$] for the GWP and [MJ/m^2] for the cumulative energy demand;
- UL_{st} is the solar thermal useful life.

4. District Heating:

$$EI_{DH} = ED_{H-DH} \times \mathrm{FC_{DH}}$$

Eq 29

Where:

- EI_{DH} is the environmental impact of the production phase of the district heating;
- $ED_{H\text{-}DH}$: is the energy demand for heating covered by district heating[kWh];
- FC_{DH} is the characterization factor of the district heating [$KgCO_{2eq}$/kWh] for the GWP and [MJ/ kWh] for the cumulative energy demand.

5. Boiler:

$$EI_B = P_B \times \mathrm{FC_B}/\mathrm{UL_B}$$

Eq 30

Where:

- EI_B is the environmental impact of the production phase of the boiler;
- P_B is the boiler capacity [kW];
- FC_B is the characterization factor of the boiler [$KgCO_{2eq}$/kW] for the GWP and [MJ/kW] for the cumulative energy demand;
- UL_B is the boiler useful life.

6. Heat Pumps:

$$EI_{HP} = P_{HP} \times \mathrm{FC_{HP}}/\mathrm{UL_{HP}}$$

Eq 31

Where:

- EI_{HP} is the environmental impact of the production phase of the heat pumps;
- P_{HP} represents the capacity of the heat pumps [kW];
- FC_{HP} is the characterization factor of the heat pumps [$KgCO_{2eq}$/kW] for the GWP and [MJ/kW] for the cumulative energy demand;
- UL_{HP} is the heat pumps useful life.

3.5.4.3 *The use phase*

For the use phase the tool assesses the environmental impacts associated with the import of electricity Eq 32 and consumption of methane, biomass or oil both within the renovation scenario and the baseline scenario with the use of the appropriate characterization factor.

Eq 32 estimate the impact of electricity imported.

$$EI_{ii} = \mathrm{E_i} \cdot \mathrm{FC_e}$$

Eq 32

Where:

- EI_{ii} is the environmental impact of electricity imported;
- E_i refers to the electricity imported from the grid [kWh];
- FC_e energy characterization factor of electricity [$KgCO_{2eq}$/kWh] for the GWP and [MJ/kWh] for the cumulative energy demand.

Eq 33 assesses the impact of methane consumed.

$$EI_{mc} = \mathrm{E_m} \cdot \mathrm{FC_m}$$

Eq 33

Where:

- EI_{mc} is the environmental impact of methane consumed;
- E_m refers to the thermal energy produced by methane combustion[kWh];
- FC_m energy characterization factor of methane [$KgCO_{2eq}$/kWh] for the GWP and [MJ/kWh] for the cumulative energy demand.

Eq 34 assesses the impact of biomass consumed.

$$EI_{bc} = \mathrm{E_b} \cdot \mathrm{FC_b}$$

Eq 34

Where:

- EI_{bc} is the environmental impact of biomass consumed;
- E_b refers to the thermal energy produced by biomass combustion[kWh];
- FC_b energy characterization factor of biomass [$KgCO_{2eq}$/kWh] for the GWP and [MJ/kWh] for the cumulative energy demand.

The following equation evaluates the impact of oil consumed.

$$EI_{oc} = \mathrm{E_o} \cdot \mathrm{FC}_o$$

Eq 35

Where:

- EI_{oc} is the environmental impact of oil consumed;
- E_o refers to thermal energy produced by oil combustion [kwh];
- FC_o energy characterization factor of oil [$KgCO_{2eq}$/kwh] for the GWP and [MJ/kwh] for the cumulative energy demand.

3.5.4.4 End of life stage

The end of life phase evaluates the environmental impacts associated with the disposal of materials and systems at the end of their useful life. It highlights the importance of sustainable disposal practices to mitigate negative environmental impacts, ensuring that the benefits of the retrofit are maintained throughout the entire lifecycle of the district.

The following equation is used to evaluate the impact of the end of life of the insulation:

$$EI_{end,i} = \mathrm{M_i} \times \mathrm{FC_{end,i}}/\mathrm{UL_i}$$

Eq 36

Where:

- $EI_{end,i}$ is the environmental impact of the end of life of the insulation;
- M_i are the mass of insulation used to renovate buildings in the district [Kg];
- $FC_{end,i}$ is the insulation characterization factor of end of life [$KgCO_{2eq}$/Kg] for the GWP and [MJ/Kg] for the cumulative energy demand;
- UL_i is the insulation useful life.

The following equation assesses the environmental impact of the end of life of the windows:

$$EI_{end,W} = \left[\left(A_f \times FC_{end,f}\right) + \left(A_g \times FC_{end,g}\right)\right]/U\mathrm{L_w}$$

Eq 37

Where:

- $EI_{end,w}$ is the environmental impact of the end of life of windows;
- A_f is the area of window frames [m^2];
- A_g is the area of window glass [m^2];
- $FC_{end,f}$ window frame characterization factor of end of life [$KgCO_{2eq}/m^2$] for the GWP and [MJ/m^2] for the cumulative energy demand;
- $FC_{end,g}$ window glass characterization factor of end of life [$KgCO_{2eq}/m^2$] for the GWP and [MJ/m^2] for the cumulative energy demand;
- UL_w is the windows useful life.

The following equations are used to evaluate the impact of the operational and end-of-life phases of the energy systems integrated within the tool:

1. Photovoltaic system:

Eq 38 calculates the environmental impact of the end of life of the photovoltaic system:

$$EI_{end,p} = \left(A_p \times FC_{end,P}\right)/\mathrm{UL_p}$$

Eq 38

Where:

- $EI_{end,p}$ is the environmental impact of the end of life of the photovoltaic system;
- A_p is the area of photovoltaic system installed [m^2];
- $FC_{end,p}$ is the photovoltaic system characterization factor of end of life [$KgCO_{2eq}/m^2$] for the GWP and [MJ/m^2] for the cumulative energy demand;

- UL_p is the photovoltaic system useful life.

2. Battery storage systems:

Eq 39 assesses the environmental impact of the end of life of the battery storage systems:

$$EI_{end,bs} = (W_{bs} \times FC_{end,bs})/\mathrm{UL_{bs}}$$

Eq 39

Where:

- $EI_{end,bs}$ is the environmental impact of the end of life of the battery system;
- W_{bs} is the mass of battery system installed [kg];
- $FC_{end,bs}$ is the battery system characterization factor of end of life [$KgCO_{2eq}$/kg] for the GWP and [MJ/kg] for the cumulative energy demand;
- UL_{bs} is the battery system useful life.

3. Solar thermal units:

The following equation evaluates the environmental impact of the end of life of the solar thermal units:

$$EI_{end,st} = \mathrm{sm_{st}} \times \mathrm{FC_{st}}/\mathrm{UL}_{st}$$

Eq 40

Where:

- $EI_{end,st}$ is the environmental impact of the end of life of the solar thermal system;
- sm_{st} is the area of solar thermal installed in the district [m^2];
- $FC_{end,st}$ is the solar thermal characterization factor of the end of life [$KgCO_{2eq}/m^2$] for the GWP and [MJ/m^2] for the cumulative energy demand;
- UL_{st} is the solar thermal useful life.

4. District heating

For the district heating system, the end-of-life impact is solely determined by the generator, as the retrofit strategy involved only its replacement, with no interventions on the distribution or emission components of the system. Therefore, the end-of-life scenario for the retrofit accounts exclusively for the annual impact of dismantling the existing generator.

5. Boiler:

The following equation calculates the environmental impact of the end of life of boilers:

$$EI_{end,B} = P_B \times \mathrm{FC}_{\mathrm{end,B}}/\mathrm{UL}_B$$

Eq 41

- $EI_{end,B}$ is the environmental impact of the end of life of the boiler;
- P_B represents the capacity of the boiler [Kw];
- $FC_{end,B}$ is the characterization factor of the end of life of boilers [$KgCO_{2eq}$/kW] for the GWP and [MJ/kW] for the cumulative energy demand;
- UL_B is the boiler useful life.

6. Heat Pumps:

The following equation assesses the environmental impact of the end of life of heat pumps:

$$EI_{end,HP} = P_{HP} \times \mathrm{FC}_{\mathrm{end,HP}}/\mathrm{UL}_B$$

Eq 42

- $EI_{end,HP}$ is the environmental impact of the end of life of the heat pumps;
- P_{HP} represents the capacity of the heat pumps [Kw];

- $FC_{end,HP}$ is the characterization factor of the of the end of life of heat pumps [$KgCO_{2eq}$/kW] for the GWP and [MJ/kW] for the cumulative energy demand;
- UL_{HP} is the heat pumps useful life.

3.5.4.5 Environmental and Energy Sustainability Indicators

The tool evaluates also three key metrics are commonly used to evaluate their environmental and energy efficiency: Energy Payback Time (EPT), Global Warming Potential Payback Time (GWP-PT) and Energy Return Ratio (EER).

The indicators are used to analyse environmental convenience, i.e., whether the additional impact caused by the retrofitting of the district is recovered thanks to the lower energy consumed in the usage phase. In particular, the comparison is between original districts (baseline) and renovated districts (renovated).

Energy Payback Time (EPT) is the time duration required for a renovated district to recover the primary energy invested in its manufacturing and end-of-life phases through the energy savings achieved during its operational phase compared to a baseline district.[179].

The EPT is described in the following equation:

$$EPT = \frac{PE_r - PE_b}{PE_{s,o}}$$

Eq 43

Where:

PE_r: is the primary energy consumed by the renovated districts in manufacturing and end of life;

PE_b: is the primary energy consumed by the baseline districts in manufacturing and end of life.

Both renovated and baseline districts incorporate technologies such as thermal insulation, photovoltaic panels, battery systems, solar thermal energy, heat pumps and boilers.

The PE_b is assumed zero, it implies that in the analysis, the baseline districts do not require any additional primary energy for their manufacturing compared to the renovated districts.

This is justified because the baseline districts are already existing and do not need significant energy inputs for their manufacturing, or in cases where the energy consumed in the construction of baseline districts is negligible relative to that of the renovated districts.

$PE_{s,o}$: is the net yearly primary energy saving during the operation phase due to the use of the renovated district instead of the baseline. In detail, it is calculated with the following equation:

$$PE_{s,o} = PE_{b,o} - PE_{r,o}$$

Eq 44

Where:

$PE_{b,o}$:is the yearly primary energy consumed by the baseline district during the operation phase;

$PE_{r,o}$:is the yearly primary energy consumed by the renovated district during the operation phase.

A low EPT value indicates that the refurbished district needs a relatively short period of time to recover the energy invested in its manufacture and final disposal. The district is more energy-efficient because it can 'pay back' the energy consumed during manufacture and end-of-life faster. A low EPT value therefore means that the refurbished district consumes less primary energy or saves a significant amount of energy during the operational phase compared to the base district, leading to a shorter period for "amortising" the energy initially consumed. This is generally desirable as it indicates greater sustainability and energy efficiency of the renovation project.

Global Warming Potential (GWP-PT) Payback Time: is the duration required for the environmental benefits of a renovated district, in terms of reduced Global Warming Potential (GWP), to offset the environmental impacts associated with its manufacturing, end-of-life, and operational phases.

The GWP payback time is described in the next equation:

$$GWP - PT = \frac{GWP_r - GWP_b}{GWP_s}$$

Eq 45

Where:

GWP_r: is the global warming potential caused by the renovated districts in manufacturing and end of life;

GWP_b: is the global warming potential caused by the baseline districts in manufacturing and end of life;

GWP_s: is the net yearly avoided global warming potential due to the use of the renovated district instead of the baseline.

Similarly to EPT, GWP caused by the baseline districts in manufacturing GWP_b is zero.

This assumption indicates that baseline districts, being already established, do not contribute additional GWP for their manufacturing relative to the renovated districts.

GWP_s is calculated with the following equation:

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$$GWP_s = GWP_{b,o} - GWP_{r,o}$$

Eq 46

Where:

$GWP_{b,o}$ is the yearly global warming potential caused by the baseline district during the operation phase;

$GWP_{r,o}$ is the yearly global warming potential caused by the renovated district during the operation phase.

Energy Return Ratio (ERR): is a measure of the effectiveness of the energy-saving measures implemented in a renovated district, specifically during its operational phase, compared to the primary energy consumed in its manufacturing and end-of-life.

The EER is described in the next equation:

$$ERR = \frac{PE_{s,o}}{PE_r}$$

Eq 47

Where:

$PE_{s,o}$: is the net yearly primary energy saving during the operation phase due to the use of the renovated district instead of the baseline;

PE_r: is the primary energy consumed by the renovated districts in manufacturing and end of life.

A higher EER indicates that the renovated district is effectively reducing yearly operational energy consumption compared to the energy required to produce and decommission it, demonstrating energy efficiency and sustainability. Conversely, a lower EER indicates less efficiency in annual energy savings relative to the initial energy investment.

These metrics collectively provide a comprehensive understanding of the environmental and energy impacts of various energy technologies. They are instrumental in lifecycle assessments, aiding in the identification of improvements in technology design and deployment.

3.5.4.6 Assumption of life cycle assessment

The LCA conducted for this study is based on the following key assumptions to estimate embodied emissions reliably and consistently across all analyzed districts:

1. **Estimation of insulation**:

- The total area of insulation required is determined by the user's retrofit choices, directly influencing the surface area to be insulated.
- The insulation thickness and consequently its volume (and weight), is derived from the transmittance value specific to each archetype. These are chosen based on the baseline performance and renovation targets defined in the archetype characterization.

2. **Estimation of windows**:

- The estimation of the windows is based on two key parameters: the Window-to-Wall Ratio (WWR) and the vertical surface area. The WWR is a characteristic value specific to each archetype. This ratio is defined according to the typical architectural features and construction practices of the archetype. The vertical surface area, on the other hand, is provided as input data by the user, reflecting the dimensions and geometry of the buildings in the district. The windowed surface area is calculated by multiplying the WWR by the total vertical surface area. This calculated value serves as the basis for assessing the embodied emissions related to glazing materials throughout their production and end-of-life phases.

3. **Type of insulation materials**:

- The analysis assumes that the same insulation material is used for both roofs and walls in the retrofit scenarios. The materials considered include: Cellulose fiber, Cork slab, Foam glass, Glass wool mat, Polystyrene foam slab, Stone wool, Tube insulation (elastomeric) and Urea formaldehyde foam slab. These materials are selected to represent a range of widely used insulation products, balancing performance and environmental impact.

4. **Standardized datasets for production and end of life phase**:

- Embodied emissions for the production and end of life phase of the materials and systems are calculated using European dataset. This ensures consistency and comparability of results, while also reflecting typical production practices and emission factors for the European context.

3.6 Data Sources

The use of various internal sources within the tool is essential for evaluating the energy generated in the district and for conducting environmental analysis.

3.6.1 PVWatts

In enhancing the TREE PED tool's capabilities for assessing and planning PEDs, are incorporate advanced solar radiation data using specialized APIs.

The tool includes PVWatts Calculator API, provided by the National Renewable Energy Laboratory (NREL) [168].

To provide a clear understanding of how the PVWatts Calculator API, operates, it is helpful to outline the process according to the following steps.

Step 1: Input Collection

The PVWatts Calculator API processes three main categories of data to estimate the energy production of photovoltaic (PV) systems:

1. User-Input Parameters:

- Latitude and Longitude: To determine solar irradiance levels specific to the location;
- Solar panel typology: Standard, Premium or Thin Film;
- Photovoltaic's area (in square meters): The total area covered by solar panels.

Each panel type has distinct characteristics described in PVWatts:

- Standard panels are Crystalline Silicon with an efficiency of 19% and a temperature coefficient of -0.37%/°C;
- Premium panels are also Crystalline Silicon but with a higher efficiency of 21% and a temperature coefficient of -0.35%/°C;
- Thin Film panels have an efficiency of 18% with a temperature coefficient of -0.32%/°C. All types are equipped with glass featuring anti-reflective coating.

2. Background data:

- The array type is assumed to be Fixed - Roof Mounted;
- System losses: 14% (default value);
- Inverter efficiency: 96% (default value);
- Panel efficiency: (depend on the photovoltaic typology);
- Tilt Angle: Ideally set to optimize solar absorption based on the location's latitude;
- System capacity.

3. Pre-Calculated Data:

The power capacity of the PV system is determined through a pre-calculated equation (Referenced as Eq 49), which considers factors like system efficiency, available installation space and is conducted for three distinct types of photovoltaic technologies.

Step 2: Sending the request to the API

These collected informations are then formatted into a request that is compatible with the PVWatts API's requirements. The request is sent over the internet to the PVWatts API server.

Step 3: Data processing by PVWatts

Upon receiving the request, the PVWatts API processes the input data using its built-in models.

Step 4: Receiving the response

The API calculates electrical energy generated from photovoltaics in AC, Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI). The latter two are fundamental for calculating the thermal energy produced by solar thermal systems.

The primary function is to streamline and automate the data collection process, thereby ensuring efficient and precise inputs for the energy models. This integration facilitates accurate calculations of potential energy generation from solar installations, essential for assessing the balance between energy consumption and local energy production within a district. Additionally, it aids in evaluating the solar radiation for thermal solar panels, which is crucial for estimating the reduction in thermal energy demand.

This automation, enabled by the VBA script, enhances the process of data acquisition. It ensures that accurate and location-specific solar radiation data are readily available, facilitating precise assessments of the potential and efficiency of thermal solar panels.

This integrated approach aligns with the objective of transforming urban districts into self-sustaining PEDs by optimizing local renewable energy production, thereby contributing significantly to the broader goals of environmental sustainability and energy efficiency.

3.6.1.1 Calculating of electricity generation with PVWatts

PVWatts uses a series of calculations to estimate the electrical energy produced by a photovoltaic system in AC. The key steps can be represented below:

- **Incident POA irradiance**: This stage quantifies the solar radiation intensity that impinges directly on the module surfaces;
- **Transmitted POA irradiance**: this is focused on the solar radiation intensity that successfully penetrates the module's glass covering;
- **Module Cell Temperature:** the assessment of the operational temperature of the photovoltaic cells, which significantly influences efficiency;
- **DC power**: The amount of electrical power produced by the modules in direct current (DC);
- **AC power:** The amount of electrical power produced by the inverter in alternating current (AC).

Step A: Calculate Plane-of-Array (POA) irradiance

POA irradiance is evaluated in the next equation and is determined based on latitude, longitude, time, panel tilt and azimuth to account for the sun's position and panel orientation.

$$I_{\mathrm{poa}} = I_{\mathrm{b}} + I_{\mathrm{d,sky}} + I_{\mathrm{d,ground}}$$

Eq 48

Where:

I_{poa} is the plane of array irradiance;

I_b represents the beam normal input multiplied by the cosine of the angle of incidence;

$I_{d,sky}$ is the total sky diffuse on the surface;

$I_{d,ground}$ is the ground reflected irradiance.

Step B: Adjust for reflection losses.

System losses due to reflection losses depend on the kind of panel. Each type affects how much sunlight gets through the panel's cover (like a protective glass) and reaches the solar cells inside.

For "Standard" and "Thin film" panels, PVWatts calculates sunlight passage through a simple glass layer. This glass has specific properties (like bending light a certain way), described by an "index of refraction" of 1.526.

His calculation assumes that little light is absorbed by the glass itself, which simplifies the model. For "Premium" panels, PVWatts uses a more complex model that includes both the glass cover, and a special thin layer designed to reduce reflection and let lighter in. This model calculates how light passes through two layers (the anti-reflective coating and the glass) using a scientific principle for light behaviour.

Step C: Calculate of the T_{cell}

This step is important because the panel's temperature affects how well it can turn sunlight into electricity. The model assumes a standard installation height of 5 meters above ground for wind speed adjustments in the weather data, aligning with empirical data collection standards. It also considers a nominal operating cell temperature (INOCT) for the module set of 49°C for the fixed roof mount option.

Step D: Calculate DC Output

The PVWatts module's calculation of DC power output from a solar array is based on the interplay between the array's nameplate DC rating (P_{dc0}), the operating cell temperature (T_{cell}) and the transmitted plane of array irradiance I_{tr}.

This model assumes that the efficiency of the solar array decreases linearly with an increase in temperature, which is quantified using the temperature coefficient y.

The baseline or reference conditions for this calculation are set at a cell temperature (T_{ref}) of 25°C and a reference irradiance of 1000 W/m^2.

The following equation evaluate the system capacity from the users:

$$P_{dcO} = (A_{SP} \times \eta_{SP} \times STC) + (A_{PP} \times \eta_{PP} \times STC) + (A_{TF} \times \eta_{TF} \times STC)$$

Eq 49

Where:

- P_{dcO} Is the is the power of the array (size) expected under standard test conditions (STC) [kW];
- A_{SP} is the area of the standard panel [m^2];
- A_{PP} is the area of the premium panel [m^2];
- A_{TF} is the area of the thin film panel [m^2];
- η_{SP} is the efficiency of the standard panel [%];
- η_{PP} is the efficiency of the premium panel [%];
- η_{TF} is the efficiency of the thin film panel [%];
- STC: standard test conditions of solar irradiance 1 kW/m^2.

The subsequent equation computes the adjusted DC power output is:

$$P_{dc} = \frac{I_{tr}}{1000} P_{dcO}(1 + \gamma(T_{cell} - T_{ref})$$

Eq 50

Where:

- P_{dc} is the DC power output from the solar array [W];
- I_{tr} is the transmitted POA irradiance;
- P_{dc0} is the power of the array (size) expected under standard test conditions (STC) [W];
- γ is the temperature coefficient;
- T_{cell} is the operating cell temperature [°C];
- T_{ref} is the reference cell temperature, set at 25°C, which is the cell temperature under standard test conditions (STC) against which performance is benchmarked.

Step E: Convert DC to AC

Finally, the DC output is converted to AC, considering the losses of the system and the inverter efficiency. The output of this step represents the photovoltaic energy generation, denoted as G(t), which is computed in Eq 17.

3.6.2 Ecoinvent

Starting from the life cycle inventory data of the Ecoinvent database these data are used to evaluate the impact of the production, use phase and end of life of the district.

3.7 Tool functionality and core principles

In the early design stages of PEDs, practitioners often require a simplified yet effective approach to evaluate the performance of a PED.

The user guide presents the development of the tool “TREE PED" (tool resource and environmental evaluation-Positive Energy District), an early design tool to help municipalities, stakeholders and practitioners in performing feasibility studies for achieving carbon neutrality at the district stage in a life cycle perspective.

The tool eliminates the need for intricate calculations and exhaustive data sets, instead offering a user-friendly interface with simplified algorithms that still provide valuable insights. This guide is structured around the tool's four principal functionalities:

1. Input Data of the District;
2. District Balance;
3. District Renovation;
4. Environmental Assessment.

This guide aims to equip users with the necessary knowledge to make informed decisions in the early design phases, thereby contributing to more effective and sustainable PED development. With the exploration of each functionality in subsequent sections, users will learn how to utilize the tool for initial data collection, energy balance evaluation and environmental impact forecasts, all geared towards facilitating the early design of PEDs.

Figure 24 is a snapshot of the tool's main page, which serves as the gateway to its various functionalities.

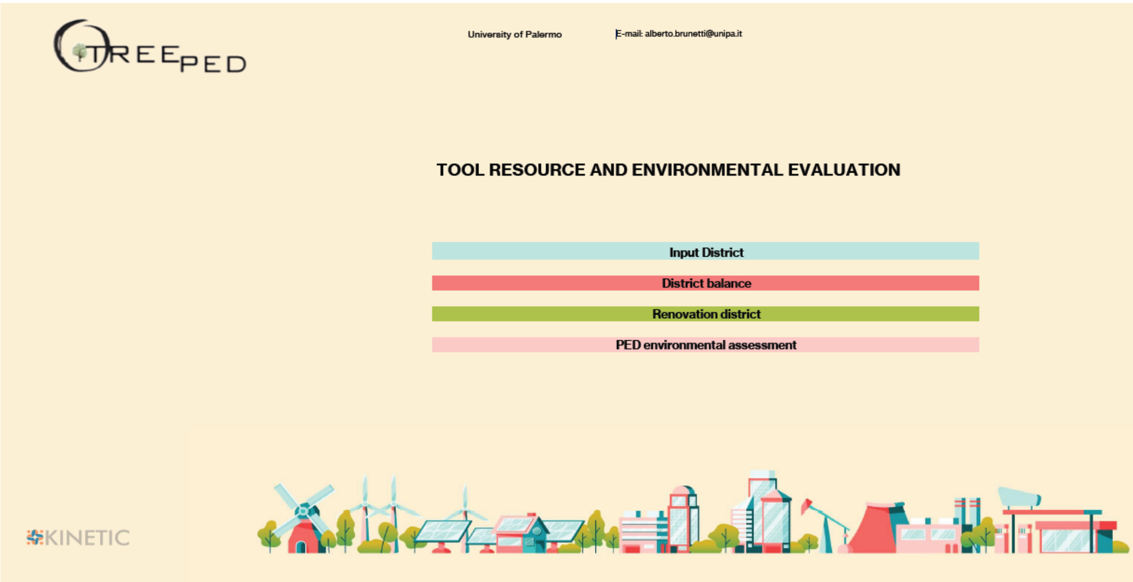


Figure 24 Main page of the tool.

The main page is designed for user-friendliness and guides the user through the four principal functionalities: Input Data of the District, District Balance, District Renovation and Environmental Assessment.

At present, the tool lacks an economic analysis component. However, plans are in place to incorporate this feature in subsequent versions of the tool to provide a more comprehensive assessment.

3.7.1 Input Data

In this section, three categories of inputs are presented:

1. Free Inputs: fields where data can be entered without any pre-set restrictions.
2. Dropdown Menu Inputs: fields with a dropdown menu offering a list of options.
3. Locked Inputs: fields that are pre-filled and unmodifiable.

The first task in this section involves the segmentation of the existing district. This is crucial for the tool to tailor subsequent analyses to the specific characteristics of the district.

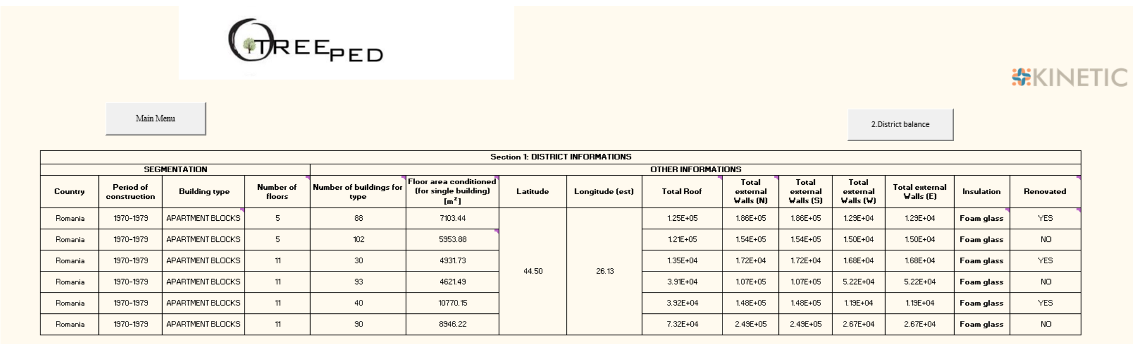
4.1.1 Input data of buildings

The description of the district is conducted based on four key parameters:

1. Country: indicating the geographical location of the district;
2. Period of construction: representing the years in which the district's buildings were erected;
3. Building type: denoting the predominant type of buildings (SFH, MFH…)
4. Number of floors.

By providing this initial description of the district, the tool can proceed with a more nuanced and accurate assessment in the later stages. This involves specifying the number of buildings per type, the conditioned floor for each building type identified within a specific category, the latitude and longitude, the number of floors and the orientation.

To better visualize the layout and the different categories of inputs, the Figure 25 showcases how the input data screen appears to users. This graphical representation aims to offer a practical understanding of the tool's interface, making it easier for users to navigate and input the required information.



Section 1: DISTRICT INFORMATIONS														
SEGMENTATION				OTHER INFORMATIONS										
Country	Period of construction	Building type	Number of floors	Number of buildings for type	Floor area conditioned (for single building) [m²]	Latitude	Longitude (est)	Total Roof	Total external Walls (N)	Total external Walls (S)	Total external Walls (W)	Total external Walls (E)	Insulation	Renovated
Romania	1970-1979	APARTMENT BLOCKS	5	88	7103.44	44.50	26.13	1.25E+05	1.86E+05	1.86E+05	1.29E+04	1.29E+04	**Foam glass**	YES
Romania	1970-1979	APARTMENT BLOCKS	5	102	5953.88			1.21E+05	1.54E+05	1.54E+05	1.50E+04	1.50E+04	**Foam glass**	NO
Romania	1970-1979	APARTMENT BLOCKS	11	30	4931.73			1.35E+04	1.72E+04	1.72E+04	1.68E+04	1.68E+04	**Foam glass**	YES
Romania	1970-1979	APARTMENT BLOCKS	11	93	4621.49			3.91E+04	1.07E+05	1.07E+05	5.22E+04	5.22E+04	**Foam glass**	NO
Romania	1970-1979	APARTMENT BLOCKS	11	40	10770.15			3.92E+04	1.48E+05	1.48E+05	1.19E+04	1.19E+04	**Foam glass**	YES
Romania	1970-1979	APARTMENT BLOCKS	11	90	8946.22			7.32E+04	2.49E+05	2.49E+05	2.67E+04	2.67E+04	**Foam glass**	NO

Figure 25 Input data of the buildings.

The Figure contains a table with segmented data entries for an urban district, detailing the characteristics of buildings within the district, which is essential for energy modelling and analysis.

The inputs of the buildings are divided into two main parts:

SEGMENTATION: This column includes the country, period of construction and it also specifies the building types (e.g., single family house, Apartment Blocks, Office…).

OTHER INFORMATIONS: This part of the table provides additional details such as the number of buildings for each type, the conditioned floor area in m² for single building, the geographical coordinates (Latitude and Longitude), the total roof, total external walls, the kind of insulation and if the building is renovated.

Information on the total roof area is primarily used to estimate the m² of insulation and glazed surface area, considering that the Window-to-Wall Ratio (WWR) is a typical parameter for each archetype. The coordinates are necessary for accurately estimating the performance of renewable systems (solar and photovoltaic). The type of insulation is required because the impact of the insulation varies. Additionally, it is important to know if the building is renovated, as non-renovated buildings will show a thermal demand that does not change.

There are also 2 buttons: "2. District balance" button implies that with this the user can go directly to the second section and the "Main Menu" button implies that users can navigate back to the main options of the tool.

4.1.2 Input data of systems

Within the data input section, users are also required to specify the types of systems installed in the district. These systems are categorized based on the type of building they are associated with, as previously identified.

The systems to be detailed include cooling systems, predominantly heat pumps and district cooling, as well as heating systems, which could either be heat pumps, boilers or district heating.

For each building type, there are multiple heat pump options, delineated by their heat exchange method—such as: air-to-air, air-to-water, ground-to-water and water-to-water, the boilers are categorized by the fuel they utilize: gas condenser, biomass and oil while district heating systems can be either heat pump systems or gas systems.

In both the baseline and renovated scenarios, users have the option to specify the percentage of buildings for each archetype managed by a specific heating or cooling energy system.

For each type of system, users have the flexibility to input the efficiency of each individual boiler and the Seasonal Energy Efficiency Ratio (SEER) and the Seasonal Coefficient of Performance (SCOP) for different types of heat pumps. For district heating, a global efficiency can be considered, which considers distribution losses as well.

The only constraint in this regard pertains to boiler systems, for which the efficiency is capped at 100%.

This system-level information is crucial for a comprehensive understanding of the district's current energy profile and for accurately modelling the impacts of potential renovation strategies.

For the generation in situ of renewable energy the user set the area of photovoltaic installations within the district of the specific solar panel and the battery capacity.

The tilt angle of the photovoltaic panels is automatically set to the optimal value to ensure maximum solar exposure throughout the year, providing a consistent basis for system performance comparison and the efficiency of the panel is predetermined by the type.

This information serves as a foundational layer upon which the tool performs its subsequent analyses and calculations. Therefore, accurate input in this phase is crucial for the reliability and effectiveness of the tool's output.

In the renovation scenario, the same analytical approach used for evaluating existing systems in the baseline condition is applicable. This enables a comprehensive comparison between the current state and potential future state of the district's energy systems. By doing so, users can make informed decisions on the most effective renovation strategies, including system upgrades and replacements.

The photovoltaic system can also be freely expanded in the renovation scenario. This flexibility allows users to assess how additional solar capacity could contribute to the district's transformation into a PED.

There is the possibility for the users to have access to real-time data, the tool offers the capability to input hourly data concerning electricity consumption.

The Figure 26 displays the interface where users can input hourly data.

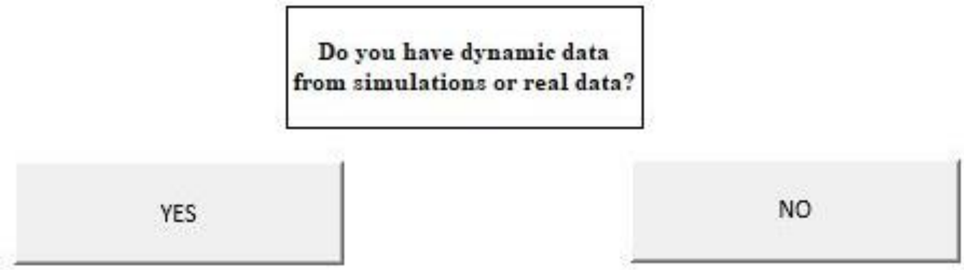


Figure 26 Input data from users.

3.7.2 District energy balance and sample data

In the "District Balance" section, users will find a dashboard of the energetic outcomes based on the input data previously entered. These outcomes both tabular and graphical insights into the existing district's energy profile. The tabular data is presented on both annual and monthly basis, offering metrics such as electricity generation, consumption, delivered energy, exported energy and primary energy balances.

Close to the tables within the tool there is an indicator that signifies the achievement of the PED target.

In the tool, this indicator can change color based on the achievement of the PED target, this operates as a straightforward, intuitive indicator for users. If the marker turns green, it indicates that the district has successfully met the PED target, which signified that the district is producing enough renewable energy to cover its energy demand over the set period. Conversely, if the marker is red, it signifies that the district has not yet achieved the PED target and that further measures may be required to reach the desired level of energy efficiency and sustainability. This color-coded system enables users to quickly assess the status of the district's energy goals immediately.

The first graph on the dashboard (Figure 27) is a representation of the district's annual UED, displayed on an hourly scale. This graph helps to visualizing energy consumption throughout the year, providing insights into the district's energy dynamics hour by hour.

This elevated level of detail is important for understanding how energy needs fluctuate over time, offering a comprehensive view in energy usage. On the graph, the horizontal axis maps out the hours of the year while the vertical axis, measuring energy demand.

Beside the graph is an interactive feature – a button that allows users to focus on days of the year. This interactivity enhances the utility of the graph significantly. By using this feature, users can zoom in on specific time frames to better understand and address peak energy demands, seasonal variations and other critical aspects of energy management.

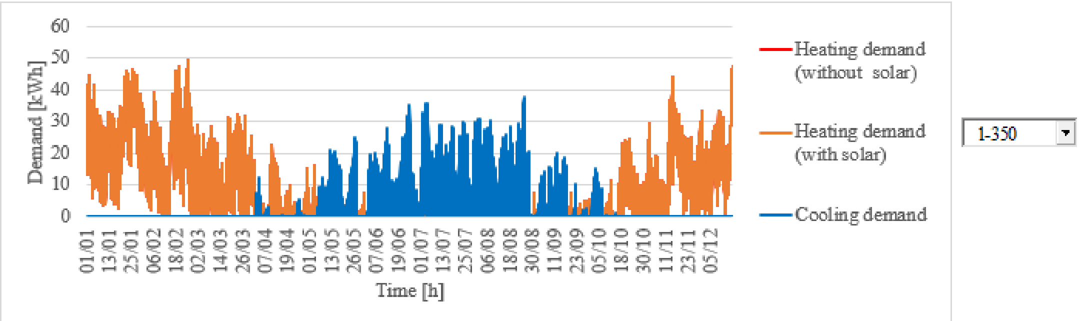


Figure 27 UED of the district.

The tool present other two graphs of energy demand. A graph (Figure 28) that arranges the demand from the smallest to the largest values, expressed as a percentage and a graph (Figure 29) that allows users to view energy consumption patterns on monthly scales.

The Figure 28 shows he demand curve, offers insights into the varying needs across the district, presenting the data from the least to the most demand.

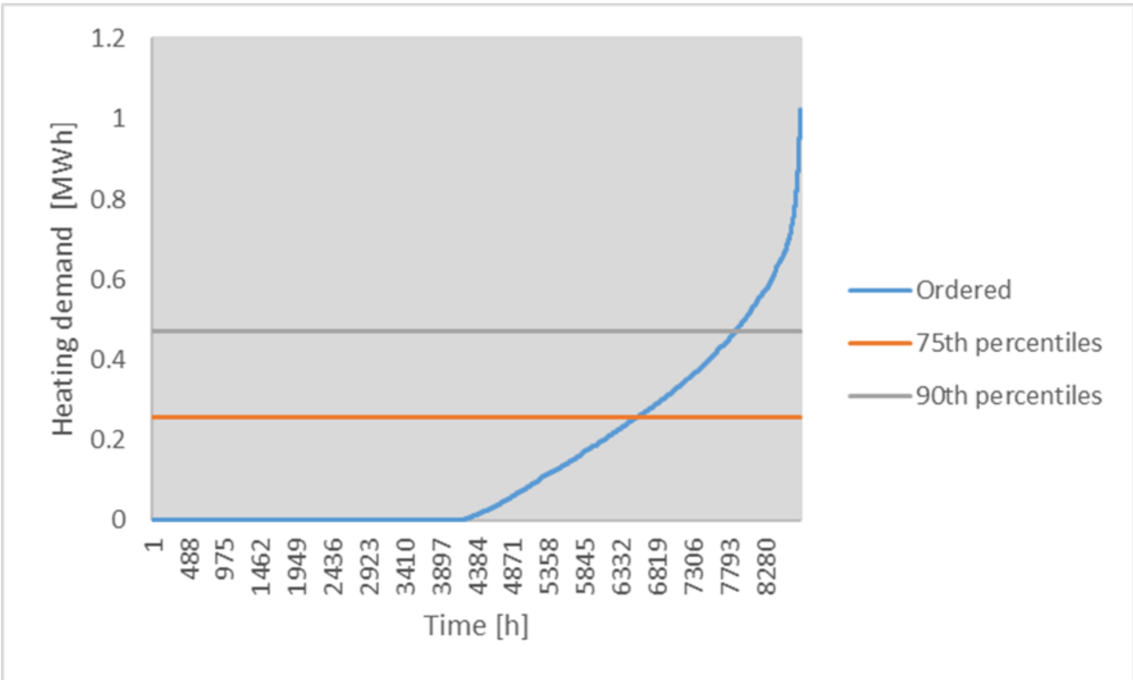


Figure 28 Thermal demand curve.

This graph represents the ordered heating demand for the district, showing the progression of heating requirements throughout the year on an hourly basis. The blue curve indicates the distribution of heating demand, ordered from lowest to highest, which reveals how often different levels of demand are experienced.

The 75th percentile and 90th percentile are marked to highlight significant thresholds of heating demand. The 75th percentile indicates that 75% of the time, the heating demand remains below approximately 0.3 MWh, while the 90th percentile suggests that 90% of the time, the heating demand is below about 0.5 MWh. These thresholds give insights into the typical and higher-end heating demands faced by the district.

The Figure 29 displaying energy usage trends over each month. This broader view is helpful for understanding seasonal variations in energy consumption and aids in strategic planning for energy management.

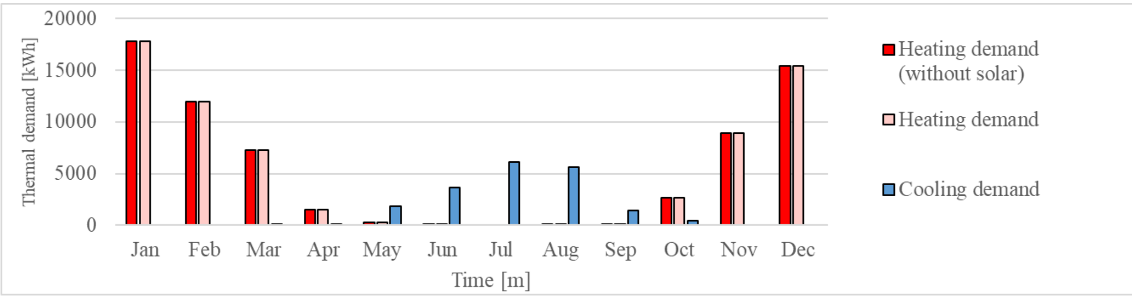


Figure 29 Monthly thermal demand.

The figure presents a monthly breakdown of thermal (heating and cooling) demand over the course of a year. The y-axis shows the demand and the x-axis represents time, organized by months.

The red bars and light red bars respectively represent the heating demand without and with the effect of solar thermal, while the blue bars represent cooling demand. From the graph, it is evident that the thermal demand is higher than the cooling demand peaks.

In addition to these graphs, are integrated two other similar yet distinct graphs that represent various aspects of energy management.

The first graph, analogous to the Figure 27 maintaining the hourly format but evaluate the energy consumption and generation.

The second graph mirrors the style of the heating and cooling demand curve (Figure 28) but focuses on energy use within the district. It permits a comparative analysis of this critical energy parameters that are crucial for comprehensive district energy management.

Building upon the insights provided by our hourly scale graphs, the TREE PED tool now expands its analytical depth with the introduction of a new series of graphs on a monthly scale. While the hourly graphs offer a detailed view of the day-to-day energy dynamics, these new monthly graphs provide a broader perspective.

The Figure 30 detailing how much of the district's electricity consumption is covered by the grid, battery or photovoltaic systems each month.

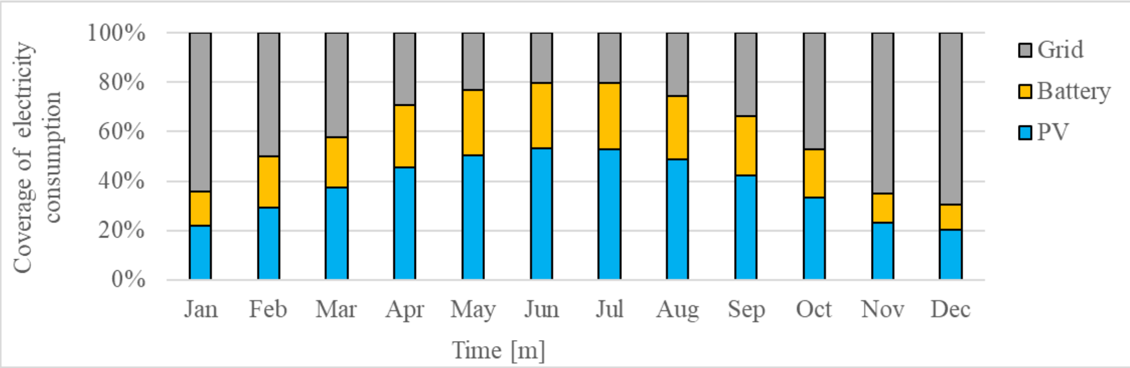


Figure 30 Monthly electricity consumption coverage.

The vertical axis of Figure represents the percentage of electricity consumption coverage, ranging from 0% to 100%.

In this chart, there are two types of bars, differentiated by their patterns, which represent two diverse sources of electricity:

- The grey bars labeled "Grid" indicate the percentage of the district's electricity consumption that is met by the grid.
- The orange bars labeled "battery" indicate the percentage of the district's electricity consumption that is met by the battery.
- The green bars labeled "PV" (photovoltaic) show the percentage of electricity consumption covered by solar energy.

The battery operates based on the principle that electrical energy comes from photovoltaic sources and not from the grid. Therefore, when referring to energy from the battery, it is renewable energy.

This visualization is critical for assessing the contribution of renewable energy sources, particularly photovoltaic solar systems, in meeting the district's electricity needs throughout the year. It provides a clear indication of the reliance on the grid versus renewable sources.

The Figure 31 presents an overview of how electricity is managed in the district across different months of the year, focusing on various aspects of generation, consumption and interaction with the grid.

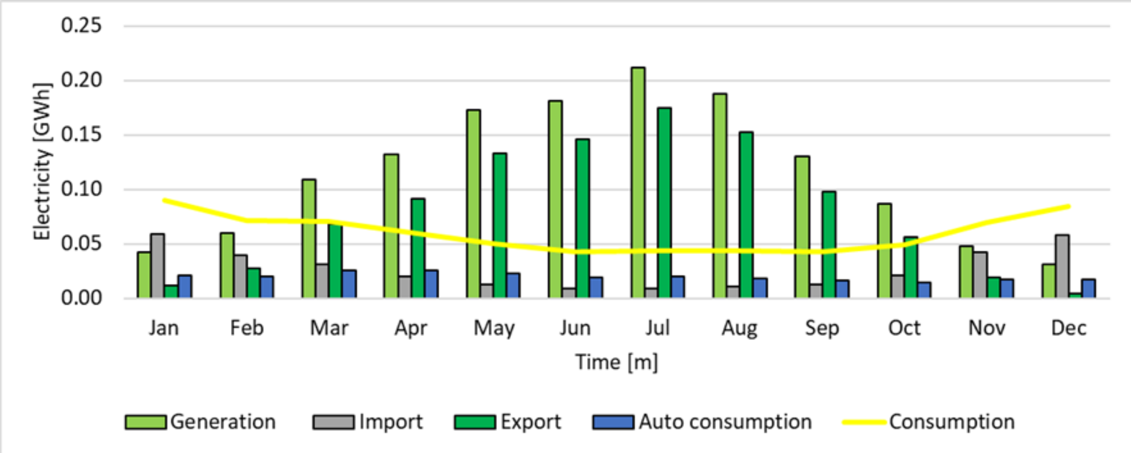


Figure 31 Monthly electricity consumption coverage disaggregated.

The chart displays the interaction between different components of the energy balance in a district, including electricity generation, import, export, auto-consumption and total consumption. This visual representation facilitates the comparison between energy production and demand, as well as the management of excess energy through export or self-consumption. Additionally, the chart highlights the need for energy imports when local generation is insufficient to meet consumption needs. The use of distinct colors allows for a clear differentiation of the various energy flows, aiding in the interpretation of the overall energy dynamics.

These monthly graphs complement the hourly data, offering a complete and integrated view of both the immediate and extended energy scenarios in urban districts. Together, they provide a comprehensive toolkit for stakeholders to analyse, plan and implement sustainable energy solutions effectively.

The district could use various fuel types in addition to electricity, for this reason there is a separate monthly graph that accounts for the consumption of these other fuels.

Different fuels measured in their natural units—such as m^3 for gas, or liters for oil and kg for biomass. To compare the energy content of these diverse fuels in a uniform way, each quantity is converted into a common energy unit by multiplying it by its calorific value.

In the Figure 32 is shown the consumption of the fuels in the district.

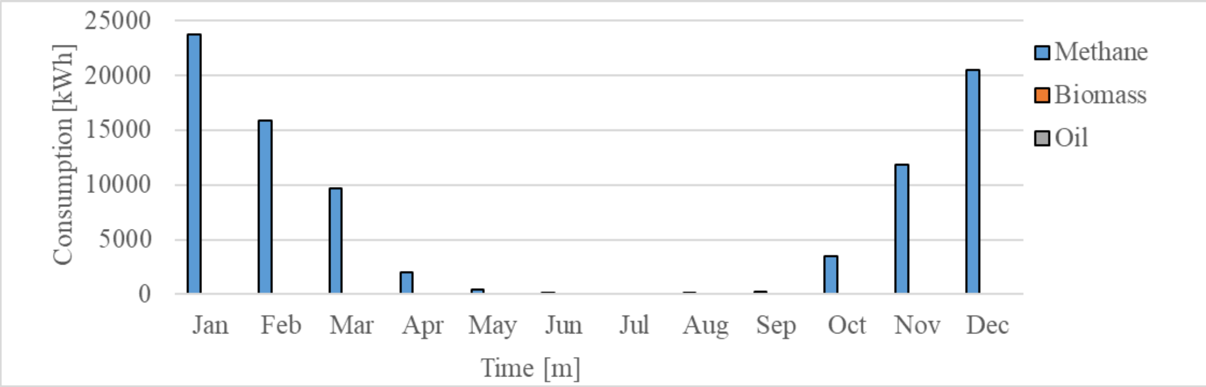


Figure 32 Monthly consumption per energy carrier.

The Figure shows that the consumption of various fuels within a district over a year are primarily used for compensating the heating demand.

The results presented earlier had already incorporated the effect of the battery system. However, in the subsequent graphs, the role of this system is more explicitly detailed. These graphs offer a clearer and more focused visualization of how the battery system contributes to the overall performance and energy management within the PEDs.

The Figure 33 offers a monthly analysis of the load cover factor.

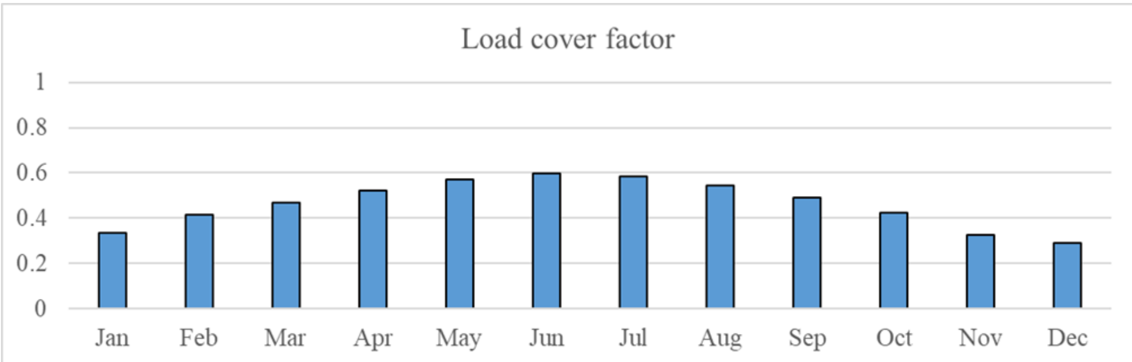


Figure 33 Monthly load cover factor.

This longer-term view is essential for understanding seasonal fluctuations in energy demand and the district's capacity to meet this demand with local generation.

The upcoming figures investigate hypothetical scenarios comparing the current state of the PEDs with and without the integration of a battery storage system. These visualizations are aimed at dissecting the impact of the storage system on key energy metrics.

Specifically, the Figure 34 examines the Grid Interaction Index. This index reflects the variance in energy exchange and how the storage system potentially stabilizes this interaction by mitigating peaks in import and export.

Figure 35 on the other hand compares the electricity import and export volumes under the two scenarios: with the battery storage system and without it. These comparisons will highlight the battery's role in achieving energy self-sufficiency for the district by reducing the need for grid imports and maximizing the use of locally generated renewable energy.

By presenting the data in this comparative format, stakeholders can more clearly appreciate the operational benefits of battery storage systems in managing energy flows within PEDs.

The Figure 34 compares two scenarios: one without a storage battery system ('F_{grid} without battery') and one with ('F_{grid}').

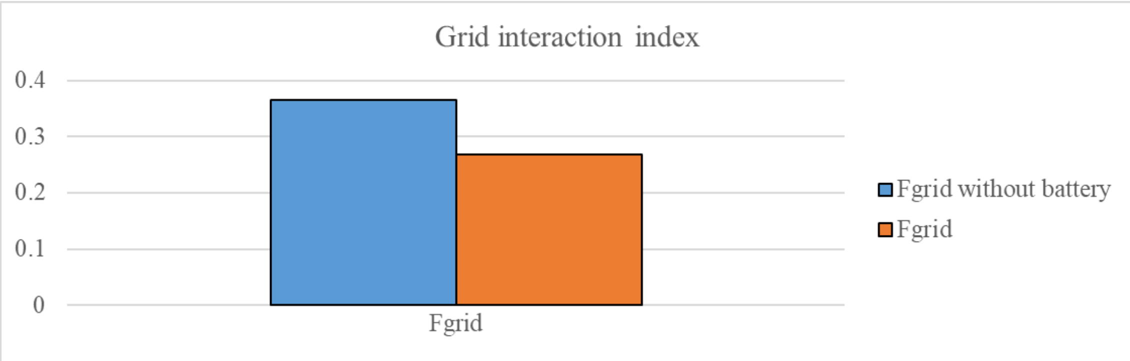


Figure 34 Grid interaction index.

In the Figure the higher value (blue bar) for 'F_{grid} without battery' indicates a larger standard deviation, which means there is more variability in the energy exchange with the grid when there is no battery system in place. This imply that without the battery, there are times when the district needs to import a significant amount of energy from the grid or is exporting a lot, depending on production and demand cycles.

The lower value (orange bar) for 'F_{grid}' indicates a smaller standard deviation when the battery system is utilized, signifying more consistent, and likely smaller, differences between energy export and import. This suggests that the battery system helps stabilize the energy exchange with the grid by storing excess production and supplying energy when production is less than the demand, leading to a more balanced and predictable interaction with the grid.

The Figure 35 compares monthly electricity exports from a PED with and without the inclusion of a battery storage system.

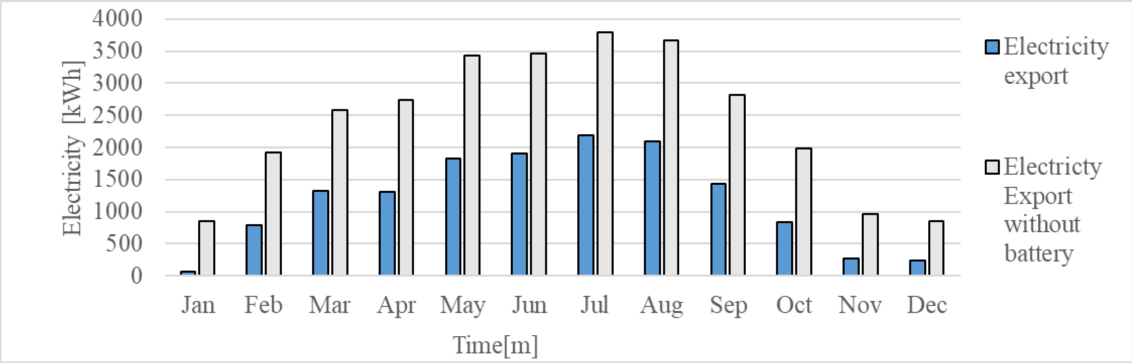


Figure 35 Monthly comparison of export with and without battery system.

In the Figure the blue bars indicate the electricity exported when the battery storage system is in use, while the grey bars represent the export levels without the battery storage system. A direct comparison between the bars for each month illustrates the effect of the battery system on the PED's ability to export electricity.

The graph can be used to identify potential for optimization. For example, if excess energy is consistently exported, it could be more beneficial to find ways to store or use it within the district to increase self-consumption.

Also, the energy demand within the PED may be consistent or the timing of the demand aligns with the lack of renewable energy generation, leading to a steady import requirement that the battery system isn't addressing.

These visualizations are crafted to broaden the scope of analysis, offering users a more holistic understanding of the energy ecosystem in their districts. By presenting these varied dimensions of energy data in a similar graphical format, is possible to ensure coherence and user-friendliness, allowing stakeholders to draw meaningful comparisons and insights across different energy aspects with ease.

3.7.3 District renovation

In this stage, users are presented with the implications of district retrofitting. While the retrofitting of energy systems is customizable according to user preferences, as illustrated in Figure 26, the parameters for building envelope renovation are pre-defined within the tool and elaborated upon in Chapter 3.5.3. The combined effects of these dual renovation strategies offer users a comprehensive insight into the district's potential for evolving into a PED.

Subsequently, users will encounter similar figures as before, but now reflecting the outcomes attributable to the district's renovation. This allows for a direct comparison between the baseline and renovated scenarios, enhancing the user's understanding of the impact of various retrofitting measures.

The same visual marker presents in the 'District balance' is present in the district renovation section. The tool provides a method for users to check the achievement of targets after the retrofit.

Also, there are graphs that compare the same parameters between the baseline and renovated scenarios. These comparative graphs help stakeholders to directly visualize the improvements and changes brought about by renovation strategies:

- **Consume renovated and baseline:** This graph compares energy consumption before and after renovation. It illustrates the effectiveness of the renovation in reducing energy demand or optimizing consumption patterns.
- **Generation renovated and baseline:** By comparing energy generation in the baseline and renovated scenarios, this graph shows the increased efficiency or capacity of energy production after renovation efforts.
- **Load cover factor renovated and baseline**: This comparison highlights changes in the proportion of the load that is covered by local generation, showcasing the improvement in self-sufficiency after renovation.
- **Grid interaction index renovated and baseline:** This graph demonstrates the difference in the variability of the net energy exchange with the grid, comparing how renovation affects the district's interaction with the external power grid.

3.7.4 Environmental Assessment

In the last step "Environmental Assessment," users are provided with comprehensive insights into two environmental impact metrics: Global Warming Potential (GWP) and Cumulative Energy Demand total (CED_{tot}), segmented into three distinct phases for more understanding.

For the use phase, the tool quantifies the environmental impacts attributed to electricity import as well as methane consumption or biomass or oil consumption.

Regarding the production phase and end of life, the tool calculates the environmental impacts of insulation materials, windows, photovoltaic systems, heat pumps, solar thermal system, boiler, battery and district heating used in the district's renovation.

The tool also facilitates a comparative assessment between the existing district and the renovated one across both impact categories. This comparison serves to quantify the environmental benefits or drawbacks resulting from the renovation strategies implemented, thereby providing a comprehensive understanding of the district's sustainability performance.

In the two subsequent figures, users can observe a comparison between the GWP and the CED of both the existing and renovated district. This comparative analysis offers insights into the environmental efficacy of the renovation measures undertaken, highlighting the changes in key impact indicators.

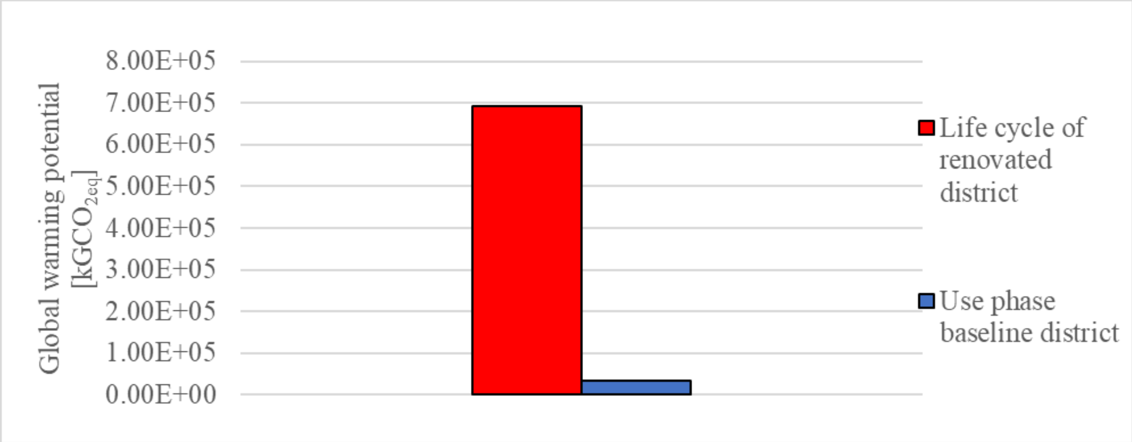


Figure 36 Comparison between the GWP of renovated and existing district.

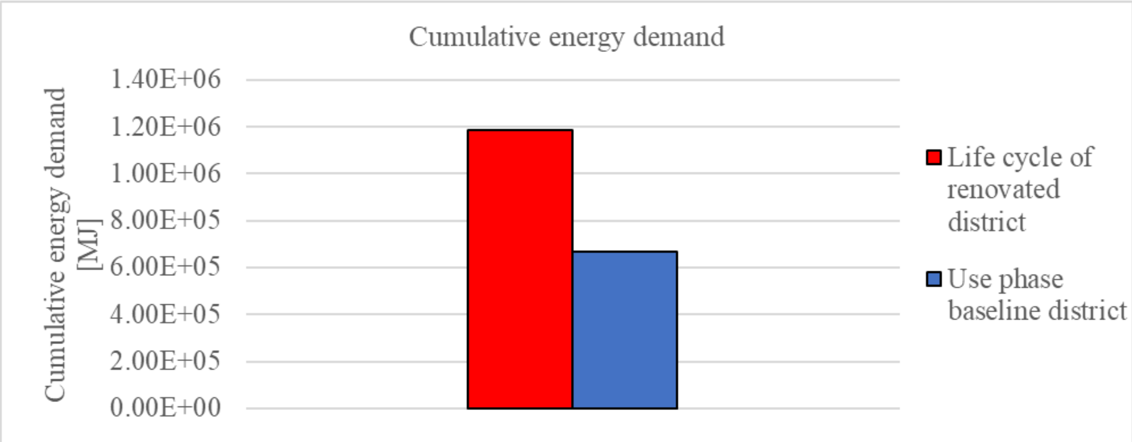


Figure 37 Comparison between the CED of renovated and existing district.

Despite the possibility to achieving the PED objective, these results highlight the importance of analysing different impact categories. A singular energy focus could lead to a false benefit of renovation. It's by examining both the GWP and the CED that is possible to have a comprehensive understanding of the environmental impacts, emphasizing that trade-offs may be involved and that improvements in one category could lead to increased impacts in another.

In the Figure 38, there is a visual representation of the environmental and energy sustainable indicators: EPT, GWP-PT and EER.

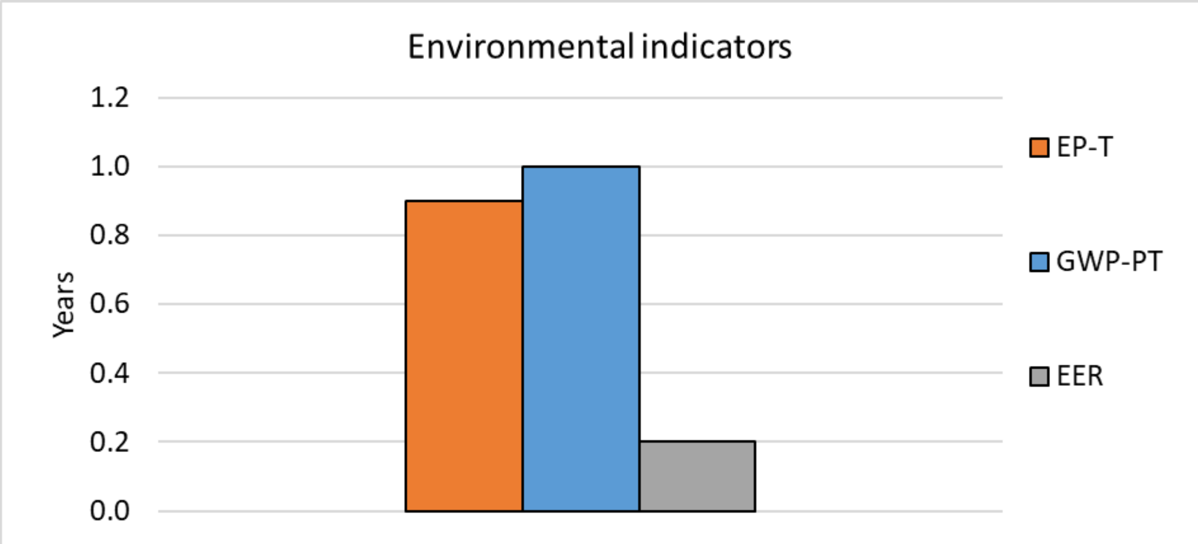


Figure 38 Environmental indicators.

The Figure shows an EPT relatively short, this efficiency metric is particularly important because it reflects the period during which the energy savings from the operational phase counterbalances the energy used in the manufacturing stage. A shorter EPT implies that the energy measures taken, possibly including the implementation of thermal insulation, photovoltaic panels, and other technologies, are effectively reducing the overall energy demand of the district.

The GWP-PT is longer than the EPT, the GWP-PT measures the time it takes for the environmental benefits, particularly the reduction in GWP, to offset the negative impacts created during the production of the renovated district. The longer GWP-PT suggests that while the district is energy-efficient, the reduction in greenhouse gas emissions is less immediate. This could be due to a variety of factors, including the types of materials used in the renovation or the methods employed in manufacturing. The implications are significant for policy and decision-making, as they highlight the need for careful selection of materials and processes that minimize the global warming impact in the short term as well as over the life of the district.

The EER shows a lower value than GWP-PT but lower than 1 year. The high EER value demonstrated in the chart indicates that the renovated district's operational phase is inefficient, as it does not have a favourable payback time. This inefficiency suggests that the energy-saving measures implemented are not effective enough compared to the energy consumed during manufacturing and end of life.

4. Results

This section presents the segmentation analysis for the four case studies, focusing on the construction periods and building typologies across the districts.

The figure presented here shows the segmentation results for the Pamplona district case study, focusing on the distribution of buildings based on their construction period.

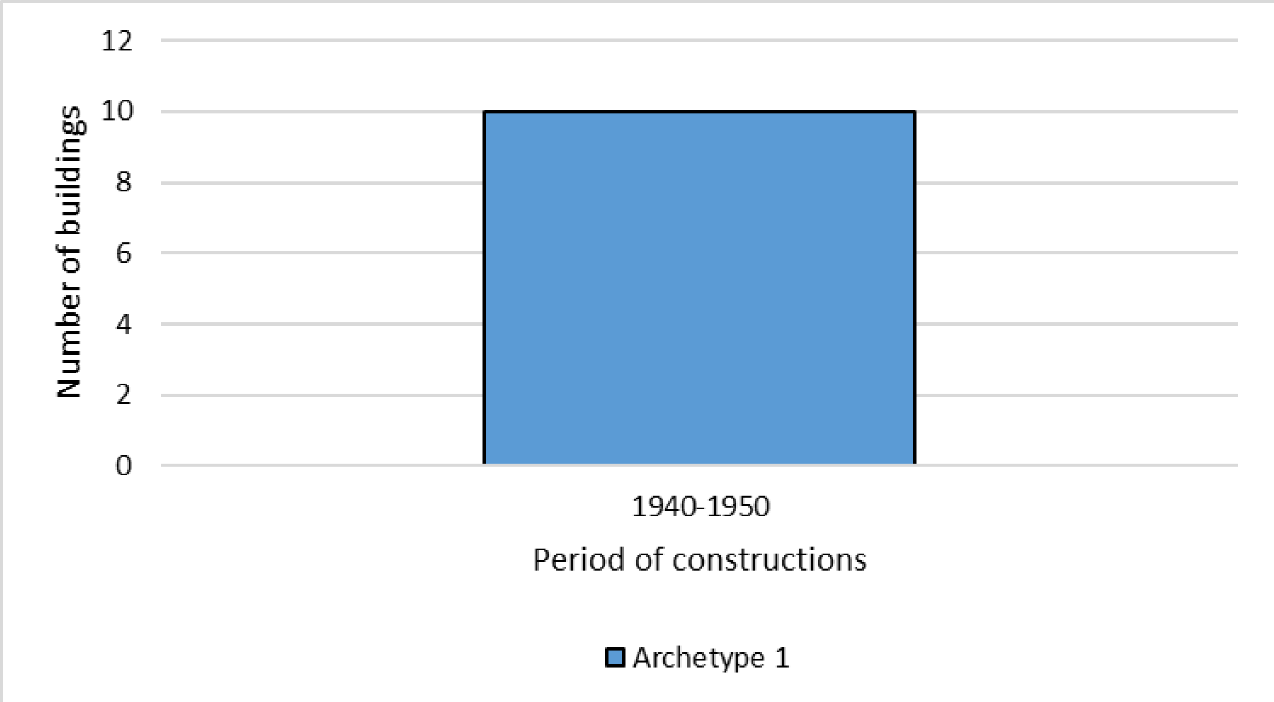


Figure 39 Distribution of buildings in the Pamplona district by construction period.

In this district, all the buildings analysed were constructed between 1940 and 1950 and consist in 10 buildings with same number of floors and similar shape. This highlights a relatively uniform building stock in terms of construction period, which provides a consistent basis for both energy performance and environmental analysis.

Additionally, it is important to note that all buildings in this district are residential, which further simplifies the modeling process and allows for the development of a single archetype that accurately reflects the characteristics of the entire district.

The next figure represents the segmentation results for the Bucharest district, illustrating the distribution of buildings based on their construction periods and corresponding archetypes.

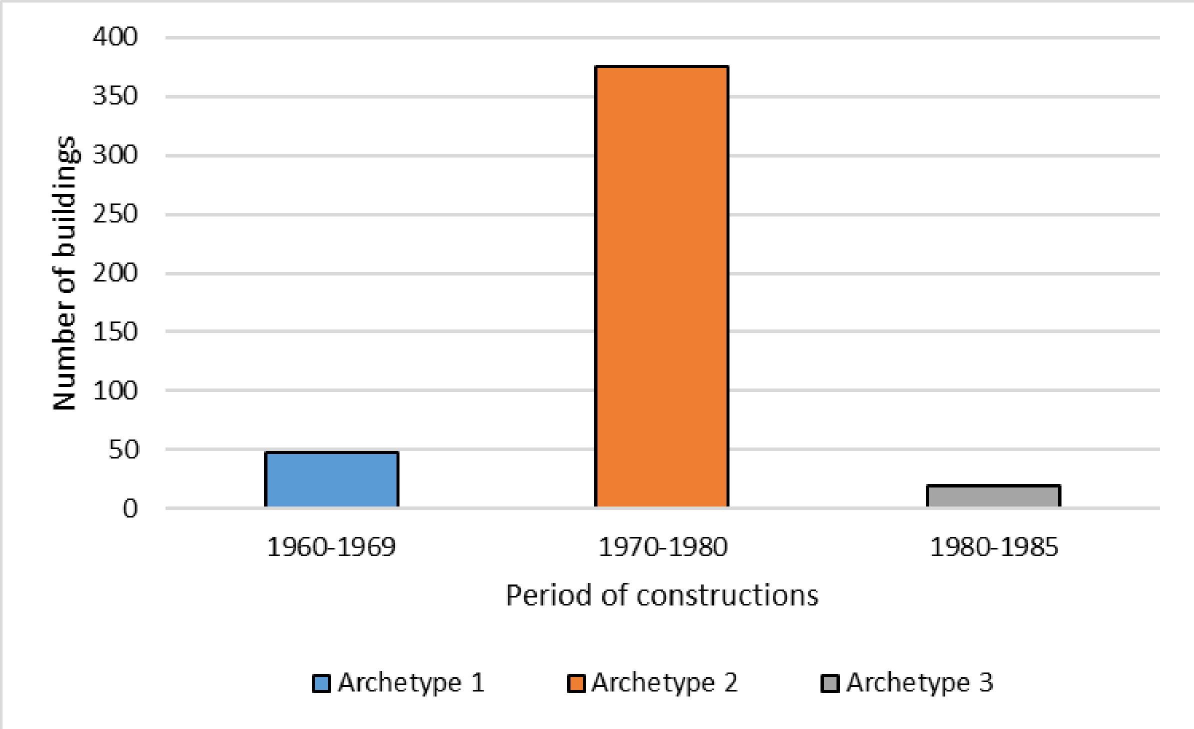


Figure 40 Distribution of buildings in the Bucharest district by construction period.

The figure shows that Archetype 1, which includes buildings constructed between 1960 and 1969, consists of 48 residential buildings. Archetype 2, the largest group, represents buildings constructed between 1970 and 1980, with 376 residential buildings. Finally, Archetype 3, covering buildings constructed between 1980 and 1985, includes 19 residential buildings.

All buildings in this district are residential. However, a notable distinction within the district is the variation in the number of floors among the archetypes. Archetype 1 consists of buildings with 5 floors, while Archetype 2 and Archetype 3 have 11 floors. Additionally, Archetype 3 stands out due to its predominant west-east orientation, further differentiating it from the other archetypes.

These characteristics differentiate the buildings within the district and adds complexity to the modeling process. The number of floors influences the total energy consumption of the buildings, making it a key factor to consider when analysing their performance and developing accurate models. Additionally, the predominantly west-east orientation of Archetype 3 can have significant effects on energy demand, particularly in terms of solar exposure, which impacts heating and cooling needs.

The next figure illustrates the distribution of buildings in the Copenhagen district, segmented by both building type and construction period. Unlike previous case studies, this district includes a variety of building uses, which adds complexity to the energy performance analysis. The buildings are classified into residential and non-residential categories, further divided by their specific functions, such as prisons and gyms, each with distinct construction periods.

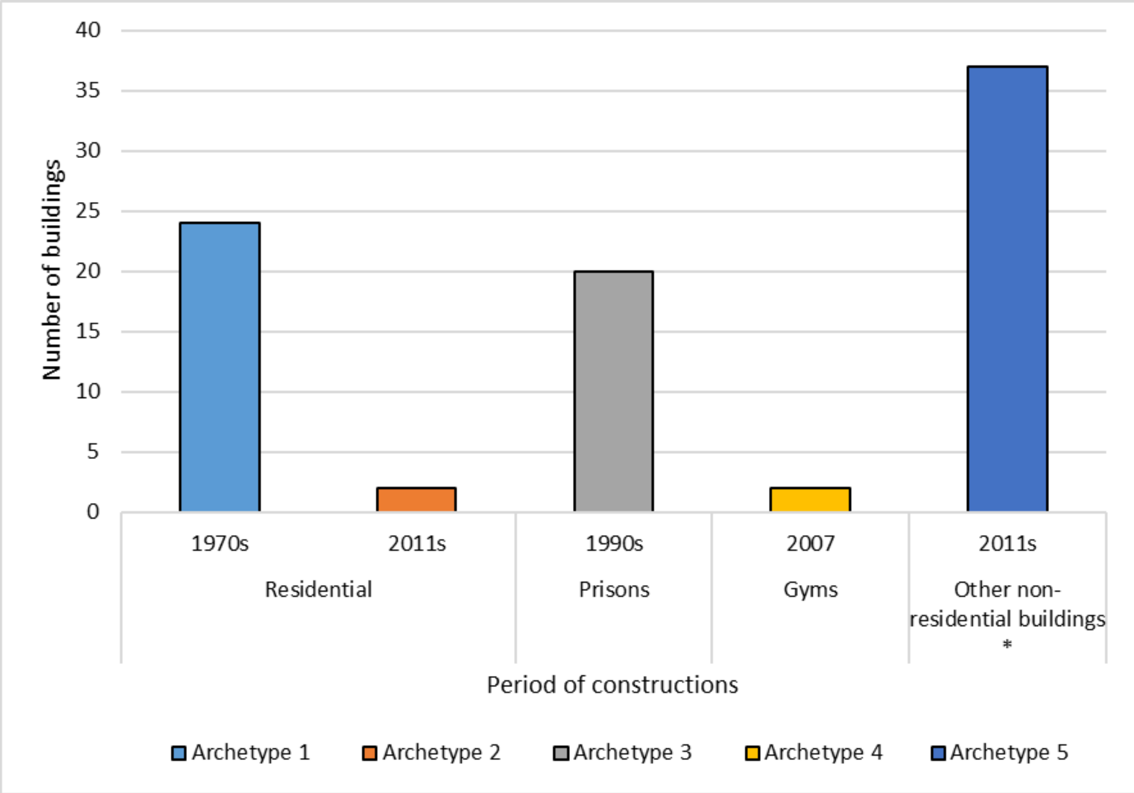


Figure 41 Distribution of building types and construction periods in the Copenhagen District

The residential buildings in the district are represented by Archetype 1, which consists of 24 buildings constructed in the 1970s, and Archetype 2, with 2 buildings constructed in the 2010s. For the non-residential buildings, Archetype 3 represents prisons built in the 1990s, with a total of 20 buildings. Archetype 4, representing gyms constructed in 2007, includes 2 buildings. Finally, Archetype 5, consisting of other non-residential buildings from the 2010s, is the largest group with 37 buildings.

This segmentation provides an overview of the building stock, highlighting both the diversity of building types and the corresponding periods of construction, which are critical for assessing energy performance and the potential for energy retrofitting in the district.

The next figure illustrates the distribution of building types within the district.

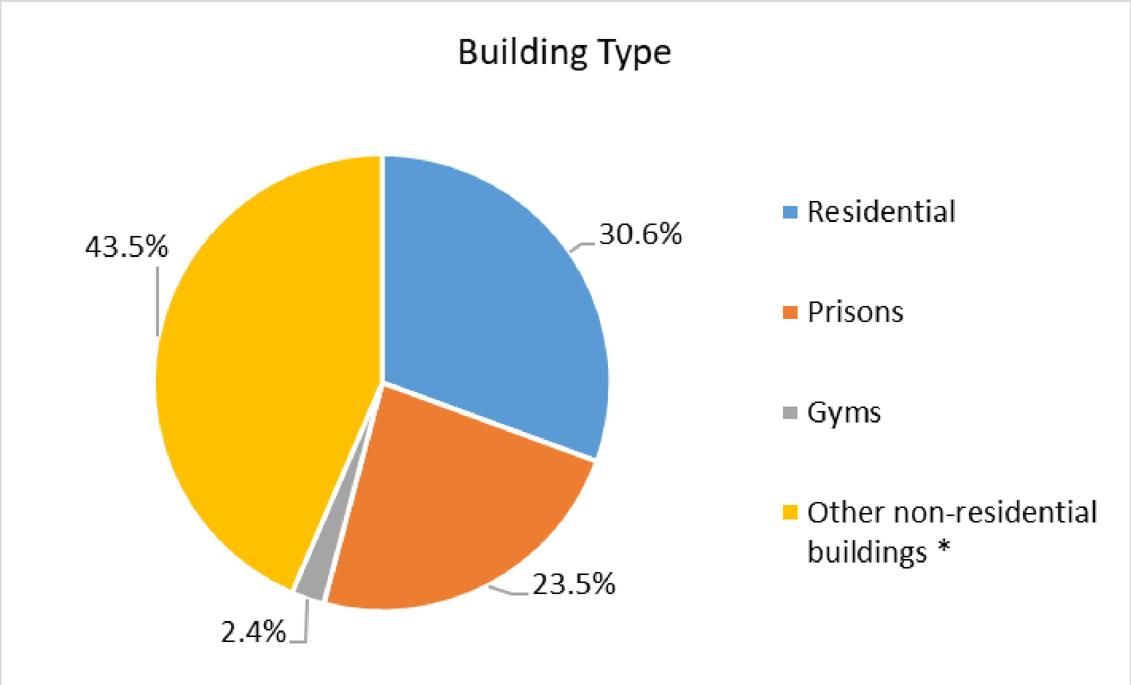


Figure 42 Distribution of building types in the Copenhagen district

The figure shows that 30.6% are residential, 23.5% are prisons, 2.4% are gyms and 43.5% are other non-residential buildings. This diversity in building functions requires a detailed approach to modeling energy consumption and performance for the district.

This figure illustrates the distribution of buildings in the district, segmented by both building type and period of construction across several archetypes.

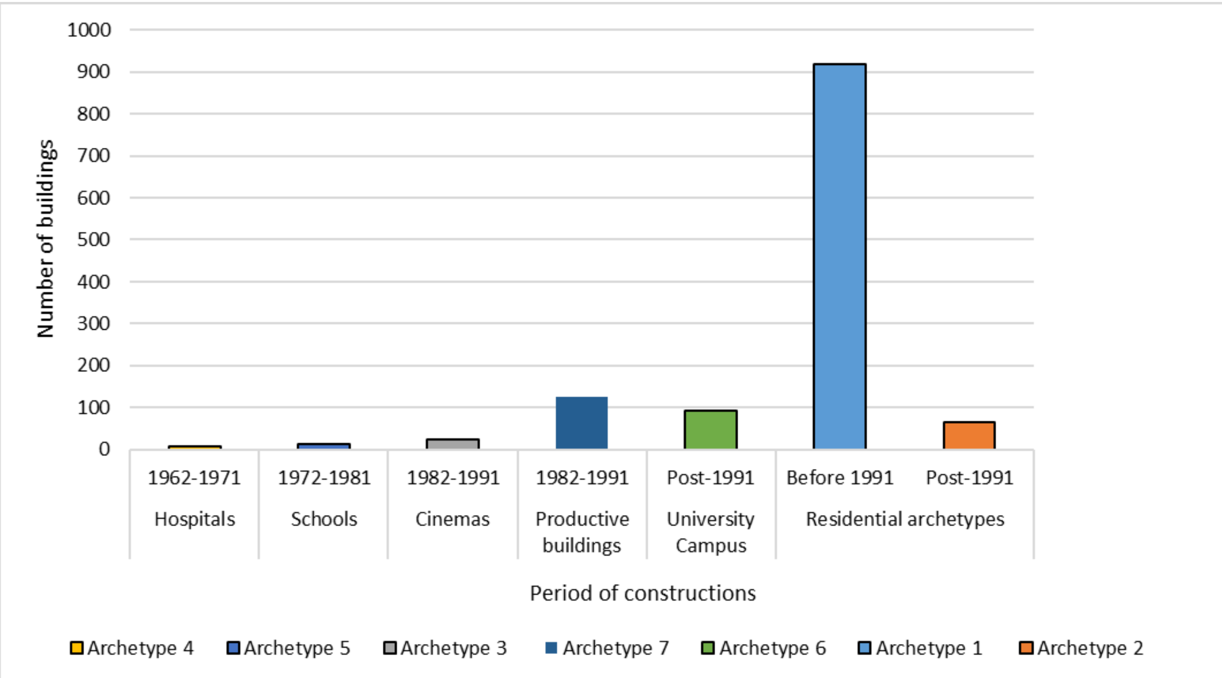


Figure 43 Distribution of building archetypes by function and construction period in the Parma district

The figure shows the distribution of buildings according to their type and period of construction.

- Archetype 1, which consists of residential buildings constructed before 1991, has the largest count with 917 buildings, dominating the building stock.
- Archetype 2, which includes post-1991 residential buildings, accounts for 65 buildings.
- Archetype 3 includes cinemas, with 23 buildings constructed between 1982 and 1991.
- Archetype 4 contains hospitals, with 7 buildings constructed between 1962 and 1971.
- Archetype 5 also includes schools, with 14 buildings constructed between 1972 and 1981.
- Archetype 6, representing university campus buildings constructed after 1991, has a total of 94 buildings.
- Archetype 7 consists of productive buildings constructed between 1982 and 1991, with 127 buildings.

The following pie chart visualizes the distribution of building types in the district, emphasizing the proportion of each category relative to the total building stock.

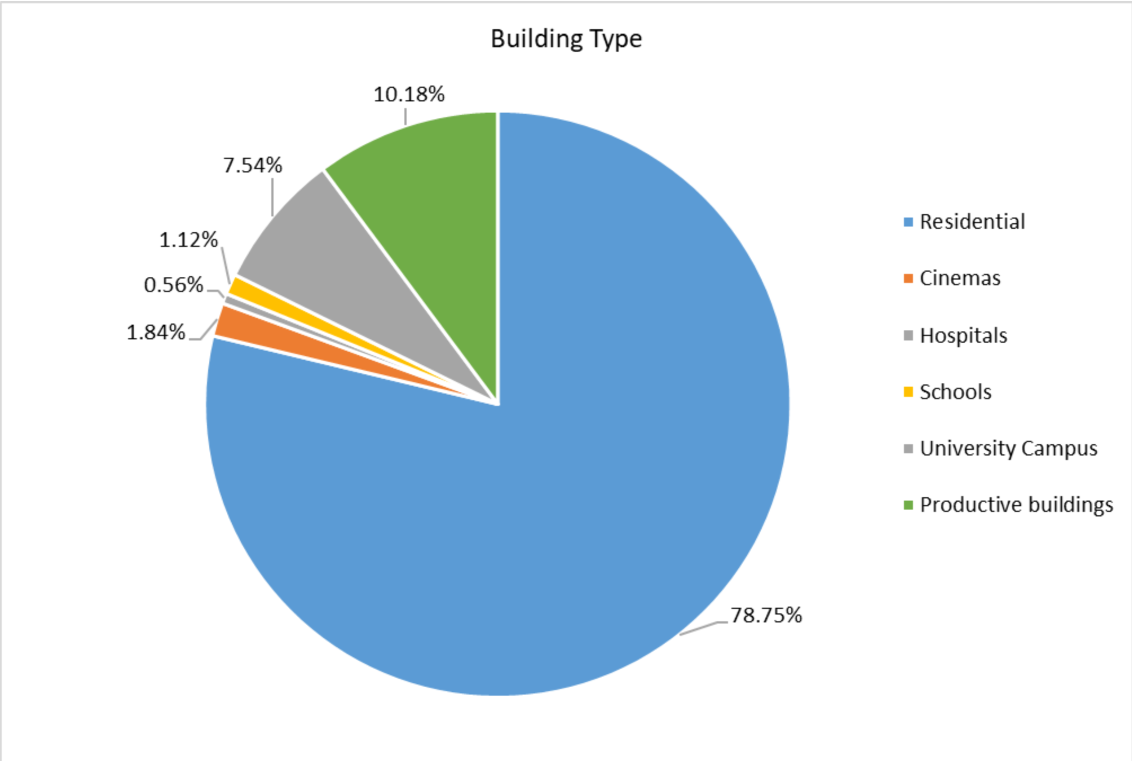


Figure 44 Distribution of building types in the Parma district

The chart shows a dominance of residential buildings, which make up 78.75% of the total building stock. The second-largest category is the productivity buildings, which account for 10.18% of the stock, highlighting their significance in the non-residential sector. Hospitals follow, contributing 7.54% to the overall composition. Schools and cinemas represent smaller portions, with schools comprising 1.12% and cinemas 0.56%.

4.1 Case Study analysis process 1 – Pamplona

The characterization of the buildings in the San Pedro district of Pamplona was carried out using data from multiple sources. Information on the building envelope, including the stratigraphy and system typology, was obtained through the OPENLAB project, which focuses on creating living labs for the energy transition in PEDs. The Pamplona living lab, one of the pilot areas in the project, provided valuable insights into building materials and system typologies.

Material properties were sourced from [180] while internal load schedules, specifically occupancy, lighting, appliance and infiltration were derived from [181] .

For health-related aspects, ventilation data was taken from [182]. Lastly, the system efficiency was evaluated using standard efficiency values. These combined sources provided a detailed description of the district's building characteristics and performance.

Archetype 1

The following figure shows the facades of the reference building for Archetype 1, which is a residential apartment block constructed between 1940 and 1950. Both the roof and the basement are unheated.

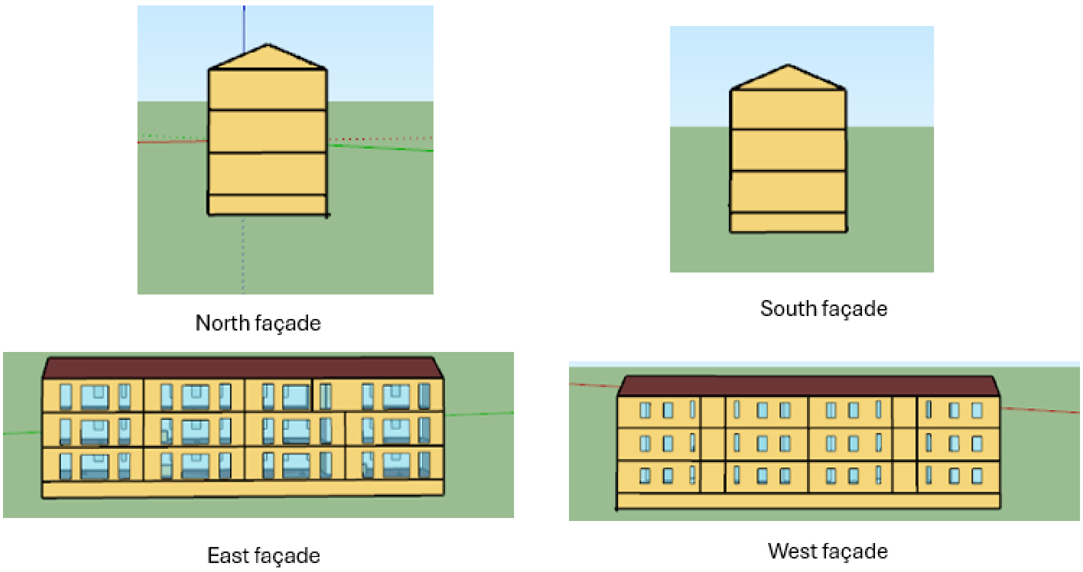


Figure 45 Facades of the reference building for archetype 1 (apartment block) in the Pamplona district.

Table 17 Detailed characteristics of residential building in the Pamplona district

Characteristics	Unit	Case study
Country	-	Spain
City	-	Pamplona
Construction year	-	1940-1950
Typology	-	Apartment Block
Number of heated floors	-	3
S/V ratio	[m^{-1}]	0.38
Area of S façade	[m^2]	89.63
Area of E façade	[m^2]	1584.84
Area of N façade	[m^2]	89.63
Area of W façade	[m^2]	344.82
Area of Roof	[m^2]	281.34
Area of Basement	[m^2]	281.34
Net floor area of heated zones	[m^2]	786.62
Height	[m]	11.8
Window area on S façade	[%]	0
Window area on E façade	[%]	7.5
Window area on N façade	[%]	0
Window area on W façade	[%]	12.98
People design level	[m^2/person]	30
Lighting design level	[W/ m^2]	4.4
Appliances design level	[W/ m^2]	4.4
Construction materials		
Ext walls	-	Brick
Floor	-	Concrete
Roof	-	Wood
Ventilation rate	[l/s m^2]	0.5
Infiltration rate	[h^{-1}]	0.24
U value of wall	[W/m^2-K]	0.59
U value of roof	[W/m^2-K]	3.5
U value of basement	[W/m^2-K]	1.27
U value of glass	[W/m^2-K]	2.69
g value of glass		0.76

4.2 Case study analysis process 2 – Bucharest

The district's building stock, characterized by its mix of original and retrofitted structures, predominantly utilizes centralized fan coil systems supported by heat pumps.

The following sections will provide a detailed description of the archetypes identified in Bucharest's district, along with an analysis of their energy performance.

Although six archetypes are analysed, the retrofitted archetypes share the same architectural form as their non-retrofitted counterparts. The only difference between the buildings is the presence of insulation in the retrofitted structures.

The characterization of the residential archetypes in the Bucharest district was carried out using data from the EPC for lighting consumption, general electricity consumption, building stratigraphy, and thermal transmittance values. The number of people (m^2/person) was determined using the EN 16798-1:2019 standard, while typical values for appliance loads (W/m²) were taken from the EN 15193-2 standard.

Archetype 1

The following figure shows the facades of the reference building of the first building archetype.

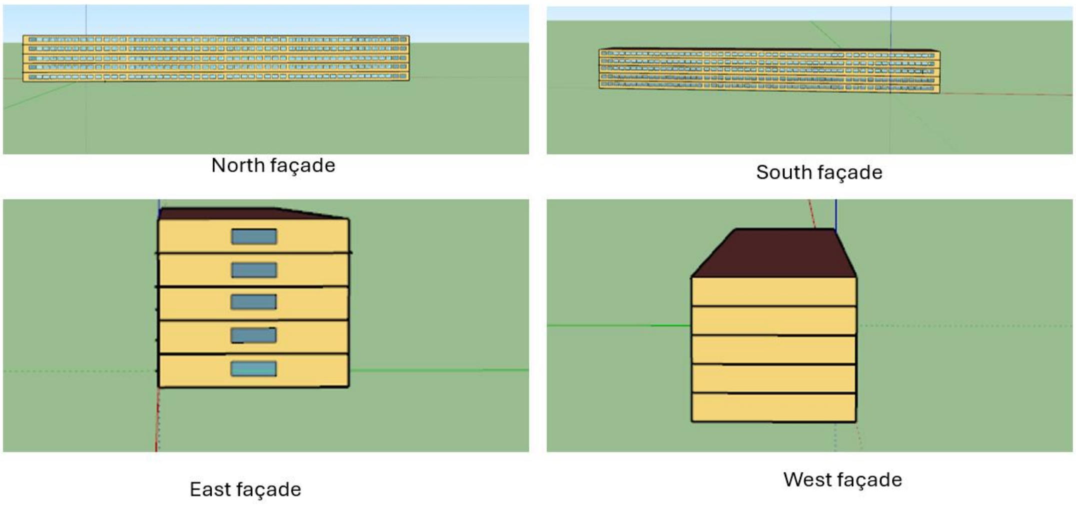


Figure 46 Facades of the reference building for the first building archetype (low-rise residential building) for the Bucharest district.

The table below details the specific characteristics of the first building archetype, including construction materials, dimensions, and energy performance indicators.

Table 18 Detailed characteristics of the first building archetype for the Bucharest district

Characteristics	Unit	Case study
Country	-	Romania
City	-	Bucharest
Construction year	-	1970-1980
Typology	-	Apartment Block
Number of heated floors	-	5
S/V ratio	[m^{-1}]	0.26
Area of S façade	[m^2]	1911
Area of E façade	[m^2]	255
Area of N façade	[m^2]	1911
Area of W façade	[m^2]	255
Area of Roof	[m^2]	2165
Area of Basement	[m^2]	2165
Net floor area of heated zones	[m^2]	10825
Height	[m]	15
Window area on S façade	[%]	24
Window area on E façade	[%]	5.9
Window area on N façade	[%]	24
Window area on W façade	[%]	-
People design level	[m^2/person]	28.3

Lighting design level	[W/ m^2]	11
Appliances design level	[W/ m^2]	3
Construction materials		
Ext walls*	-	Prefabricated reinforced concrete panels
Floor	-	Concrete
Roof	-	Concrete
Ventilation rate	[l/s m^2]	0.5
Infiltration rate	[h^{-1}]	0.4
U value of wall	[W/m^2-K]	1.5
U value of roof	[W/m^2-K]	1.3
U value of basement	[W/m^2-K]	1.9
U value of glass	[W/m^2-K]	2.7
g value of glass		0.7

*The retrofitted buildings have an additional 8 cm layer of expanded polystyrene insulation.

Archetype 2

The following figure shows the facades of the reference building of the second building archetype, a mid-rise residential building.

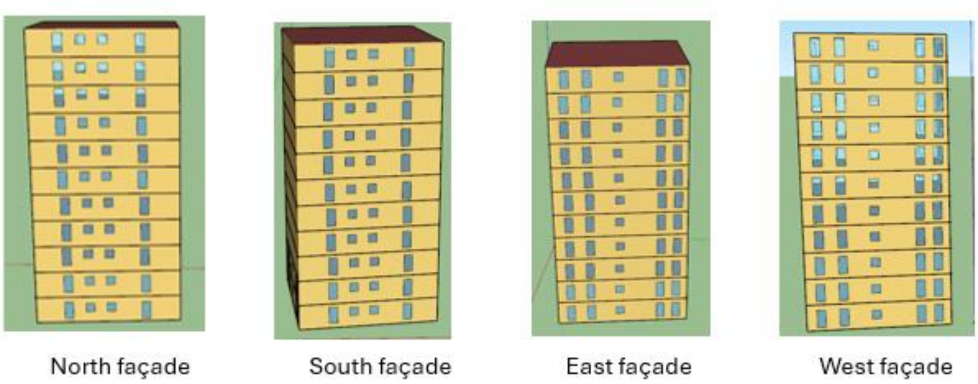


Figure 47 Facades of the reference building of second building archetype for the Bucharest district.

The table below details the specific characteristics of the second building archetype, including construction materials, dimensions, and energy performance indicators.

Table 19 Detailed characteristics of the second building archetype for the Bucharest district

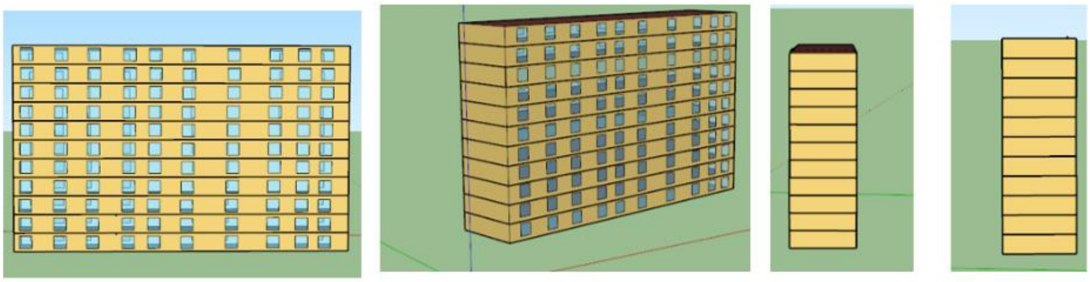
Characteristics	**Unit**	**Case study**
Country	-	Romania
City	-	Bucharest
Construction year	-	1970-1980
Typology	-	Apartment Block
Number of heated floors	-	11
S/V ratio	[m^{-1}]	0.3
Area of S façade	[m^2]	541.85
Area of E façade	[m^2]	542.19
Area of N façade	[m^2]	541.85
Area of W façade	[m^2]	542.19

Area of Roof	[m^2]	270
Area of Basement	[m^2]	270
Net floor area of heated zones	[m^2]	2970
Height	[m]	33
Window area on S façade	[%]	15
Window area on E façade	[%]	10
Window area on N façade	[%]	15
Window area on W façade	[%]	10
People design level	[m^2/person]	28.3
Lighting design level	[W/ m^2]	11
Appliances design level	[W/ m^2]	3
Construction materials		
Ext walls*	-	Prefabricated reinforced concrete panels
Floor	-	Concrete
Roof	-	Concrete
Ventilation rate	[l/s m^2]	0.5
Infiltration rate	[h^{-1}]	0.35
U value of wall	[W/m^2-K]	1.9
U value of roof	[W/m^2-K]	1.4
U value of basement	[W/m^2-K]	2.3
U value of glass	[W/m^2-K]	2.7
g value of glass		0.7

*The retrofitted buildings have an additional 8 cm layer of expanded polystyrene insulation.

Archetype 3

The following figure shows the reference building of the facades of the third building archetype, a mid-rise (West-East oriented) residential building.



North façade South façade East façade West façade

Figure 48 Facades of the reference building of the third building archetype for the Bucharest district.

The table below details the specific characteristics of the third building archetype, including construction materials, dimensions and energy performance indicators.

Table 20 Detailed characteristics of the third building archetype for the Bucharest district

Characteristics	**Unit**	**Case study**
Country	-	Romania
City	-	Bucharest
Construction year	-	1970-1980
Typology	-	Apartment Block
Number of heated floors	-	11
S/V ratio	[m^{-1}]	0.27
Area of S façade	[m^2]	1782.33

Area of E façade	[m^2]	372.9
Area of N façade	[m^2]	1782.33
Area of W façade	[m^2]	372.9
Area of Roof	[m^2]	610
Area of Basement	[m^2]	610
Net floor area of heated zones	[m^2]	6713
Height	[m]	33
Window area on S façade	[%]	19.4
Window area on E façade	[%]	0
Window area on N façade	[%]	26
Window area on W façade	[%]	0
People design level	[m^2/person]	28.3
Lighting design level	[W/ m^2]	11
Appliances design level	[W/ m^2]	3
Construction materials		
Ext walls*	-	Prefabricated reinforced concrete panels
Floor	-	Concrete
Roof	-	Concrete
Ventilation rate	[l/s m^2]	0.5
Infiltration rate	[h^{-1}]	0.1
U value of wall	[W/m^2-K]	1.46
U value of roof	[W/m^2-K]	1.31
U value of basement	[W/m^2-K]	1.85
U value of glass	[W/m^2-K]	2.7
g value of glass		0.7

*The retrofitted buildings have an additional 8 cm layer of expanded polystyrene insulation.

4.3 Case study analysis process 3 – Copenhagen

The Copenhagen district is composed of both residential and non-residential buildings, each requiring specific methods for energy characterization.

The energy characterization process for these buildings was based primarily on data from EPCs, supplemented by additional sources where necessary to ensure accurate and consistent modeling.

For residential buildings, the EPCs provided essential data on lighting consumption, general electricity consumption, and the building's stratigraphy. However, they did not include explicit U-values (thermal transmittance) for the building envelope. To address this, U-values were sourced from the TABULA database, ensuring accurate modeling of thermal properties such as walls, windows, and floors.

Regarding occupancy profiles and internal loads, the EPCs lacked detailed information. As a result, the number of people (m^2/person) and occupancy schedules were characterized using the EN 16798-1:2019 standard, while typical appliance load values (W/m^2) were derived from the EN 15193-2 standard.

For non-residential buildings, including the gym (archetype 4) and other non-residential building (archetype 5), the EPCs provided useful thermal consumption data. However, internal load profiles for lighting and appliance use were not provided. In the case of the

gym, internal loads could be evaluated using the ISO 18523-1 standard, which is specifically designed to define internal loads for such non-residential buildings. This standard allowed for a more precise assessment of energy consumption in the gym.
For the prison, no specific standards exist to define internal loads, so the energy modeling for this building type relied heavily on the real consumption data provided by the EPC.

Archetype 1

The following figure shows the facades of reference building of the first building archetype, a residential building constructed in the 1970s.

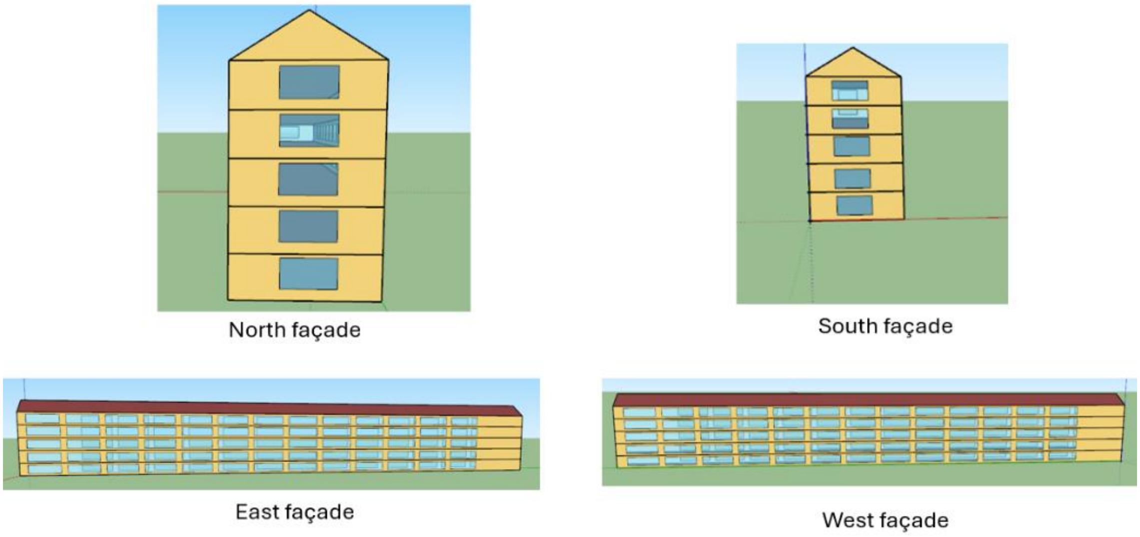


Figure 49 Facades of the reference building of the first building archetype (1970s residential building) for the Copenhagen district.

The table below details the specific characteristics of the first building archetype, including construction materials, dimensions, and energy performance indicators.

Table 21 Detailed characteristics of the first building archetype (1970s residential building) for the Copenhagen district

Characteristics	Unit	Case study
Country	-	Denmark
City	-	Copenhagen
Construction year	-	1970-1980
Typology	-	Apartment Block
Number of heated floors	-	5
S/V ratio	[m^{-1}]	0.33
Area of S façade	[m^2]	147
Area of E façade	[m^2]	1965
Area of N façade	[m^2]	147
Area of W façade	[m^2]	1965
Area of Roof	[m^2]	1283.8
Area of Basement	[m^2]	1283.8
Net floor area of heated zones	[m^2]	6419

Height	[m]	15
Window area on S façade	[%]	25
Window area on E façade	[%]	48
Window area on N façade	[%]	25
Window area on W façade	[%]	60
People design level	[m^2/person]	28.3
Lighting design level	[W/ m^2]	11
Appliances design level	[W/ m^2]	3
Construction materials		
Ext walls	-	Brick (with cavity)
Ext walls 2		Brick (with insulation)
Floor	-	Prefabricated reinforced concrete
Roof	-	Prefabricated panels
Ventilation rate	[l/s m^2]	0.5
Infiltration rate	[h^{-1}]	0.5
U value of wall	[W/m^2-K]	0.5
U value of wall 2	[W/m^2-K]	0.6
U value of roof	[W/m^2-K]	0.2
U value of basement	[W/m^2-K]	2.9
U value of glass	[W/m^2-K]	2.8
g value of glass		0.7

Archetype 2

The following figure shows the facades of the reference building second building archetype, a residential building constructed in 2011 with an elongated shape.

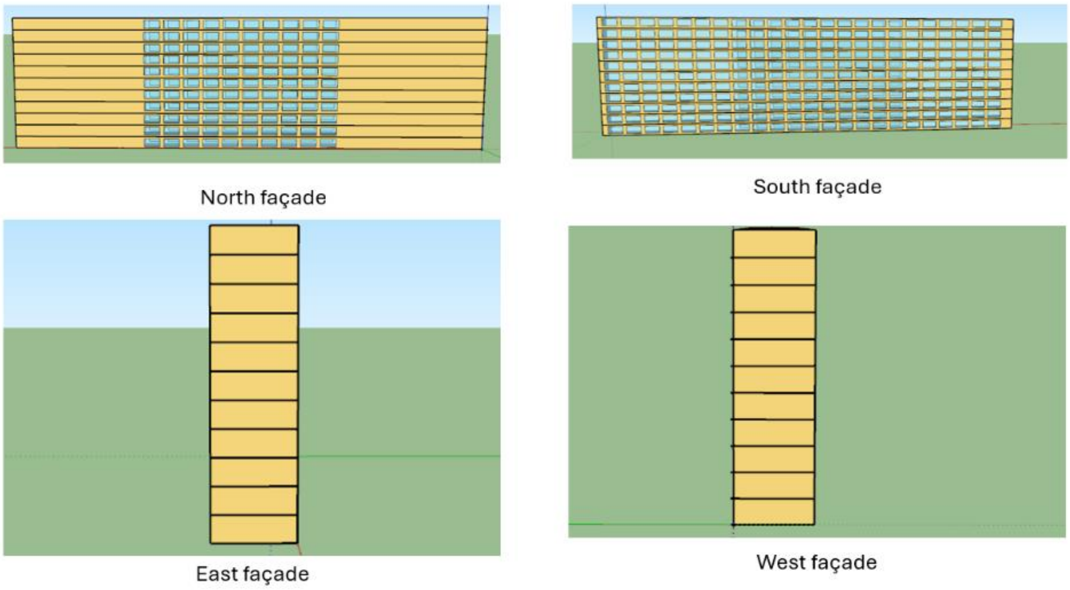


Figure 50 Facades of the reference building second building archetype (2011 residential building) for the Copenhagen district.

Table 22 Detailed characteristics of the second building archetype (2011 residential building) for the Copenhagen district.

Characteristics	Unit	Case study
Country	-	Denmark
City	-	Copenhagen
Construction year	-	2007-2010
Typology	-	Apartment Block
Number of heated floors	-	11
S/V ratio	[m^{-1}]	
Area of S façade	[m^2]	3927
Area of E façade	[m^2]	302.61
Area of N façade	[m^2]	3927
Area of W façade	[m^2]	302.61
Area of Roof	[m^2]	1091.23
Area of Basement	[m^2]	1091.23
Net floor area of heated zones	[m^2]	12003.53
Height	[m]	33
Window area on S façade	[%]	56.86
Window area on E façade	[%]	0
Window area on N façade	[%]	21.15
Window area on W façade	[%]	0
People design level	[m^2/person]	28.3
Lighting design level	[W/ m^2]	11
Appliances design level	[W/ m^2]	3
Construction materials		
Ext walls	-	Brick
Floor	-	Concrete
Roof	-	Concrete
Ventilation rate	[l/s m^2]	0.5
Infiltration rate	[h^{-1}]	0.2
U value of wall	[W/m^2-K]	0.24
U value of roof	[W/m^2-K]	0.19
U value of basement	[W/m^2-K]	0.14
U value of glass	[W/m^2-K]	1.6
g value of glass		0.7

Archetype 3

The following figure illustrates the facades of the reference building of third building archetype, representing a prison facility, characterized by its reinforced concrete construction.

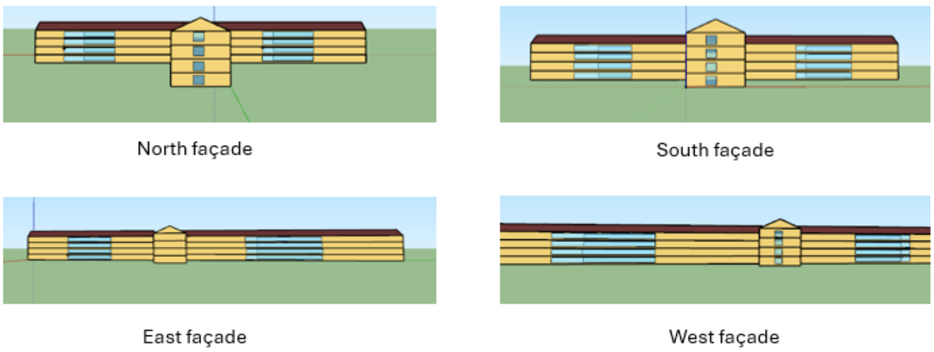


Figure 51 Facades of the reference building of the third building archetype (prison facility) for the Copenhagen district.

The table below details the specific characteristics of the third building archetype, including construction materials, dimensions and energy performance indicators, for the prison facility.

Table 23 Detailed characteristics of the third building archetype (prison facility) for the Copenhagen district

Characteristics	**Unit**	**Case study**
Country	-	Denmark
City	-	Copenhagen
Construction year	-	2016
Typology	-	Prison
Number of heated floors	-	4
S/V ratio	[m^{-1}]	0.33
Area of S façade	[m^2]	1705
Area of E façade	[m^2]	2437
Area of N façade	[m^2]	1686
Area of W façade	[m^2]	2437
Area of Roof	[m^2]	6687.18
Area of Basement	[m^2]	3770
Net floor area of heated zones	[m^2]	15080
Height	[m]	15
Window area on S façade	[%]	18.58
Window area on E façade	[%]	19.13
Window area on N façade	[%]	18.79
Window area on W façade	[%]	19.90
People design level	[m^2/person]	104
Lighting design level	[W/ m^2]	10
Appliances design level	[W/ m^2]	7.65
Construction materials		
Ext walls	-	Brick
Floor	-	Concrete
Roof	-	Concrete
Ventilation rate	[m^3/h-m^2]	3.6
Infiltration rate	[h^{-1}]	0.7
U value of wall	[W/m^2-K]	0.5
U value of roof	[W/m^2-K]	0.2
U value of basement	[W/m^2-K]	2.7
U value of glass	[W/m^2-K]	2.8
g value of glass		0.7

Archetype 4

The following figure illustrates the facades of the reference building of the fourth building archetype, representing a gym facility.

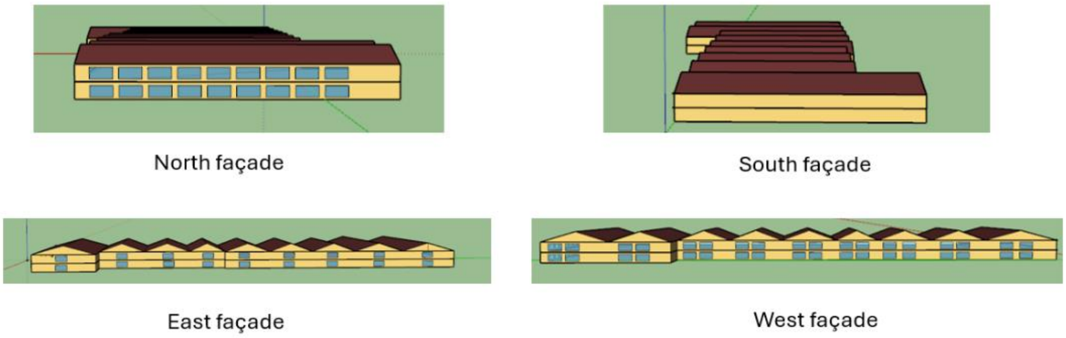


Figure 52 Facades of the reference building of the fourth building archetype (gym facility) for the Copenhagen district.

The table below details the specific characteristics of the third building archetype, including construction materials, dimensions, and energy performance indicators, for the gym facility.

Table 24 Detailed characteristics of the fourth building archetype (Gym facility) in the Copenhagen district

Characteristics	Unit	Case study
Country	-	Denmark
City	-	Copenhagen
Construction year	-	1900
Typology	-	Gym
Number of heated floors	-	2
S/V ratio	[m^{-1}]	
Area of S façade	[m^2]	409.8
Area of E façade	[m^2]	1179.75
Area of N façade	[m^2]	409.8
Area of W façade	[m^2]	1155
Area of Roof	[m^2]	27807.26
Area of Basement	[m^2]	7147.80
Net floor area of heated zones	[m^2]	14295.6
Height	[m]	9
Window area on S façade	[%]	0
Window area on E façade	[%]	17.5
Window area on N façade	[%]	36.44
Window area on W façade	[%]	34.63
People design level	[person/ m^2]	0.1
Lighting design level	[W/ m^2]	60
Appliances design level	[W/ m^2]	0
Construction materials		
Ext walls	-	Brick with insulation
Ext walls 2	-	Small bricks
Floor	-	Concrete
Roof	-	Concrete
Ventilation rate	[m^3/h-m^2]	12.5
Infiltration rate	[h^{-1}]	0.6
U value of wall	[W/m^2-K]	0.4
U value of wall 2	[W/m^2-K]	1.34
U value of roof	[W/m^2-K]	0.22
U value of basement	[W/m^2-K]	2.94
U value of glass	[W/m^2-K]	2.55
g value of glass		0.35

Archetype 5

The following figure illustrates the facades of the reference building of the fifth building archetype, representing another non-residential building non-residential facility.

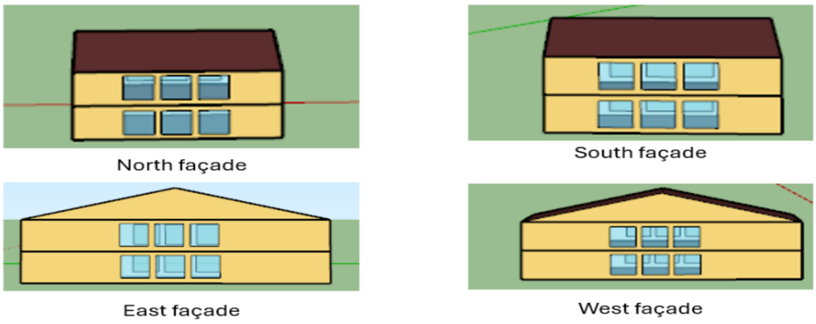


Figure 53 Facades of the reference building for the fifth building archetype (other non-residential buildings) in the Copenhagen district

The next table summarizes the detailed characteristics of the fifth building archetype identified in the Copenhagen district, representing another non-residential buildings.

Table 25 Detailed characteristics of the fifth building archetype (other non-residential buildings) in the Copenhagen district

Characteristics	Unit	Case study
Country	-	Denmark
City	-	Copenhagen
Construction year	-	2007
Typology	-	Other non-residential buildings
Number of heated floors	-	2
S/V ratio	[m^{-1}]	0.33
Area of S façade	[m^2]	84
Area of E façade	[m^2]	165
Area of N façade	[m^2]	84
Area of W façade	[m^2]	165
Area of Roof	[m^2]	319.24
Area of Basement	[m^2]	308
Net floor area of heated zones	[m^2]	616
Height	[m]	9
Window area on S façade	[%]	39
Window area on E façade	[%]	19
Window area on N façade	[%]	39
Window area on W façade	[%]	19
People design level	[m^2/person]	12.5
Lighting design level	[W/ m^2]	10
Appliances design level	[W/ m^2]	8
Construction materials		
Ext walls	-	Brick
Floor	-	Concrete
Roof	-	Concrete
Ventilation rate	[m^3/h-m^2]	7.5
Infiltration rate	[h^{-1}]	0.3
U value of wall	[W/m^2-K]	0.4
U value of roof	[W/m^2-K]	0.22
U value of basement	[W/m^2-K]	2.9
U value of glass	[W/m^2-K]	2.6

g value of glass		0.35

4.4 Case Study analysis process 4 – Parma

The thermal characteristics of the buildings was derived from EPCs, while the electrical analysis predominantly relied on the EN ISO 16798-1:2019, EN 15193-2 and ISO 18523-1 standards.

Specifically, for non-residential buildings, the schedules and power densities (expressed in W/m²) are provided by the ISO 18523-1 standard.

For residential buildings, the schedules for lighting, equipment and occupancy, as well as the W/m² values for people and appliances, are determined according to the EN 16798-1:2019 standard, while the W/m² values for lighting provided by the EN 15193-2 standard, are calculated as the average value of the typical specific loads defined for kitchens, living rooms, bathrooms, and bedrooms.

Additionally, in order to compare ISO 18523-1 with the usage categories defined in DPR 412-93, a parallel approach similar to the one adopted in the study [183] was applied. This ensured consistency between the international standards and national regulations for energy performance and building use classification.

Archetype 1

The following figure shows the facades of the reference building for archetype 1, which is a residential apartment block built before 1991.

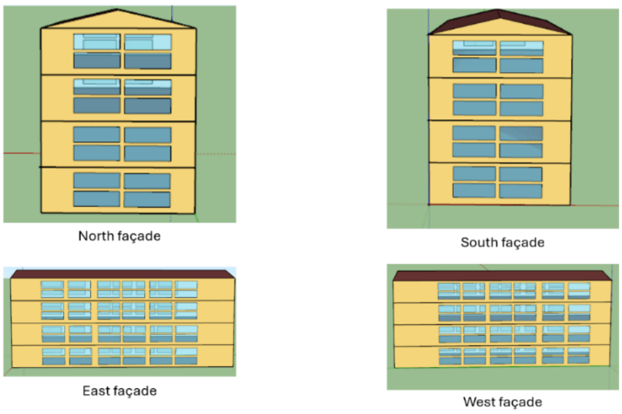


Figure 54 Facades of the reference building for archetype 1 in the Parma district.

The following table summarizes the detailed characteristics of the first building archetype identified in the Parma district, representing apartment blocks constructed before 1991.

Table 26 Detailed characteristics of residential type 1 building in Parma district

Characteristics	**Unit**	**Case study**
Country	-	Italy
City	-	Parma
Construction year	-	Before 1991
Typology	-	Apartment Block
Number of heated floors	-	4
S/V ratio	[m^{-1}]	0.43
Area of S façade	[m^2]	125.8
Area of E façade	[m^2]	360
Area of N façade	[m^2]	125.8
Area of W façade	[m^2]	360
Area of Roof	[m^2]	307.97
Area of Basement	[m^2]	300
Net floor area of heated zones	[m^2]	1200
Height	[m]	13.16
Window area on S façade	[%]	38.16
Window area on E façade	[%]	40
Window area on N façade	[%]	38.16
Window area on W façade	[%]	40
People design level	[m^2/person]	28.3
Lighting design level	[W/ m^2]	11
Appliances design level	[W/ m^2]	3
Construction materials		
Ext walls	-	Brick
Floor	-	Concrete
Roof	-	Wood
Ventilation rate	[l/s m^2]	0.5
Infiltration rate	[h^{-1}]	
U value of wall	[W/m^2-K]	1.5
U value of roof	[W/m^2-K]	1.5
U value of basement	[W/m^2-K]	1.2
U value of glass	[W/m^2-K]	3.23
g value of glass		0.7

Archetype 2

The following figure presents the facades of archetype 2, which is another residential apartment block built after 1991.

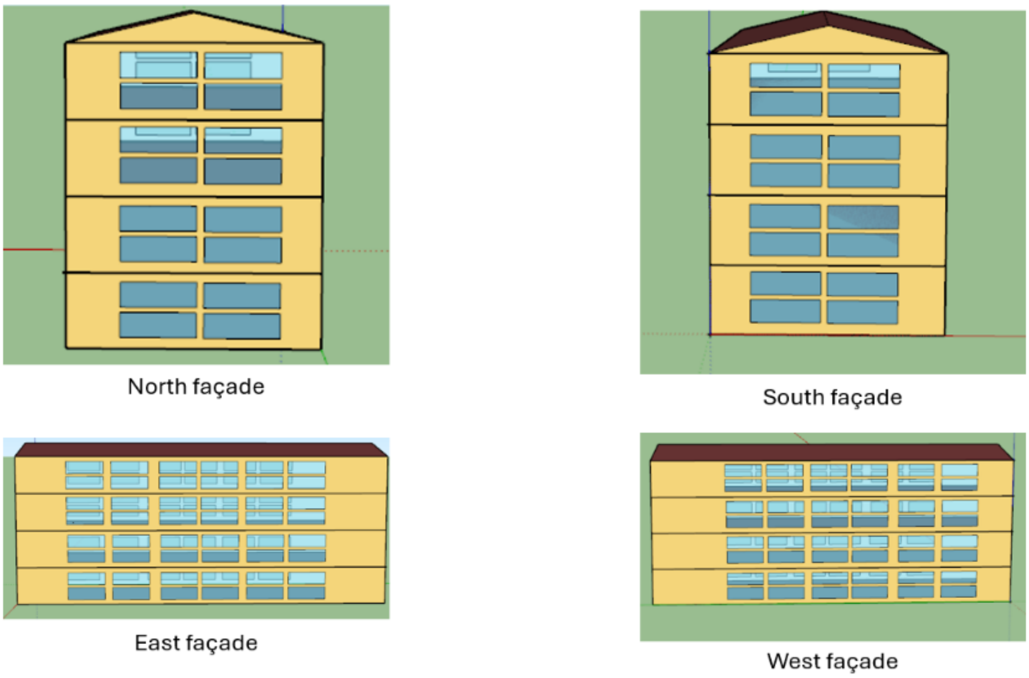


Figure 55 Facades of the reference building for archetype 2 in the Parma district.

The following table provides an overview of the detailed characteristics of the second building archetype identified in the Parma district, representing residential buildings constructed after 1991.

Table 27 Detailed characteristics of residential type 2 building in Parma district

Characteristics	Unit	Case study
Country	-	Italy
City	-	Parma
Construction year	-	After 1991
Typology	-	Apartment Block
Number of heated floors	-	4
S/V ratio	[m^{-1}]	0.43
Area of S façade	[m^2]	125.8
Area of E façade	[m^2]	360
Area of N façade	[m^2]	125.8
Area of W façade	[m^2]	360
Area of Roof	[m^2]	307.97
Area of Basement	[m^2]	300
Net floor area of heated zones	[m^2]	1200
Height	[m]	13.16
Window area on S façade	[%]	38.16
Window area on E façade	[%]	40
Window area on N façade	[%]	38.16
Window area on W façade	[%]	40
People design level	[m^2/person]	28.3
Lighting design level	[W/ m^2]	11

Appliances design level	[W/ m²]	3
Ext walls	-	Brick
Floor	-	Concrete
Roof	-	Wood
Ext walls	-	Brick
Ventilation rate	[l/s m²]	0.5
Infiltration rate	[h⁻¹]	0.3
U value of wall	[W/m²-K]	1.16
U value of roof	[W/m²-K]	0.8
U value of basement	[W/m²-K]	1.55
U value of glass	[W/m²-K]	2.69
g value of glass		0.6

Archetype 3

The following figure depicts archetype 3, a building designated as a cinema, constructed in 1991.

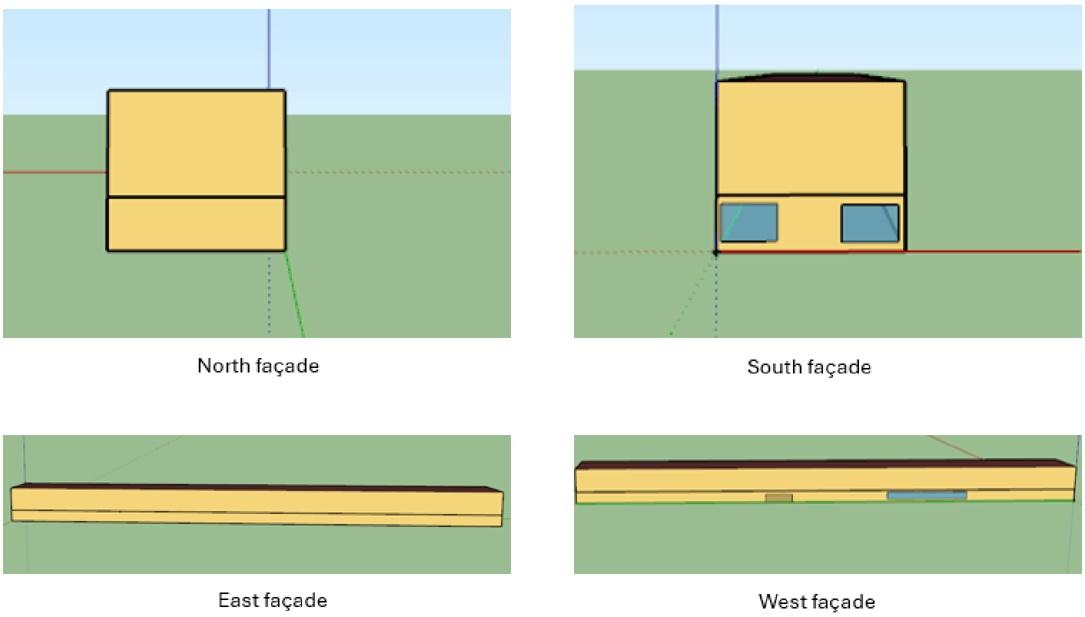


Figure 56 Facades of the reference building for cinemas in the Parma district.

The following table outlines the detailed characteristics of the third building archetype identified in the Parma district, representing cinemas constructed in 1991.

Table 28 Detailed characteristics of cinema buildings in Parma district

Characteristics	**Unit**	**Case study**
Country	-	Italy
City	-	Parma
Construction year	-	1991
Typology	-	Cinema
Number of heated floors	-	2
S/V ratio	[m⁻¹]	0.48

Area of S façade	[m^2]	90
Area of E façade	[m^2]	1170
Area of N façade	[m^2]	90
Area of W façade	[m^2]	1170
Area of Roof	[m^2]	1300
Area of Basement	[m^2]	1300
Net floor area of heated zones	[m^2]	2600
Height	[m]	6
Window area on S façade	[%]	13.33
Window area on E façade	[%]	0
Window area on N façade	[%]	0
Window area on W façade	[%]	3.5
People design level	[person/m^2]	1
Lighting design level	[W/ m^2]	50
Appliances design level	[W/ m^2]	0
Construction materials		
Ext walls	-	Brick
Floor	-	Concrete
Roof	-	Wood
Ventilation rate	[m^3/h-m^2]	25
Infiltration rate	[h^{-1}]	0.4
U value of wall	[W/m^2-K]	1.87
U value of roof	[W/m^2-K]	0.3
U value of basement	[W/m^2-K]	1.43
U value of glass	[W/m^2-K]	4.85
g value of glass		0.75

Archetype 4

The following figure illustrates the facades of archetype 4, which is a hospital built between 1960 and 1970.

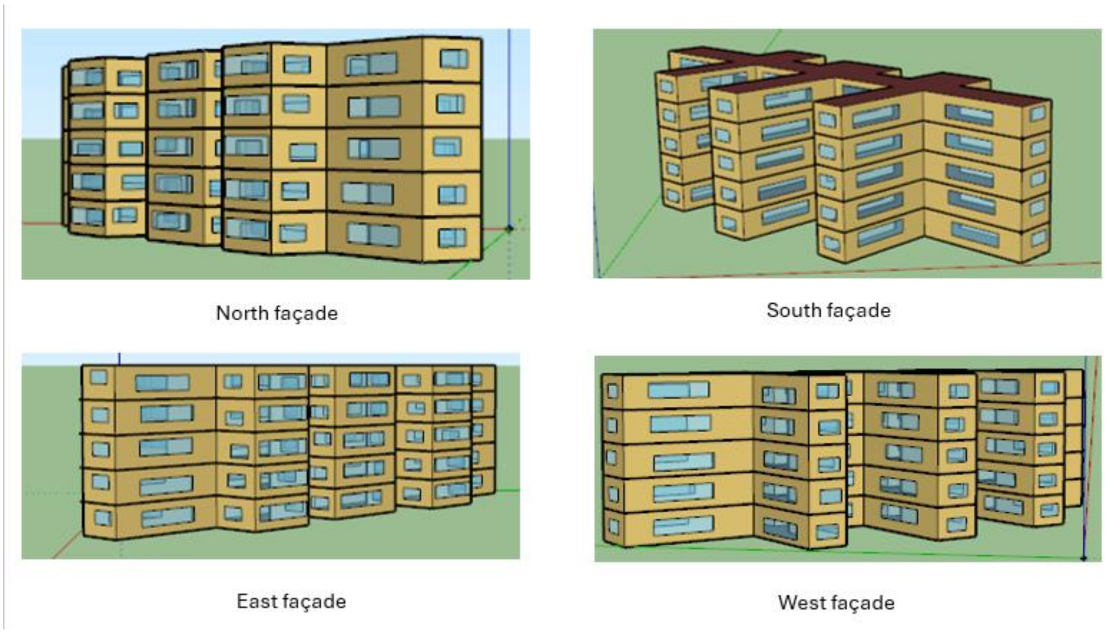


Figure 57 Facades of the reference building for hospitals in the Parma district.

The following table outlines the detailed characteristics of the fourth building archetype identified in the Parma district, representing hospitals constructed between 1960 and 1970.

Table 29 Detailed characteristics of hospital buildings in Parma district

Characteristics	**Unit**	**Case study**
Country	-	Italy
City	-	Parma
Construction year	-	1960-1970
Typology	-	Hospital
Number of heated floors	-	5
S/V ratio	[m^{-1}]	0.33
Area of S façade	[m^2]	2335.64
Area of E façade	[m^2]	2297.44
Area of N façade	[m^2]	2142.36
Area of W façade	[m^2]	2112.28
Area of Roof	[m^2]	1371.23
Area of Basement	[m^2]	1371.23
Net floor area of heated zones	[m^2]	6856.15
Height	[m]	25
Window area on S façade	[%]	21.71
Window area on E façade	[%]	28.57
Window area on N façade	[%]	23.01
Window area on W façade	[%]	25.28
People design level	[person/ m^2]	0.1
Lighting design level	[W/ m^2]	12
Appliances design level	[W/ m^2]	3
Construction materials		
Ext walls	-	Brick
Floor	-	Concrete
Roof	-	Wood
Ventilation rate	[m^3/h-m^2]	4
Infiltration rate	[h^{-1}]	0.4
U value of wall	[W/m^2-K]	1.64
U value of roof	[W/m^2-K]	1.66
U value of basement	[W/m^2-K]	1.27
U value of glass	[W/m^2-K]	2.24
g value of glass		0.6

Archetype 5

The following figure displays a school building (archetype 5), constructed between 1970 and 1980.

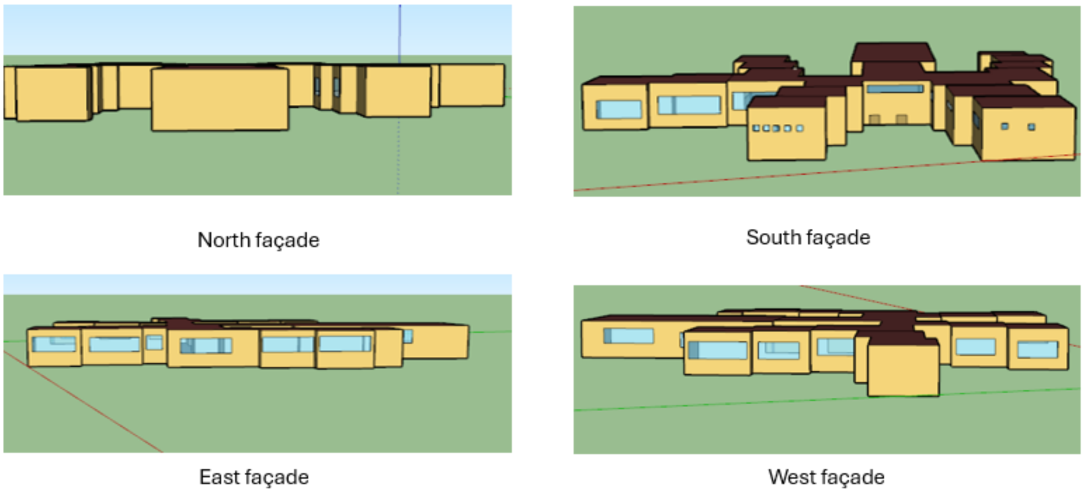


Figure 58 Facades of the reference building for schools in the Parma district.

The following table outlines the detailed characteristics of the fifth building archetype identified in the Parma district, representing schools constructed between 1970 and 1980.

Table 30 Detailed characteristics of school buildings in Parma district

Characteristics	**Unit**	**Case study**
Country	-	Italy
City	-	Parma
Construction year	-	1970-1980
Typology	-	School
Number of heated floors	-	1
S/V ratio	[m^{-1}]	0.2
Area of S façade	[m^2]	1139.80
Area of E façade	[m^2]	2180.05
Area of N façade	[m^2]	1130.34
Area of W façade	[m^2]	2061.33
Area of Roof	[m^2]	4089.71
Area of Basement	[m^2]	4089.71
Net floor area of heated zones	[m^2]	4089.71
Height	[m]	9
Window area on S façade	[%]	12.33
Window area on E façade	[%]	17.50
Window area on N façade	[%]	0
Window area on W façade	[%]	13.78
People design level	[person/ m^2]	0.5
Lighting design level	[W/ m^2]	20
Appliances design level	[W/ m^2]	0.5
Construction materials		
Ext walls	-	Brick
Floor	-	Concrete
Roof	-	Wood
Ventilation rate	[m^3/h-m^2]	12.5
Infiltration rate	[h^{-1}]	0.3
U value of wall	[W/m^2-K]	1.06
U value of roof	[W/m^2-K]	0.99
U value of basement	[W/m^2-K]	0.30
U value of glass	[W/m^2-K]	5.26
g value of glass		0.6

Archetype 6

The following figure shows archetype 6, which represents the university campus constructed after 1991.

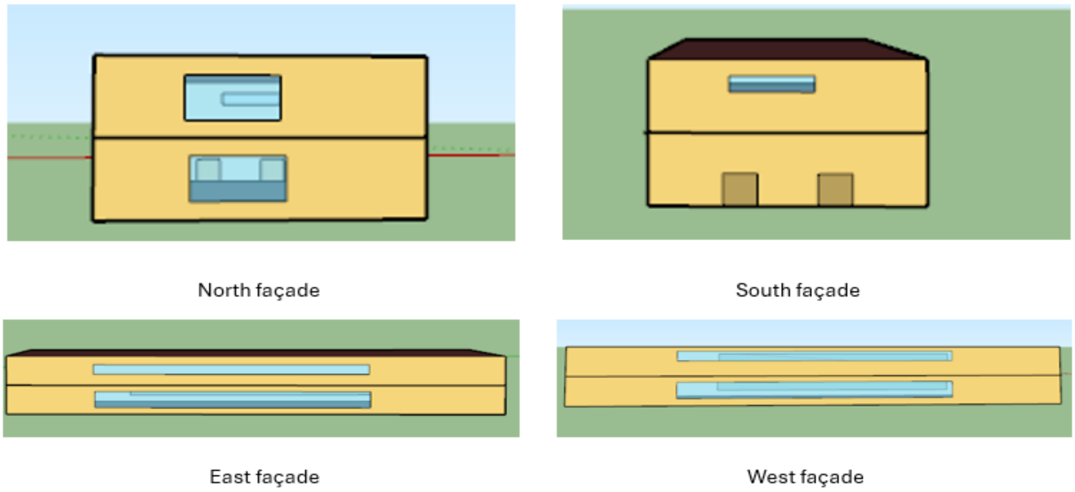


Figure 59 Facades of the reference building for university campus in the Parma district.

The following table outlines the detailed characteristics of the sixth building archetype identified in the Parma district, representing university campus buildings constructed after 1991.

Table 31 Detailed characteristics of university campus buildings in Parma district

Characteristics	**Unit**	**Case study**
Country	-	Italy
City	-	Parma
Construction year	-	After 1991
Typology	-	Campus
Number of heated floors	-	2
S/V ratio	[m^{-1}]	0.37
Area of S façade	[m^2]	146.21
Area of E façade	[m^2]	651.50
Area of N façade	[m^2]	155.96
Area of W façade	[m^2]	647.37
Area of Roof	[m^2]	1210.97
Area of Basement	[m^2]	1210.97
Net floor area of heated zones	[m^2]	2421.94
Height	[m]	9
Window area on S façade	[%]	3.42
Window area on E façade	[%]	24.56
Window area on N façade	[%]	16.03
Window area on W façade	[%]	24.72
People design level	[person/ m^2]	0.5
Lighting design level	[W/ m^2]	20
Appliances design level	[W/ m^2]	0.5
Construction materials		

Ext walls	-	Brick
Floor	-	Concrete
Roof	-	Wood
Ventilation rate	[m^3/h-m^2]	12.5
Infiltration rate	[h^{-1}]	0.5
U value of wall	[W/m^2-K]	1.06
U value of roof	[W/m^2-K]	0.98
U value of basement	[W/m^2-K]	1.39
U value of glass	[W/m^2-K]	3.04
g value of glass		0.75

Archetype 7

The following figure depicts archetype 7, a productive building constructed between 1982 and 1991.

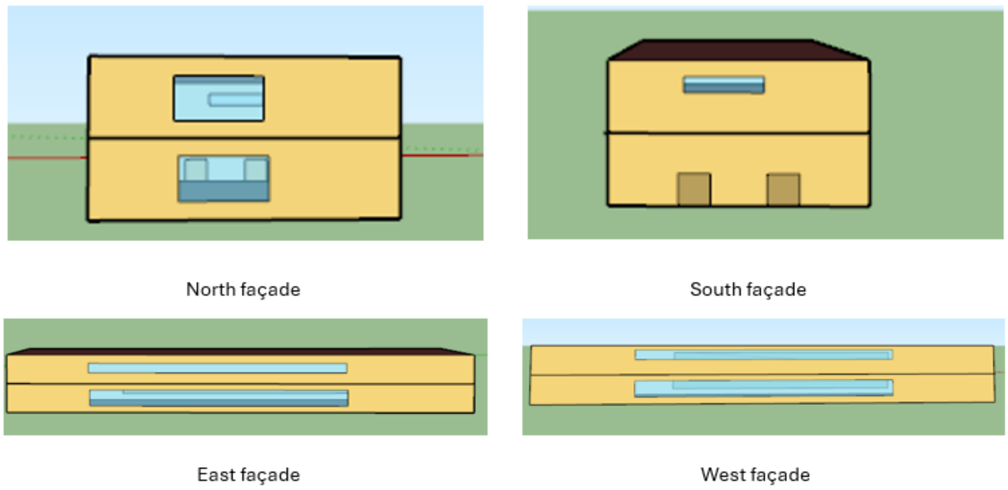


Figure 60 Facades of the reference building for productive buildings in the Parma district

The following table details the characteristics of the seventh building archetype identified in the Parma district, representing productive buildings constructed between 1982 and 1991.

Table 32 Detailed characteristics of productive buildings in Parma district

Characteristics	**Unit**	**Case study**
Country	-	Italy
City	-	Parma
Construction year	-	1982-1991
Typology	-	Office
Number of heated floors	-	2
S/V ratio	[m^{-1}]	0.37
Area of S façade	[m^2]	146.21
Area of E façade	[m^2]	651.50
Area of N façade	[m^2]	155.96
Area of W façade	[m^2]	647.37
Area of Roof	[m^2]	1210.97
Area of Basement	[m^2]	1210.97
Net floor area of heated zones	[m^2]	2421.94
Height	[m]	9
Window area on S façade	[%]	3.42

Window area on E façade	[%]	24.56
Window area on N façade	[%]	16.03
Window area on W façade	[%]	24.72
People design level	[person/ m^2]	0.1
Lighting design level	[W/ m^2]	12
Appliances design level	[W/ m^2]	12
Construction materials		
Ext walls	-	Brick
Floor	-	Concrete
Roof	-	Wood
Ventilation rate	[m^3/h-m^2]	12.5
Infiltration rate	[h^{-1}]	0.5
U value of wall	[W/m^2-K]	1.44
U value of roof	[W/m^2-K]	1.24
U value of basement	[W/m^2-K]	1.15
U value of glass	[W/m^2-K]	3.56
g value of glass		0.7

5. Calibration and validation of archetypes

In the calibration process, the aim is to maintain a difference of less than 10% between real data and simulated values. Since each archetype represents buildings with varying heated areas, it was necessary to initially apply weighted averages based on these areas. This method provided a single representative value for thermal or electricity consumption, to be used as a comparison between simulation results and real data.

Not all archetypes were calibrated for both electricity and thermal energy, primarily due to differences information in EPCs, which follow specific national regulations. In cases where EPCs did not provide complete information for electricity, energy consumption of the internal loads was estimated based on potential loads, determined by the building's intended use and guided by standards such as ISO 18523-1 or EN 16798-1:2019. Additionally, where available, energy bills were used alongside EPCs to enhance the accuracy of the consumption data.

Case study 1 – Pamplona

Calibration was conducted by comparing the simulated electricity consumption and heating demand of the building with actual energy bills from the apartments. For thermal consumption, the analysis focused on the methane consumption of the apartments. The portion of methane consumption attributable solely to space heating was estimated by separating it from the domestic hot water (DHW) usage. The heating-related methane consumption was then averaged and compared with the building's simulated heating demand. This step was critical, as the boiler provides both DHW and space heating, requiring a precise allocation of energy usage between the two functions prior to the comparison.

Table 33 Calibration results for heating demand in the Pamplona district

	Heating demand simulated [kWh/m^2]	Heating demand from Bills [kWh/m^2]	Deviation from Bills [%]
Archetype 1	73.89	66.90	-9.37%

For electricity consumption, the building's consumption was assessed using the median of the apartments' electricity consumption and compared with the national average from the Spanish standard and bills.

Table 34 Calibration results for electricity consumption: comparison of simulated electricity consumption with energy bills in the Pamplona district

	Electricity consumption simulated [kWh/m^2]	Electricity consumption from Bills [kWh/m^2]	Deviation from Bills [%]
Archetype 1	29.06	27.13	7.12%

Table 35 Calibration results for electricity consumption: comparison of simulated electricity consumption with Spanish Standard in the Pamplona district

	Electricity consumption simulated [kWh/m^2]	**Electricity consumption from Spanish standard [kWh/m^2]**	**Deviation from Spanish Standard[%]**
Archetype 1	29.06	36.11	19.51%*

* The building's electricity consumption is significantly lower than expected. This can be attributed to the fact that the building consists of social housing units, which tend to have lower energy usage compared to typical residential buildings.

Comparison of TREEPED with the CEA in the Pamplona case study

The developed tool, TREEPED, was compared to the CEA to evaluate its performance in modeling the energy demand of the San Pedro district in Pamplona. This comparison was carried out exclusively for this case study due to the availability of detailed field data collected during the study period. Pamplona was selected because it represents a typical mid-sized urban area, with well-documented building characteristics and energy usage profiles. The data collected during the research period provided a robust basis for an in-depth evaluation of the two tools.

This case study offered a unique opportunity to assess the performance of the developed tool under realistic conditions, particularly in the early stages of PED planning when data availability is limited. While the CEA could theoretically be applied to other case studies, the lack of equivalent field data in those districts would have introduced inconsistencies and reduced the validity of the comparison. Thus, focusing on Pamplona ensured a meaningful analysis that could highlight the strengths and limitations of both tools.

The annual deviations observed between TREEPED and CEA were minimal, with differences of -8% for heating demand, -12% for cooling demand and 1% for electricity consumption. These results demonstrate TREEPED's ability to produce reliable outputs while maintaining simplicity and requiring fewer input data compared to CEA.

To gain deeper insights, a monthly comparison was conducted, as shown in the next Figures.

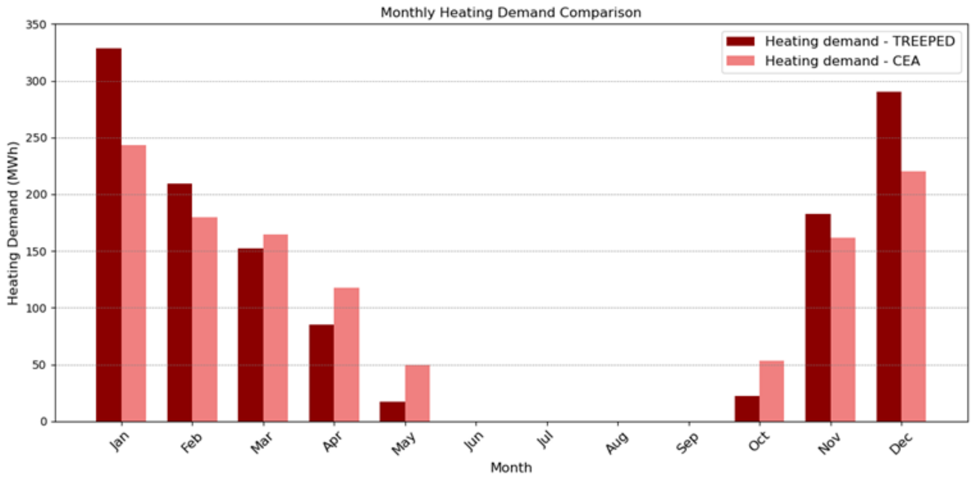


Figure 61 Monthly comparison of heating demand between TREEPED and CEA.

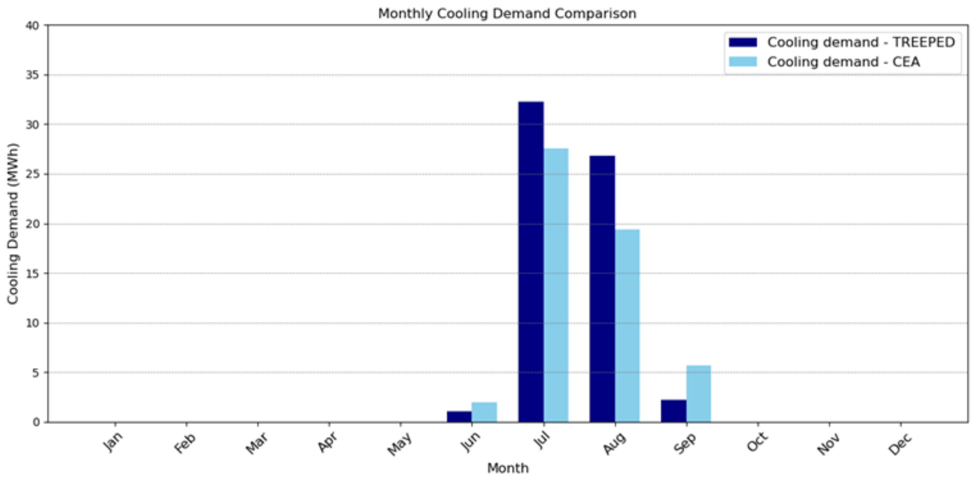


Figure 62 Monthly comparison of cooling demand between TREEPED and CEA.

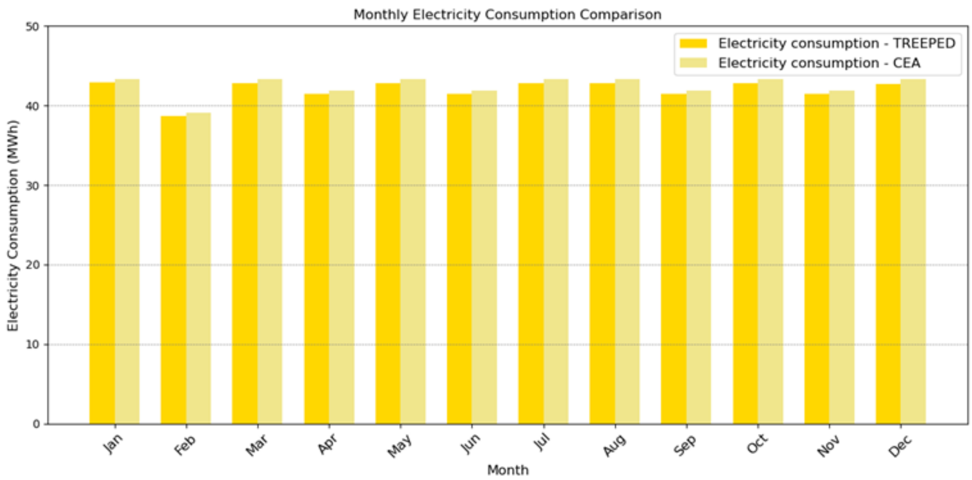


Figure 63 Monthly comparison of electricity consumption between TREEPED and CEA

Figure 61 compares the monthly heating demand results between TREEPED and CEA. The largest differences occurred in the peak winter months, such as January and December, where TREEPED overestimated heating demand by 35% and 32%, respectively. Conversely, during transitional months, such as May and October, TREEPED underestimated heating demand, with deviations reaching -66% and -58%. These discrepancies reflect methodological differences in how the two tools account for seasonal variations, particularly in extreme or transitional conditions. However, these variations offset each other over the year, resulting in a modest annual difference.

Figure 62 illustrates the monthly cooling demand. TREEPED tended to underestimate cooling demand during months with lower requirements, such as June (-49%), but slightly overestimated during peak summer months like July, with a deviation of 30%. Despite these monthly fluctuations, the overall annual cooling demand showed reasonable alignment between the two tools, with a deviation of just 12%.

Figure 63 compares monthly electricity consumption, showing strong consistency between TREEPED and CEA. The deviation remained minimal at 1%, reflecting the stability of non-thermal energy use patterns, such as lighting and appliances, over the year.

These results highlight that while methodological differences between the tools become more pronounced at finer temporal resolutions, such as monthly scales, their impact diminishes when aggregated to an annual scale. This demonstrates that both tools provide comparable insights for annual energy performance assessments, with TREEPED maintaining an acceptable level of accuracy despite its simplified approach.

Case Study 2 – Bucharest

The calibration process in Bucharest considered both heating demand and electrical consumption for all six archetypes. The electricity consumption data specifically accounted for lighting and internal appliances, excluding HVAC systems.

The following tables provide the calibration results for heating demand and electricity consumption in the Bucharest district, respectively. The tables compare the simulated values with those obtained from the EPCs.

Table 36 Calibration results for heating demand in the Bucharest district

	Heating demand simulated [kWh/m^2]	**Heating demand from EPC [kWh/m^2]**	**Deviation from EPC [%]**
Archetype 1 renovated	87.38	89.59	-2.46
Archetype 1	108.19	116.05	-6.78
Archetype 2 renovated	77.14	80.31	-3.95
Archetype 2	110.79	118.90	-6.82
Archetype 3 renovated	93.24	86.07	8.33
Archetype 3	129.03	120.00	7.53

Table 37 Calibration results for electricity consumption in the Bucharest district

	Electricity consumption simulated [kWh/m^2]	**Electricity consumption from EPC [kWh/m^2]**	**Deviation from EPC [%]**
Archetype 1 renovated	91.01	96.16	-5.36

Archetype 1	91.01	94.30	-3.49
Archetype 2 renovated	70.89	74.53	-4.88
Archetype 2	76.64	72.74	5.36
Archetype 3 renovated	76.64	78.96	-2.94
Archetype 3	85.26	80.30	6.18

Case Study 3 – Copenhagen

The calibration of the archetypes for Copenhagen used EPC data. For the electricity consumption of residential buildings, the calibration referenced the electrical consumption data of a specific residential building. For non-residential buildings, particularly archetypes 4 and 5, the calibration considered the energy consumption of appliances, lighting, office equipment, and other devices used by the building's occupants.

The following tables present the calibration results for heating demand and electricity consumption in the Copenhagen district. These tables compare the simulated values with those derived from the EPCs.

Table 38 Calibration results for heating demand in the Copenhagen district

	Heating demand simulated [kWh/m^2]	**Heating demand from EPC [kWh/m^2]**	**Deviation from EPC [%]**
Archetype 1	142.34	133.00	-6.56
Archetype 2	70.06	68.00	-2.94
Archetype 3	128.08	118.09	-7.80%
Archetype 4	194.53	201.00	3.32%
Archetype 5	105.18	96.97	-7.80%

Table 39 Calibration results for electricity consumption in the Copenhagen district

	Electricity consumption simulated [kWh/m^2]	**Electricity consumption from Bills [kWh/m^2]**	**Deviation from EPC [%]**
Archetype 1	23.49	25.86	-9.14
Archetype 2	25.86	25.86	0
Archetype 4	25.59	23.12	-9.6
Archetype 5	67.27	60.60	-9.91%

Case Study 4 – Parma

In the case of Parma, calibration was performed using EPC data exclusively for thermal energy consumption.

The following table presents the calibration results for heating demand in the Parma district. The table compares the simulated values with those derived from the EPCs.

Table 40 Calibration results for electricity consumption in the Parma district

	Heating demand simulated [kWh/m^2]	Heating demand from EPC [kWh/m^2]	Deviation from EPC [%]
Archetype 1	130.88	141.49	-7.50%
Archetype 2	105.25	113.98	-7.66%
Archetype 3	299.14	312.82	4.57%
Archetype 4	182.08	175.64	3.66%
Archetype 5	314.42	289.13	8.75%
Archetype 6	233.75	217.63	7.41%
Archetype 7	155.64	147.91	5.24%

6. Simulation of Districts

For the simulation of the district, it is necessary to specify how many buildings belong to a particular archetype and identify the floor area in square meters from GIS data for buildings that belong to each archetype. The thermal and electrical consumption results, evaluated per square meter of heated floor area, are then multiplied by the actual estimated floor area. In the absence of specific data, it is assumed that all floors of the buildings are heated.

Case Study 1- Pamplona

Table 41 presents the heating demand for the building archetype in the Pamplona district. The analysis provides detailed data on the total area of the archetype and the corresponding heating requirements, considering the district's specific characteristics.

Table 41 Heating demand in the Pamplona district

	Heating demand [kWh/m^2]	Number of buildings	Total area [km^2]	Heating demand [GWh]
Archetype 1	73.89	10	0.02	1.29

The following graph represents an hourly annual analysis of the thermal demand, distinguishing between heating demand and cooling demand.

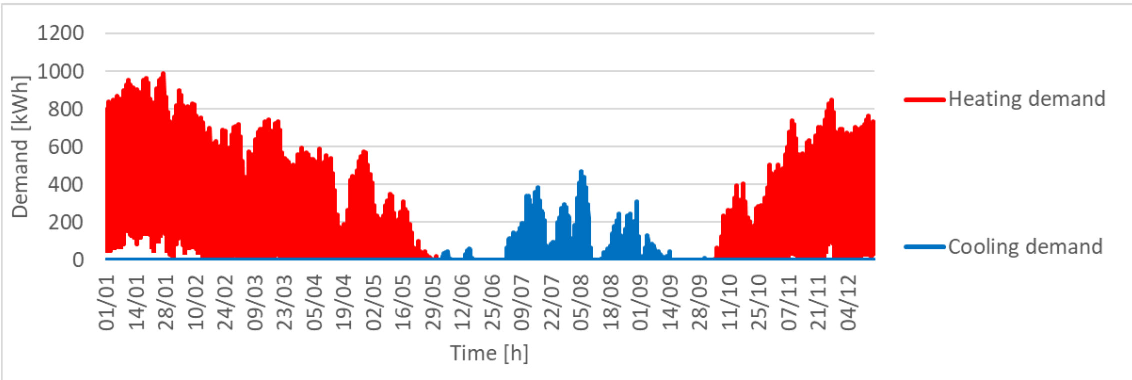


Figure 64 Hourly annual analysis of the thermal demand in Pamplona.

The figure illustrates that heating demand peaks reach nearly 1,000 kWh, reflecting substantial thermal requirements driven by colder winter temperatures. In contrast, cooling demand remains significantly lower, with peaks typically below 500 kWh. This disparity reveals a pronounced seasonal imbalance, with heating needs in winter far exceeding summer cooling demands. Such an imbalance underscores the necessity for targeted strategies to enhance heating efficiency and integrate renewable energy effectively during peak winter periods, optimizing energy use and reducing reliance on external sources.

The following figure shows the hourly heating demand of the Pamplona district over a typical winter week.

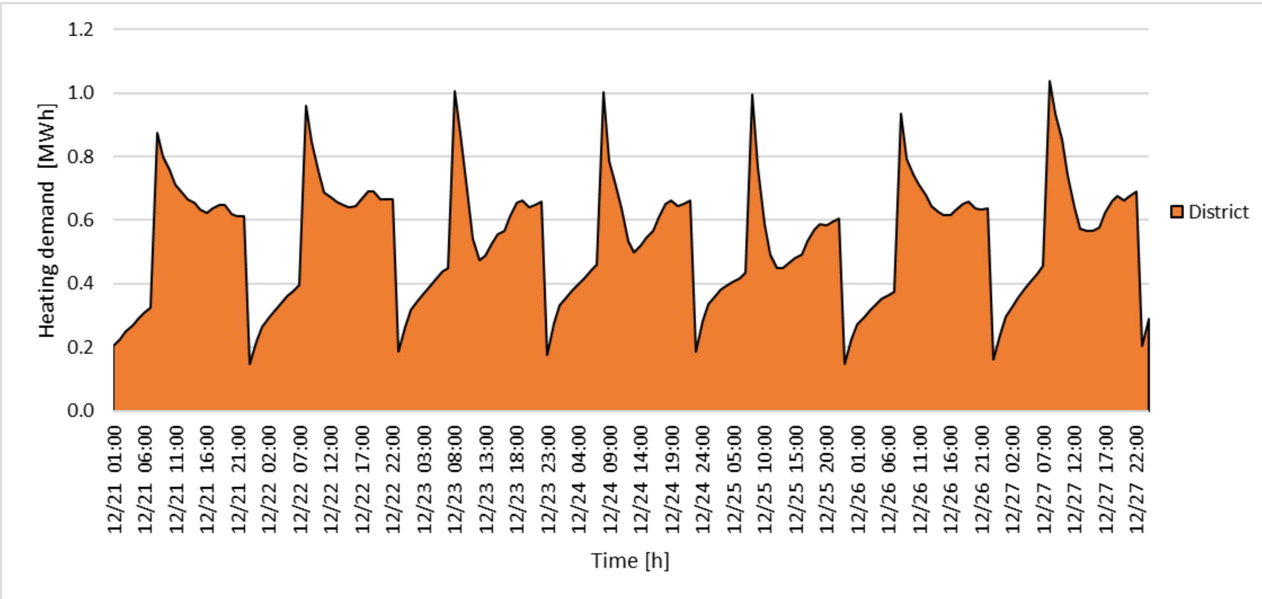


Figure 65 Typical week heating demand profile for the Pamplona district.

The heating demand follows a typical daily pattern for residential buildings, with peaks in the morning and evening when residents are most likely at home. Lower demand occurs during the night and early afternoon, reflecting reduced heating needs and occupancy during these periods.

The following figure represents the ordered heating demand for a district over a one-year period. The curve indicates how heating demand varies throughout the year. In addition, specific percentile levels are marked to provide further insights into the distribution of heating demand.

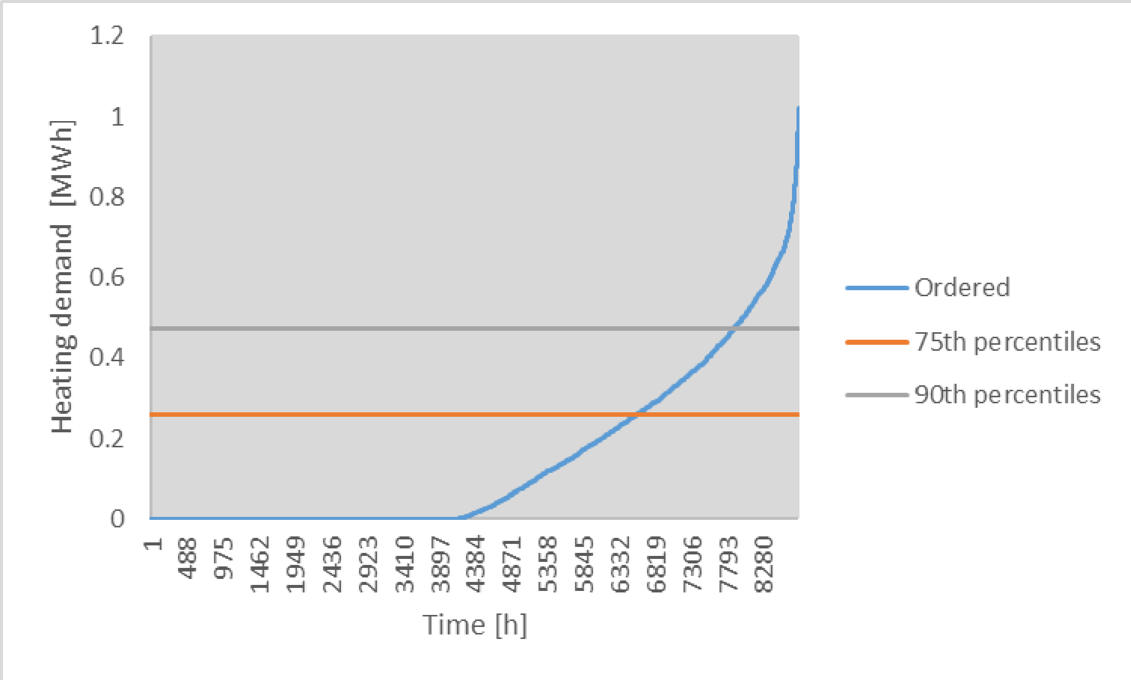


Figure 66 Annual distribution of heating demand with 75th and 90th percentiles.

The distribution shows a considerable portion of the year with relatively low heating needs, suggesting that for most of the year, the heating system is expected to operate with lower energy demands. The gradual rise in demand towards the higher end of the curve reflects peak heating requirements during colder periods.

The distinction between the 75^{th} and 90^{th} percentile levels is crucial for understanding both the typical and peak heating loads. For most of the year, the heating demand remains moderate, aligning with the 75^{th} percentile, whereas the 90^{th} percentile indicates the threshold for managing more significant demand spikes.

Table 42 presents an overview of the cooling demand for the single building archetype in the Pamplona district, providing detailed information on the total area and the corresponding cooling requirements.

Table 42 Cooling demand in the Pamplona district

	Cooling demand [kWh/m^2]	**Number of buildings**	**Total area [km^2]**	**Cooling demand [GWh]**
Archetype 1	3.57	10	0.02	0.06

Figure 67 shows the cooling demand over a typical summer week, providing insights into how cooling energy needs fluctuate for residential buildings in Spain.

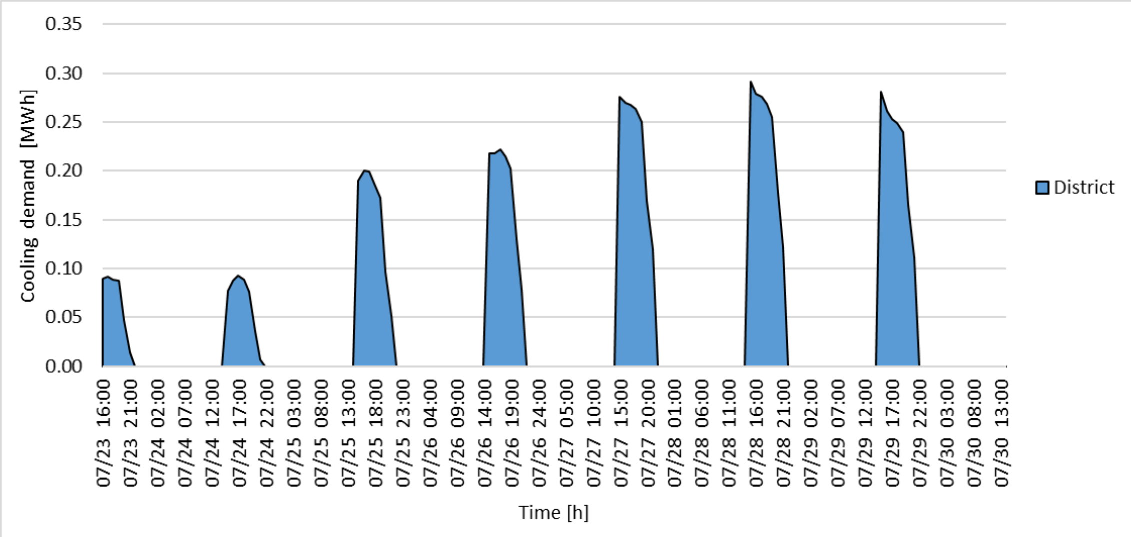


Figure 67 Typical week cooling demand profile for the Pamplona district.

The graph exhibits a diurnal cycle in cooling demand, with peaks occurring consistently in the afternoon hours. These peaks are linked to external factors such as ambient temperature rise and increased solar gains, which drive the cooling requirements to their maximum during this period.

The next figure shows the monthly electricity consumption for the Pamplona district.

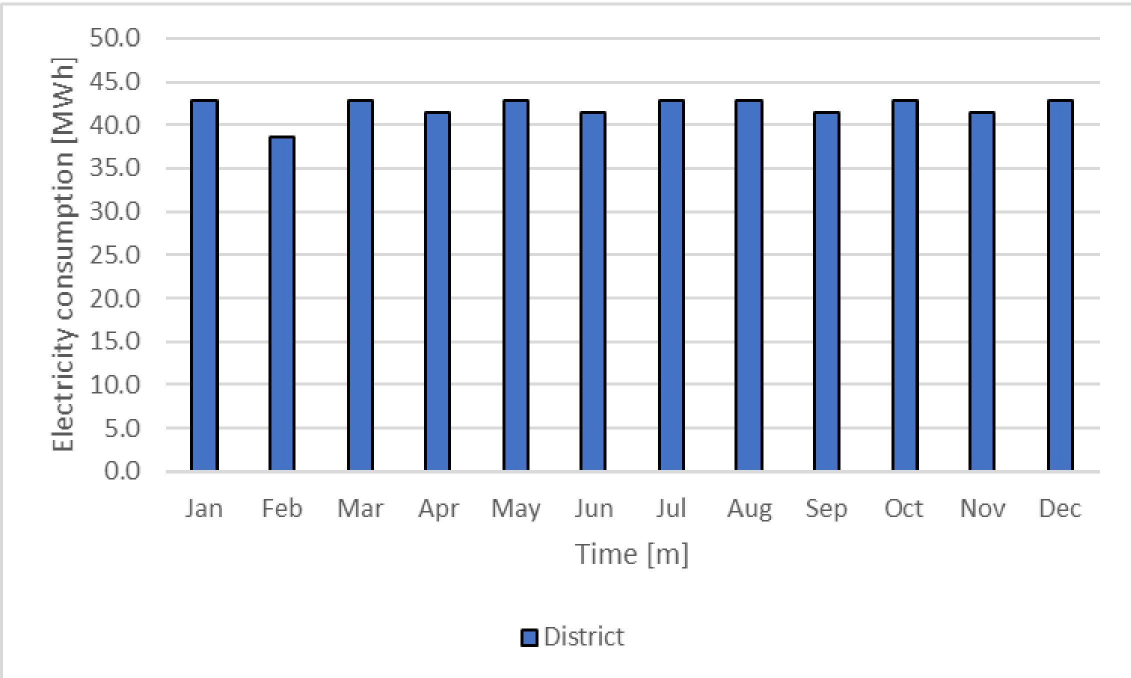


Figure 68 Distribution of total electricity consumption in the Pamplona district.

The figure shows a constant monthly electricity consumption for the district, which is a direct consequence of the absence of systems that rely on electricity for heating or cooling. This results in a steady demand throughout the year, primarily driven by typical building operations and appliances.

Case Study 2 – Bucharest

Table 43 presents the heating demand across different building archetypes in the Bucharest district, providing detailed data on the total area and corresponding heating requirements.

Table 43 Heating demand in the Bucharest district

	Heating demand [kWh/m^2]	Number of buildings	Total area [km^2]	Heating demand [GWh]
Archetype 1	87.38	88	0.63	54.62
Archetype 2	108.19	102	0.61	65.71
Archetype 3	77.14	30	0.15	11.41
Archetype 4	110.79	93	0.43	47.62
Archetype 5	93.24	40	0.43	40.17
Archetype 6	129.03	90	0.81	103.89

The following graph illustrates the hourly heating and cooling demands for the Bucharest district over the course of a year.

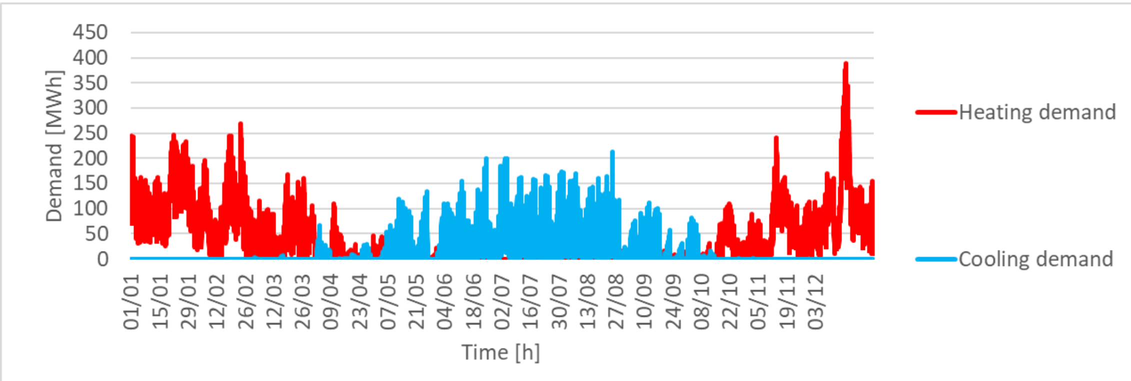


Figure 69 Hourly annual analysis of the thermal demand in Bucharest

The figure shows that the heating demand is particularly significant, with peaks reaching 400 MWh, indicating the substantial energy requirements for maintaining warmth during Bucharest's colder months. On the other hand, cooling demand has lower peaks, reaching around 200 MWh, suggesting that the energy needed for cooling is generally less intensive compared to heating. This difference is likely due to the specific climatic conditions of

Bucharest, where cold winters necessitate greater heating, while the demand for cooling during summer, although present, does not reach the same magnitude.

Figure 70 visually represents the heating demand during a typical winter week, highlighting how energy needs fluctuate based on the specific characteristics of each building type.

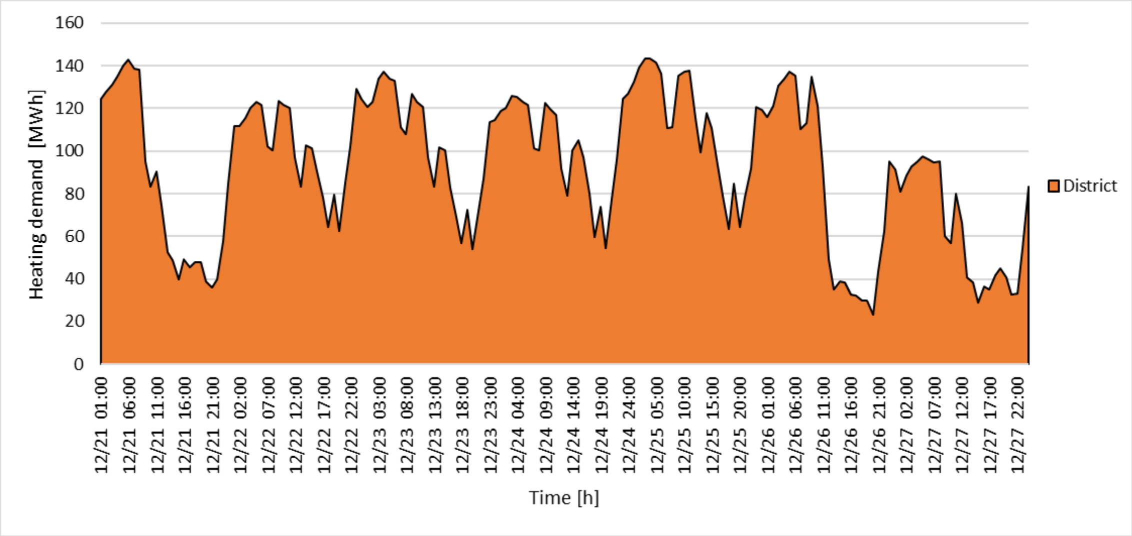


Figure 70 Typical week heating demand profile for the Bucharest district.

The following figure shows the heating demand distribution over time, along with the 75th and 90th percentile markers.

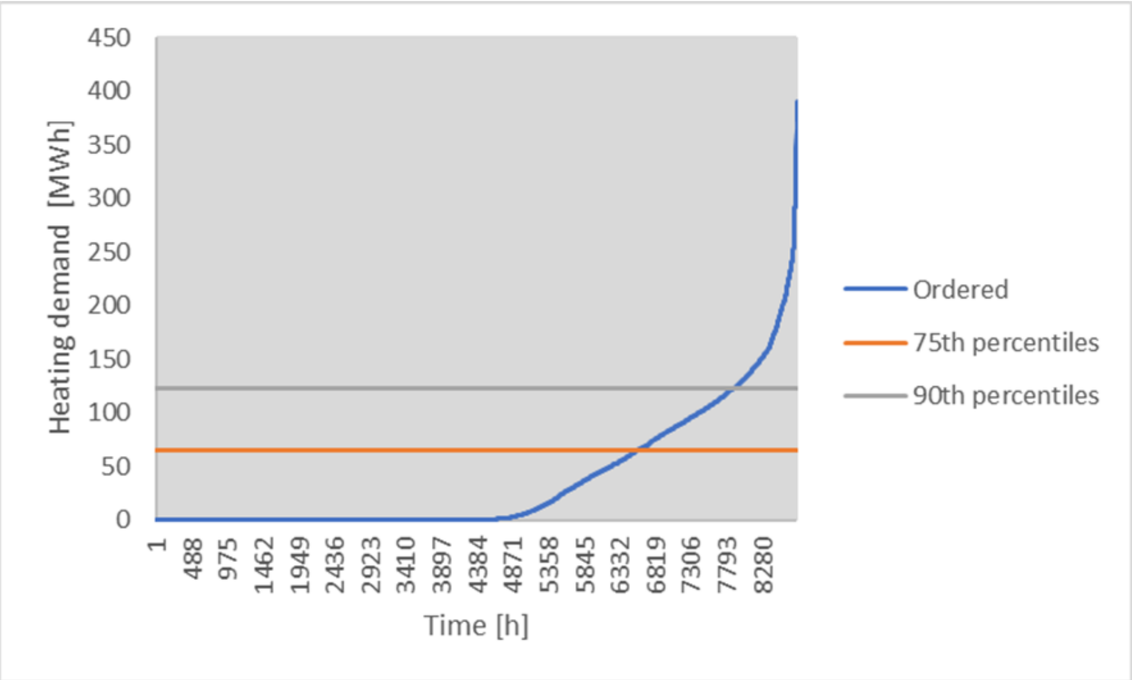


Figure 71 Annual distribution of heating demand with 75th and 90th percentiles.

The graph illustrates that for a significant portion of the year, the heating demand remains relatively low, with values predominantly below the 75th percentile threshold. This is represented by most of the data points on the left-hand side of the graph, where the demand remains well under 64 MWh, indicating a consistent, low demand for heating over an extended period.

Table 44 provides an overview of the cooling demand across different building archetypes in the Bucharest district, presenting detailed data on the total area and the corresponding cooling requirements.

Table 44 Cooling demand in the Bucharest district

	Cooling demand [kWh/m^2]	**Number of buildings**	**Total area [km^2]**	**Cooling demand [GWh]**
Archetype 1	48.28	88	0.63	30.18
Archetype 2	47.59	102	0.61	28.91
Archetype 3	22.63	30	0.15	3.35
Archetype 4	29.88	93	0.43	12.84
Archetype 5	34.85	40	0.43	15.01
Archetype 6	38.94	90	0.81	31.35

Figure 72 illustrates this cooling demand during a typical summer week, offering insights into how energy needs for cooling vary for residential buildings in Bucharest.

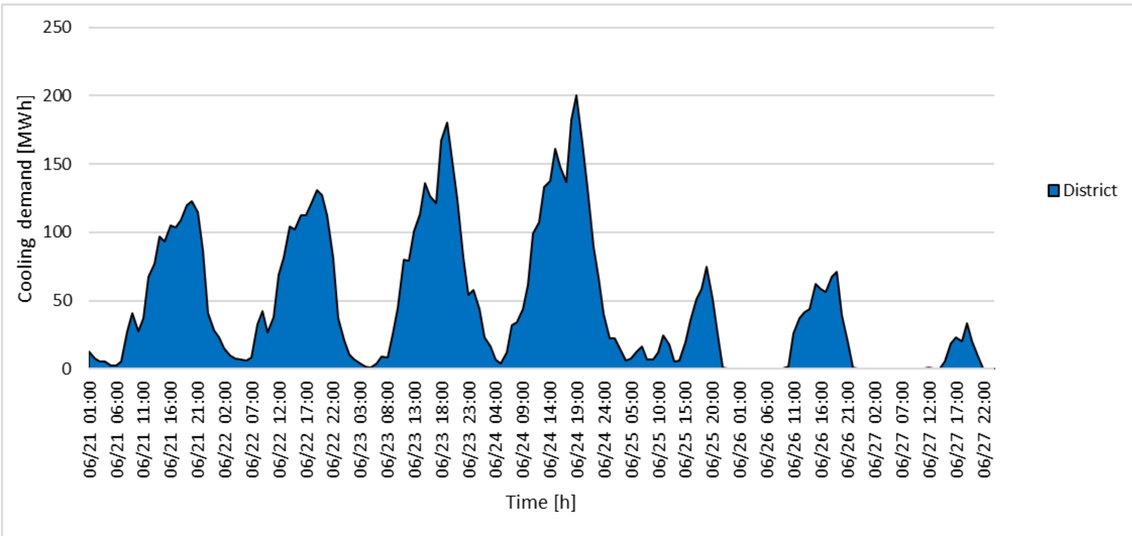


Figure 72 Typical week cooling demand profile for the Bucharest district.

The results show that heating demand in Bucharest is significantly higher than cooling demand. Specifically, the heating demand is three times the cooling demand, with values of 323 GWh for heating and 121 GWh for cooling. This substantial difference underscores the impact of the cold winter climate on energy requirements, where heating dominates over cooling.

Figure 73 illustrates the total electricity consumption in the Bucharest district, which accounts not only for internal gains such as lighting and appliances but also includes the electricity usage associated with the centralized systems for cooling and the consumption related to domestic hot water (DHW). In the absence of specific data for DHW, a conservative assumption was made that electric water heaters are used, ensuring a cautious estimation of the total energy demand.

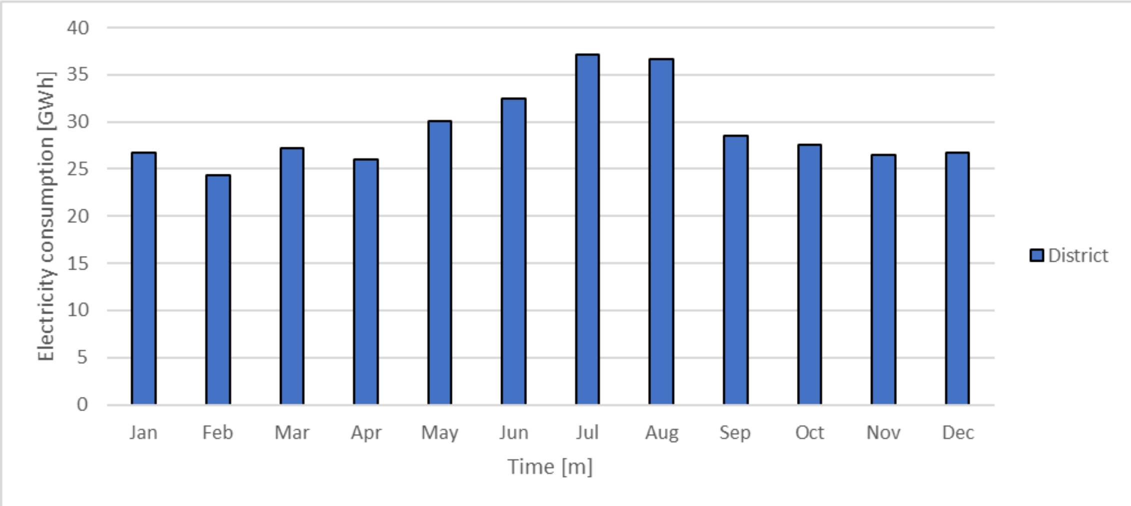


Figure 73 Distribution of total electricity consumption in the Bucharest district.

The data indicate a noticeable increase in electricity demand during the summer months, peaking in July and August at approximately 35-38 GWh. This higher consumption is likely due to the use of heat pumps for cooling during the hot summer period.

In contrast, during the winter months, the electricity consumption is comparatively lower, between 25-30 GWh, reflecting the presence of a district heating system that primarily handles heating needs, reducing the reliance on electricity. The relatively consistent electricity usage observed during the remaining months, at around 30-35 GWh, is indicative of a steady base load due to regular household activities and other electrical needs.

Case Study 3 – Copenhagen

Table 45 provides a detailed breakdown of heating demand across these building types, offering insights into the total area and corresponding heating requirements.

This is further illustrated in Figure 74, which visualizes the heating demand for a typical winter week.

Table 45 Heating demand in the Copenhagen district

	Heating demand [kWh/m²]	Number of buildings	Total area [km²]	Heating demand [GWh]
Archetype 1	142.34	24	0.13	19.16
Archetype 2	70.06	2	0.02	1.51
Archetype 3	128.08	20	0.03	3.37
Archetype 4	194.53	2	0.03	5.49
Archetype 5	105.18	37	0.02	2.54

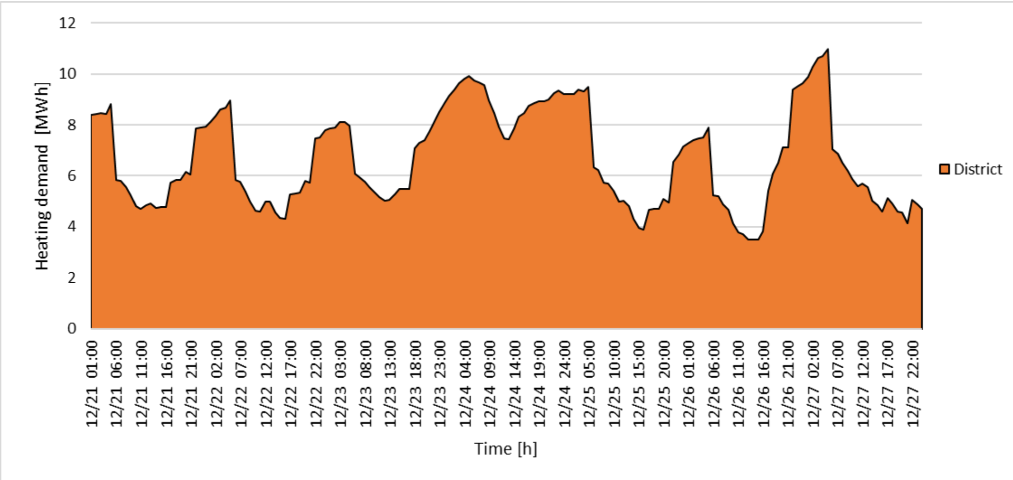


Figure 74 Typical week heating demand profile for the Copenhagen district.

The graph represents the duration curve of district heating demand over an entire year, highlighting 75th and 90th percentiles.

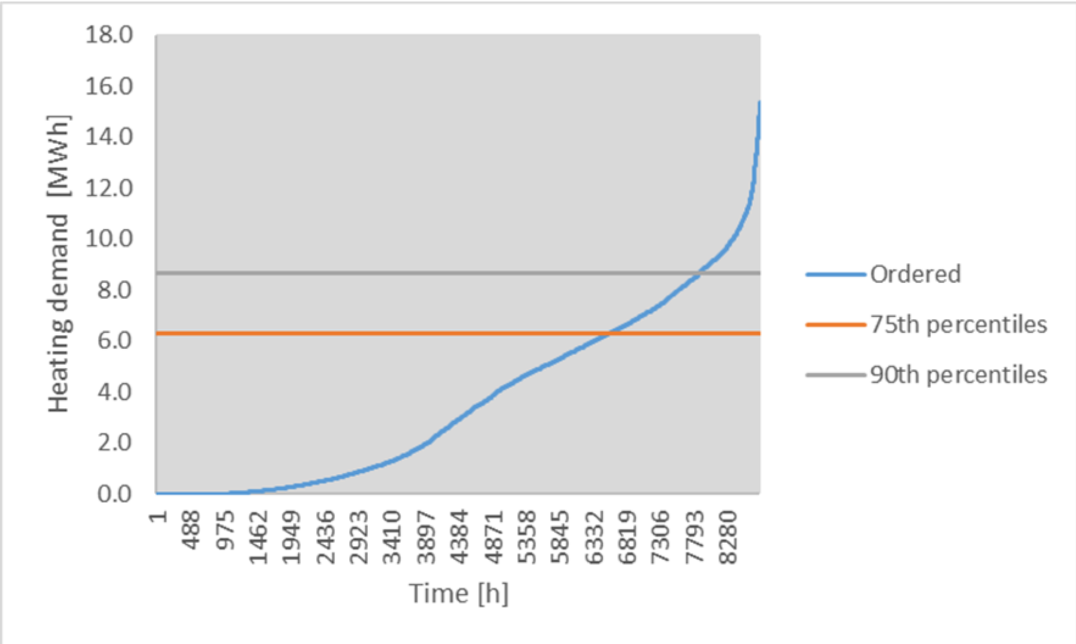


Figure 75 Heating demand duration curve with 75th and 90th percentiles.

The graph shows that for a significant portion of the year, the heating demand remains below the 75th percentile, which is around 6 MWh. This indicates that the heating demand is moderate most of the time.

Table 46 provides a detailed breakdown of cooling demand across different building archetypes in the Copenhagen district, offering insights into the total area and corresponding cooling requirements for each building type.

Table 46 Cooling demand in the Copenhagen district

	Cooling demand [kWh/m^2]	**Number of buildings**	**Total area [Km^2]**	**Cooling demand [GWh]**
Archetype 1	18.89	24	0.13	2.54
Archetype 2	25.68	2	0.02	0.55
Archetype 3	1.76	20	0.03	0.05
Archetype 4	0.24	2	0.03	0.01
Archetype 5	3.42	37	0.02	0.08

Figure 76 complements this by visually representing the cooling demand distribution, highlighting the differences in energy consumption for cooling during a typical summer week.

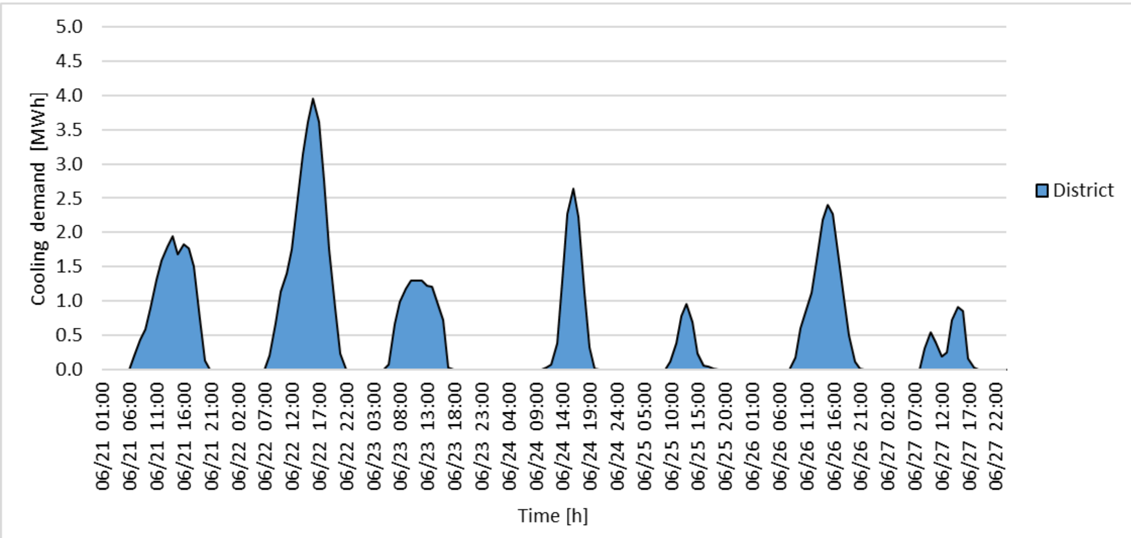


Figure 76 Typical week cooling demand profile for the Copenhagen district.

The results for heating and cooling demands in Copenhagen show significant variations in energy consumption across different building typologies. In a city like Copenhagen, which experiences cold winters, the heating demand is approximately 30 GWh, while the cooling demand is significantly lower, around 3 GWh.

The following graph illustrates the monthly electricity consumption for the district throughout the year.

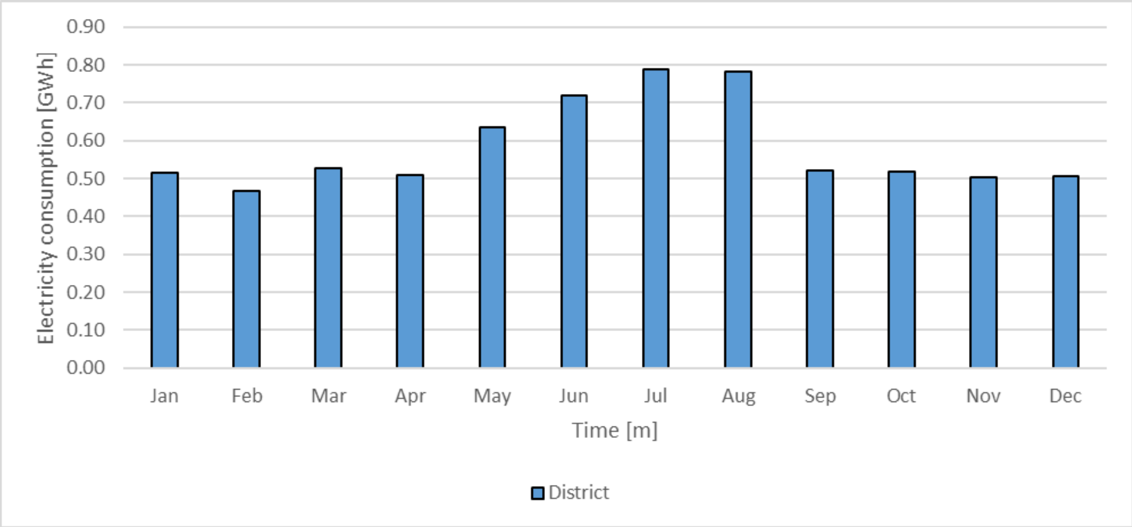


Figure 77 Electricity consumption in the Copenhagen district.

The graph shows stable values across most months. However, there is a noticeable increase in electricity consumption during the summer months, attributed to the additional energy required for cooling systems.

Case Study 4 – Parma

Table 47 and Table 48 present a detailed analysis of the energy demands within the Parma district. Table 47 outlines the heating demand across different building archetypes. Table 48 complements this with an analysis of cooling demand, offering insights into the energy requirements for cooling systems in the same building

Figure 78 and Figure 80 provide a visual representation of the energy demand distribution, illustrating the spatial variability in heating and cooling needs across the district.

Table 47 Heating demand in the Parma district

	Heating demand [kWh/m²]	**Number of buildings**	**Total area [km²]**	**Heating demand [GWh]**
Archetype 1	130.88	917	0.110	14.46
Archetype 2	105.25	65	0.004	0.44
Archetype 3	299.14	23	0.003	1.00
Archetype 4	182.08	7	0.006	1.18
Archetype 5	314.42	14	0.016	5.18
Archetype 6	233.75	94	0.043	10.12
Archetype 7	155.67	127	0.049	7.66

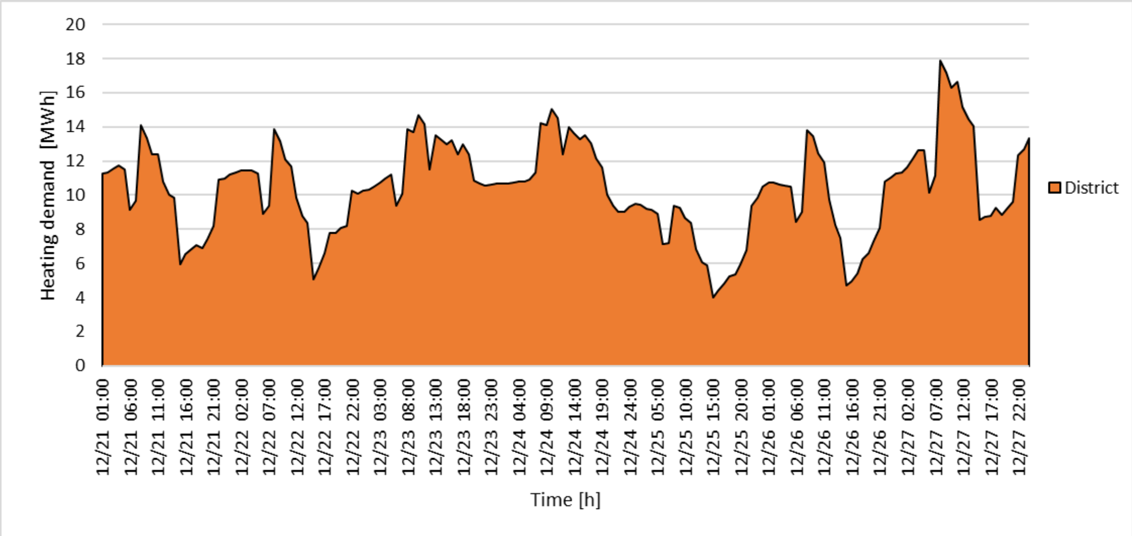


Figure 78 Typical week heating demand profile for the Parma district.

The following graph presents the heating demand duration curve, highlighting the 75th and 90th percentiles.

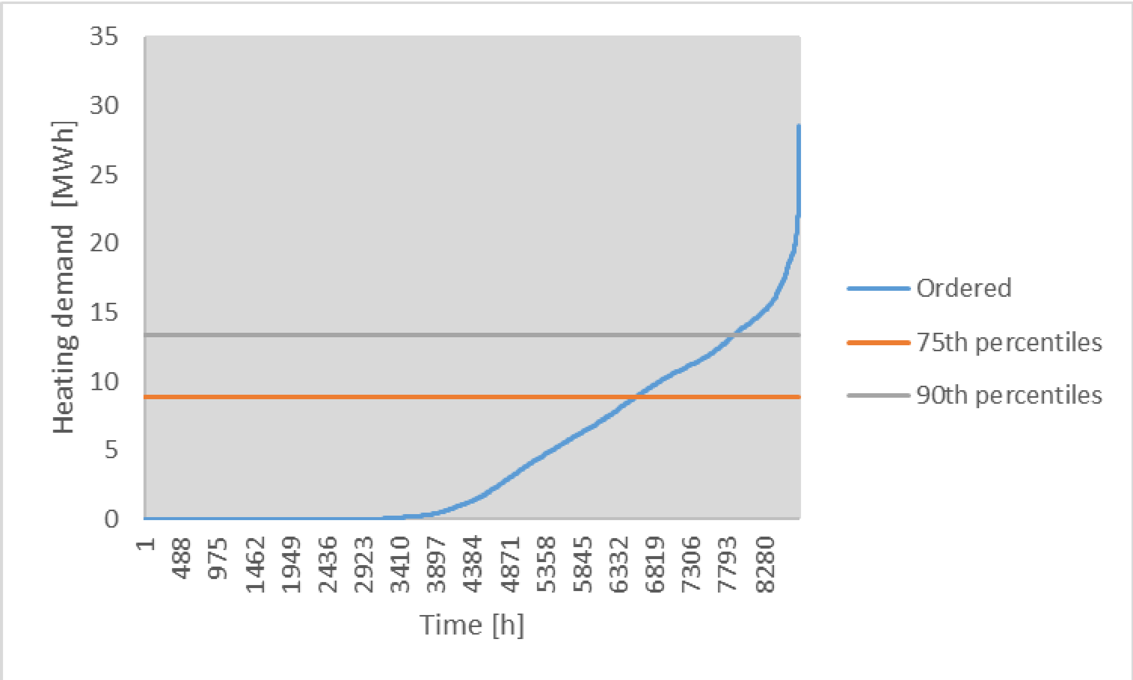


Figure 79 Heating demand duration curve with 75th and 90th percentiles.

The curve indicates that for most of the time (up to the 75th percentile), the heating demand remains below approximately 10 MWh. This suggests that most of the time, the heating demand is at moderate levels, with only a relatively small proportion of the hours exceeding this value.

Table 48 Cooling demand in the Parma district

	Cooling demand [kWh/m^2]	Number of buildings	Total area [km^2]	Cooling demand [GWh]
Archetype 1	27.05	917	0.110	2.99
Archetype 2	21.84	65	0.004	0.09
Archetype 3	16.12	23	0.003	0.05
Archetype 4	34.46	7	0.006	0.22
Archetype 5	63.28	14	0.016	1.04
Archetype 6	49.40	94	0.043	2.14
Archetype 7	56.91	127	0.049	2.80

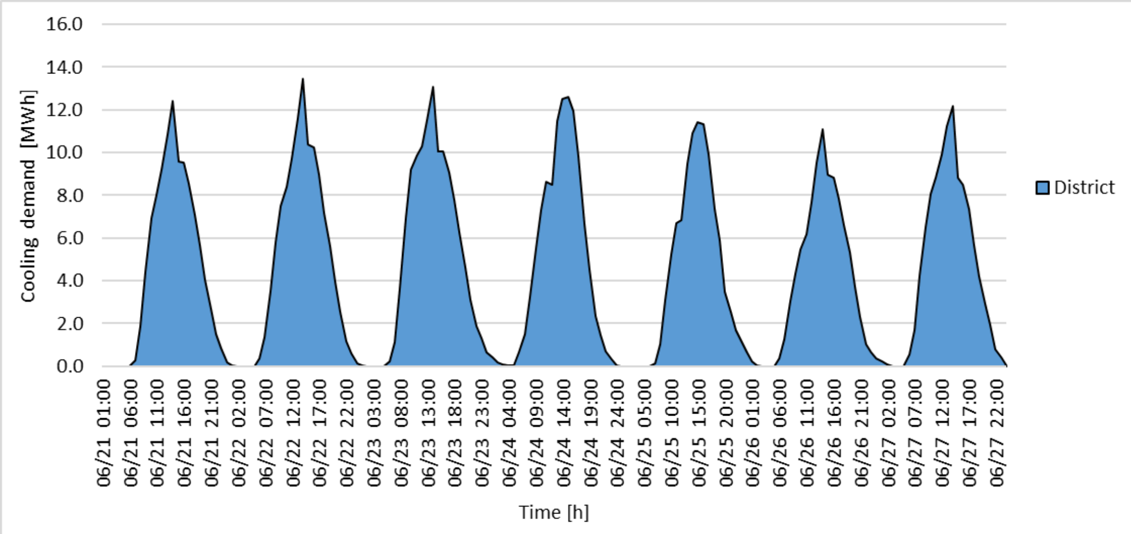


Figure 80 Typical week cooling demand profile for the Parma district.

The district shows a total heating demand of 40.05 GWh, highlighting that the energy requirement to maintain thermal comfort during winter is significant. In contrast, cooling demand is much lower at 9.34 GWh, reflecting a climate in which heating is the main source of energy consumption, while cooling plays a secondary role.

One of the main actions that could be implemented concerns improving the insulation of the building envelope. The application of insulation materials on walls, roofs, and floors would help to significantly reduce heat loss and, therefore, heating demand. Another effective measure could be the replacement of heating systems with more efficient systems, such as heat pumps or condensing boilers, which would immediately reduce energy consumption.

The next chart illustrates the monthly electricity consumption for a district over the course of a year.

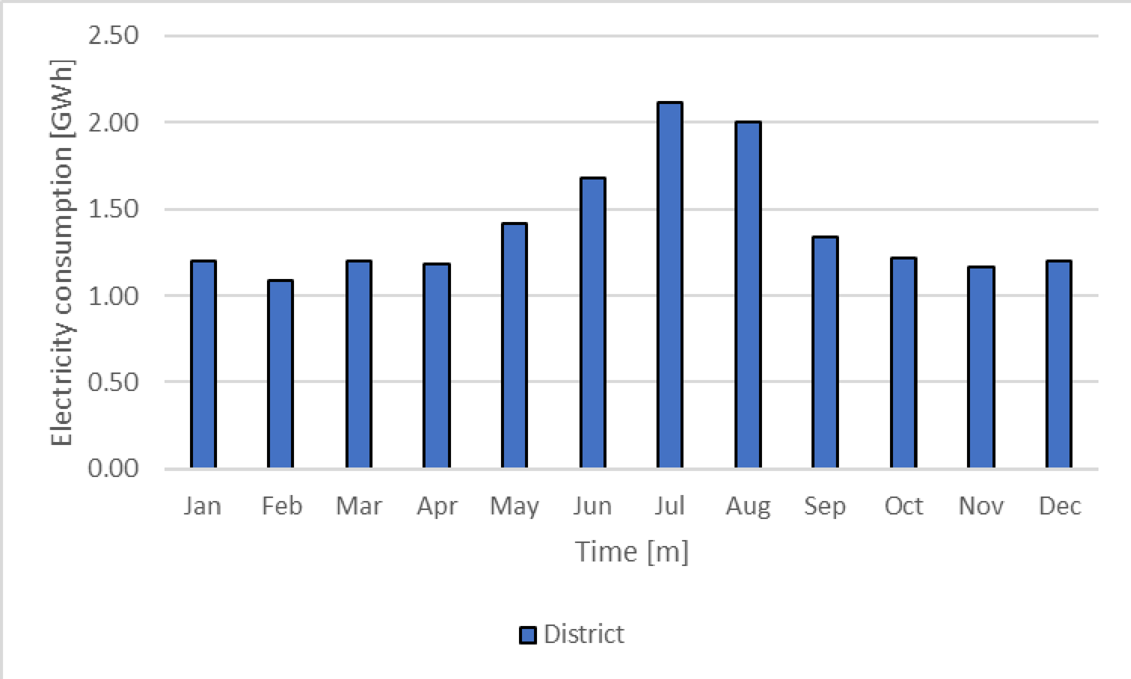


Figure 81 Electricity consumption in the Parma district.

The electricity consumption for the district of Parma, as shown in the graph, follows a similar dynamic to Bucharest. Electricity consumption is relatively stable during the year, with an increase during the summer months.

7. Optimization scenarios for case studies

In the optimization of districts, strategies are tailored to each case, but they typically include key elements such as reducing energy consumption through the application of insulation and the replacement of windows, as well as upgrading heating systems and installing photovoltaic panels. The decisions made for each component are as follows:

- Insulation: EPS (Expanded Polystyrene) was selected due to its cost-effectiveness, thermal efficiency and wide use in construction projects;
- Window frames: Plastic frames were chosen to meet the low transmittance requirements for new windows, considering their widespread use in modern installations;
- Double glazing: The use of double-glazed windows was implemented to comply with transmittance limits, improving energy performance;
- Photovoltaic panels: Monocrystalline panels were selected because of their market dominance and high efficiency, as highlighted in industry reports[184].

Case Study 1 – Pamplona

The energy simulation indicates a significant heating demand, which supports the need for targeted retrofit strategies to improve energy efficiency and reduce carbon emissions. The proposed measures include enhancing building insulation, upgrading windows, replacing existing methane boilers with heat pumps and integrating photovoltaic systems. By upgrading insulation, thermal losses can be minimized, which directly lowers the heating demand. The introduction of heat pumps, powered by on-site photovoltaic energy, will further reduce reliance on fossil fuels and decrease the district's carbon footprint. Together, these measures will effectively meet energy needs while moving the district towards achieving PED target.

Insulation and windows

The following table presents the cooling and heating demands for Archetype 1 in the Pamplona district, comparing the scenarios with and without enhancing building insulation and upgrading windows:

Table 49 Impact of enhancing building insulation and upgrading windows on cooling and heating demand for archetype 1 in the Pamplona district.

Archetype 1	**Cooling [kWh/m²]**	**Heating [kWh/m²]**
Without retrofit	3.57	73.89
With retrofit	0.57	61.34
Difference	-84%	-17%

The heating demand represents a 17% decrease in annual heating demand, from 73.89 kWh/m² to 61.34 kWh/m². Though this percentage may not seem as remarkable as the reduction for cooling, it reflects a meaningful decrease considering the substantial initial heating load.

The cooling demand decreases by 84%, from 3.57 kWh/m² to 0.57 kWh/m². While this percentage indicates a substantial improvement, it is important to consider that the original cooling demand was relatively low, meaning the absolute energy savings are smaller in scope. Nonetheless, this retrofit effectively limits heat gains, enhancing thermal performance during summer and reducing cooling energy requirements.

The next figure presents the monthly heating and cooling demand for the district, comparing the conditions before and after renovation.

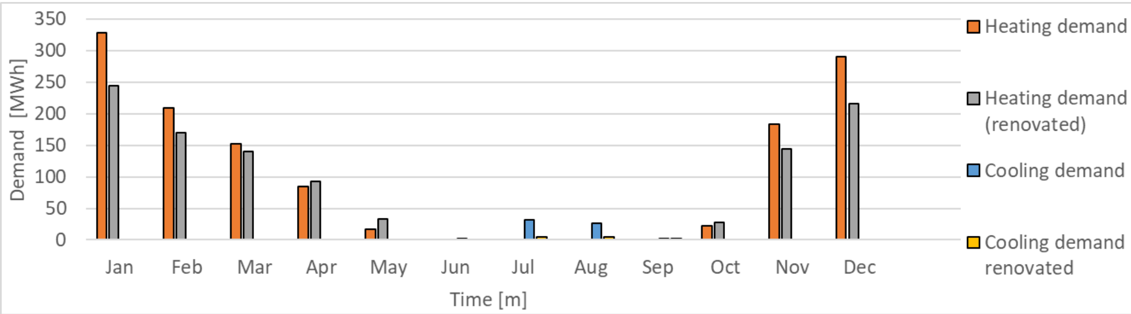


Figure 82 Monthly comparison of thermal demand with and without enhancing building insulation and upgrading windows in Pamplona.

The impact of insulation and windows on heating demand is huge. For instance, in January, heating demand decreases from around 350 MWh without retrofit to approximately 250 MWh with the renovation, indicating a substantial reduction in energy needs due to improved thermal efficiency. Similar reductions are visible across all winter months, underscoring the effectiveness of this retrofit in maintaining indoor temperatures and reducing heating requirements.

In the summer months, cooling demand has a small decrease in demand for the renovated scenario. For instance, in July, cooling demand drops from 32 MWh to 5MWh post-renovation. This indicates that the retrofit also contributes to mitigating overheating, thereby reducing the energy required for cooling.

The following graph represents the heating demand for a typical winter week, comparing scenarios with and without enhancing building insulation and upgrading windows in the district.

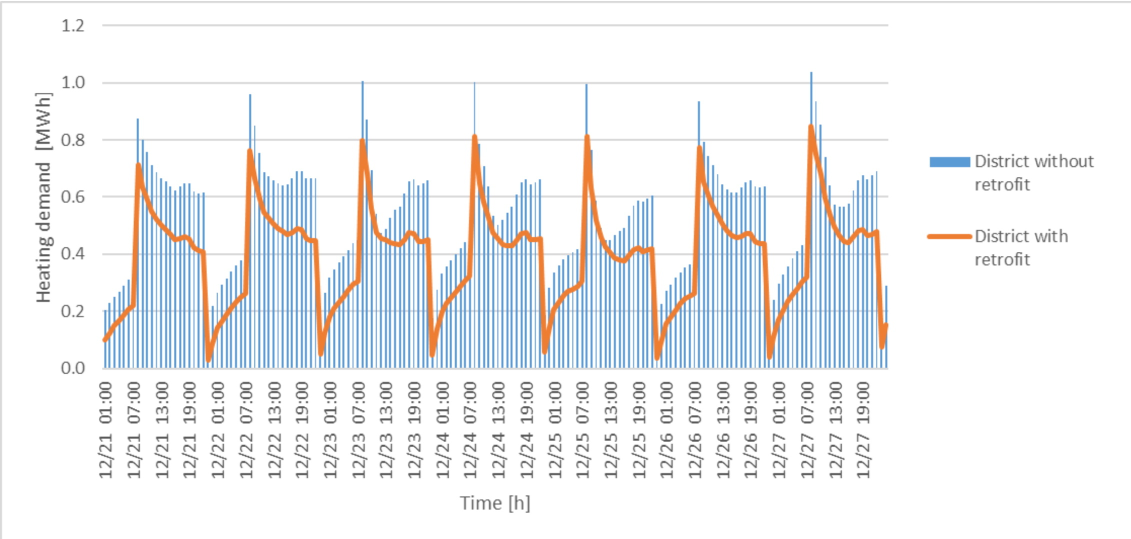


Figure 83 Heating demand with and without enhancing building insulation and upgrading windows in the Pamplona District

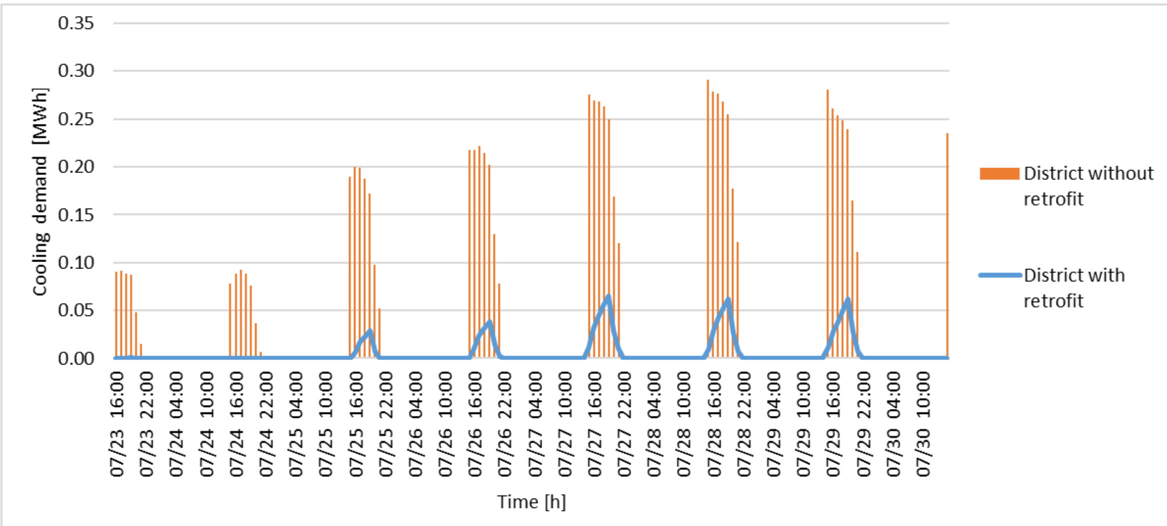


Figure 84 Cooling demand with and without enhancing building insulation and upgrading windows in the Pamplona District

The demand curve shows consistently lower peaks compared without retrofit.

The heating demand figure shows a clear reduction in peak and overall heating requirements with this retrofit and the cooling demand shows a more pronounced effect, but a minor peak compared to the higher peaks observed without retrofit.
The reduced peaks indicate that the solution contributes to lowering overall energy consumption while also smoothing out demand spikes, leading to more stable heating system performance during winter.

Replacement of gas boiler

The introduction of heat pumps as the second retrofit strategy involves replacing the existing methane boilers with electric-driven heating systems.

The following figure presents the monthly electricity consumption for the Pamplona district, comparing two scenarios: one with enhancing building insulation and upgrading windows and heat pumps, and one without retrofit.

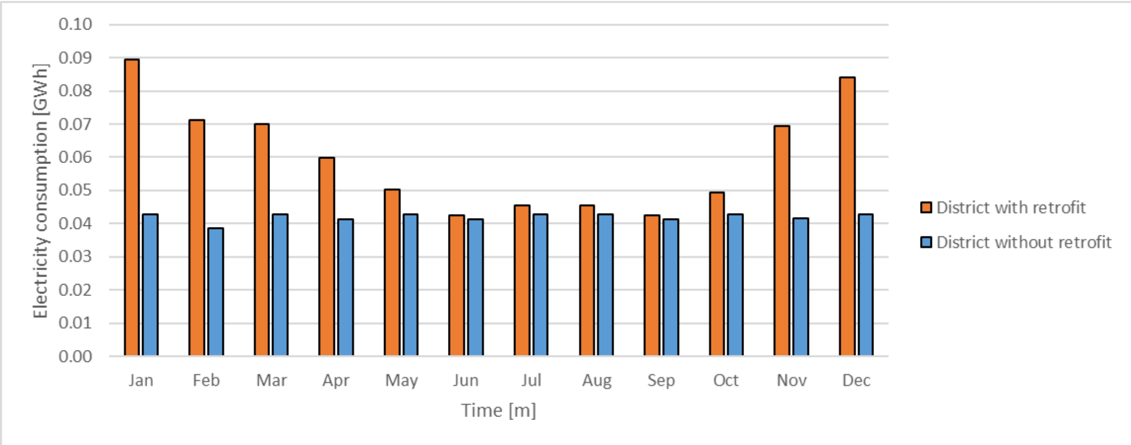


Figure 85 Comparison of monthly electricity consumption: district with and without enhancing building insulation, upgrading windows and replacement of heat pumps.

The scenario with retrofit shows a noticeable increase in electricity consumption compared to the scenario without retrofit. This increase is particularly evident during the colder months, reflecting the additional electrical load required to operate the heat pumps for heating purposes. However, this shift in energy usage represents an intentional move towards a fully electric system, eliminating the dependency on methane as a heating source.

While electricity consumption rises, it is important to highlight the benefits of this transition. By adopting heat pumps, the energy balance becomes entirely electric, which allows for integration with renewable energy sources, such as photovoltaic systems.

Photovoltaic system

The third proposed retrofit strategy for the Pamplona district involves integrating photovoltaic systems with a storage system to generate on-site renewable electricity.

In this case, where all roofs are sloped, the potential for photovoltaic installation is based on two key factors. First, the average ratio between the available area and the installed capacity is approximately 7 square meters per kilowatt peak (kWp). Second, given that not all roof orientations are optimal, only 75% of the available area is considered for installation. These two conditions lead to a total installed capacity of about 350 kW. Given the number of buildings and the potential for optimal energy management, the PV system is coupled with a storage solution to enhance the share of energy that can be self-consumed within the district. This approach aims to maximize the utilization of locally generated renewable energy by storing excess electricity produced during peak generation periods for use during times of higher demand or when solar production is low.

Table 50 Analysis of energy generation and consumption from photovoltaics in Pamplona district

Area available [m^2]	3300
Total power installed [kW]	350(75% utilization of the area available on roofs)
Battery capacity [kWh]	600
Generation [GWh]	0.34
Electricity consumption [GWh]	0.72
Import [GWh]	0.46
Export [GWh]	0.07
Auto-consumption [GWh]	0.17

The total annual generation from the PV system is 0.34 GWh, which contributes to meeting the district's annual electricity consumption of 0.72 GWh.

With the integration of battery storage, the PV system can effectively store surplus energy during high generation periods, optimizing energy use throughout the day.

In terms of energy flows, the district imports 0.46 GWh of electricity from the grid to meet the remainder of its energy needs. The integration of a battery storage system plays a crucial role in limiting the amount of electricity exported to the grid, the total export is limited to only 0.07 GWh.

The integration of PV with battery storage increases the share of energy self-consumed within the district, reducing dependence on grid electricity and improving sustainability. Although there is still a significant amount of electricity imported from the grid, renewable generation and enhanced auto-consumption contribute positively towards reducing overall carbon emissions and advancing the district's goals towards PED objectives.

Extension of renewable energy generation through nearby parking area integration

The last analysis considers an additional renewable energy source, specifically utilizing available space in a nearby parking area to further support the district's energy generation. By installing photovoltaic panels in this parking area, the overall renewable energy capacity of the district can be increased, thereby contributing more significantly to meeting energy demands locally.

The next figure shows the photovoltaic installation in the nearby parking area, which contributes an additional 1.1 MW of solar capacity to the Pamplona district.

Figure 86 Photovoltaic Installation at parking area: 1.1 MW renewable energy integration.

The following figure shows the distance between the district and the photovoltaic installation at Parking area.

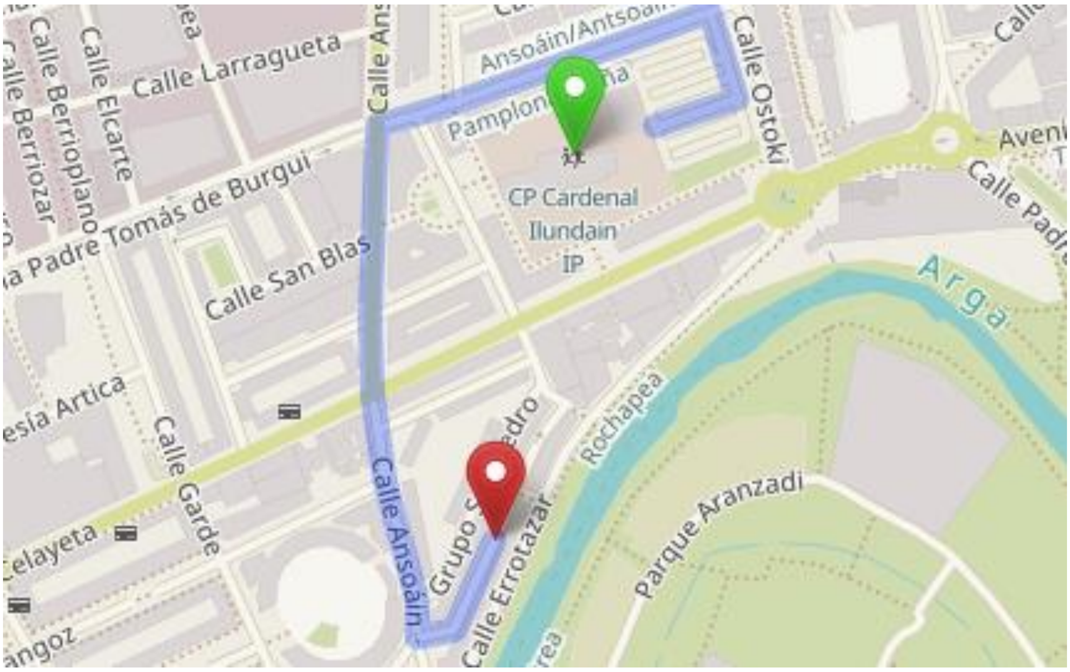


Figure 87 Distance between the District and the photovoltaic system.

The following figure analyses the potential monthly energy dynamics in the Pamplona district if all the available energy from both the nearby parking area and local sources were used to meet the district's energy demands.

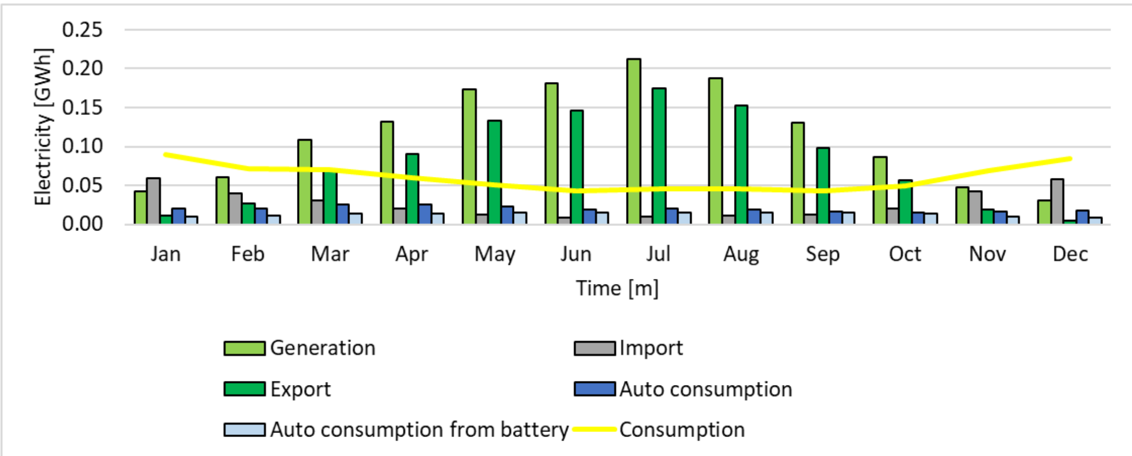


Figure 88 Monthly comparison of energy balance in the Pamplona district.

The figure shows that local generation exceeds the district's consumption for most months reaching values above 0.2 GWh, while the district's energy consumption remains stable, fluctuating around 0.05 GWh during the same period.

In the winter months, such as January and February, the energy generation drops to around 0.05 GWh, which is closer to the consumption level of approximately 0.10 GWh. As a result, there is a need for energy imports during these colder months to compensate for the lower generation levels. Despite this seasonal variation, the overall trend shows that for most of the year, the energy generated within the district is more than sufficient to meet its consumption needs, allowing the district to export surplus energy.

The next figure presents an analysis of how the district's electricity consumption is covered throughout the year, broken down by different energy sources: Grid, Battery and PV.

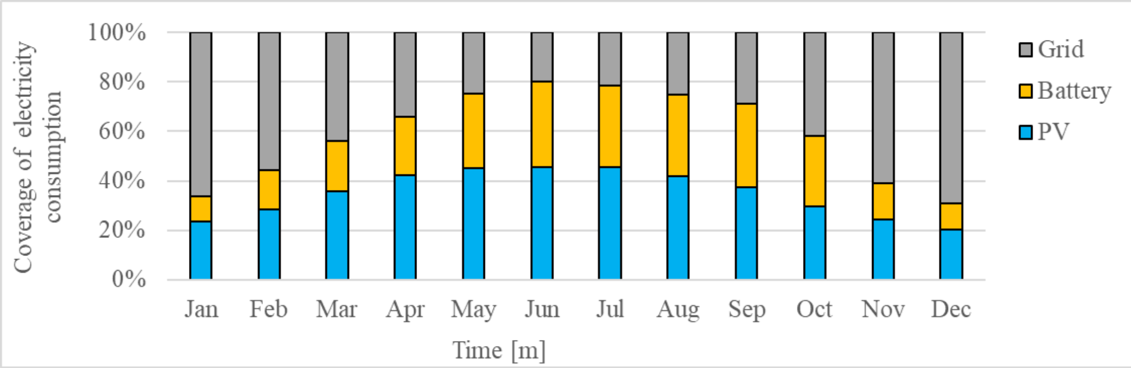


Figure 89 Monthly electricity consumption coverage in Pamplona.

During the summer months, specifically in June to August, the district reaches a peak of 80% self-consumption (combined contribution from PV and battery). This high level of self-sufficiency is largely due to the increased solar availability, allowing the PV system to generate a significant portion of the required energy. Additionally, the battery plays a critical role by storing excess solar power and helping to cover more of the energy demand locally.

In contrast, the winter months, particularly December, show a notable decrease in self-sufficiency, with only 30% of the electricity consumption being covered by local PV and battery resources. During this time, the contribution from the Grid increases substantially to compensate for the lower solar generation and the limited capacity of the battery to store energy for extended low-solar conditions.

The next figure shows the monthly load cover factor for the renovated state of the district over the course of a year.

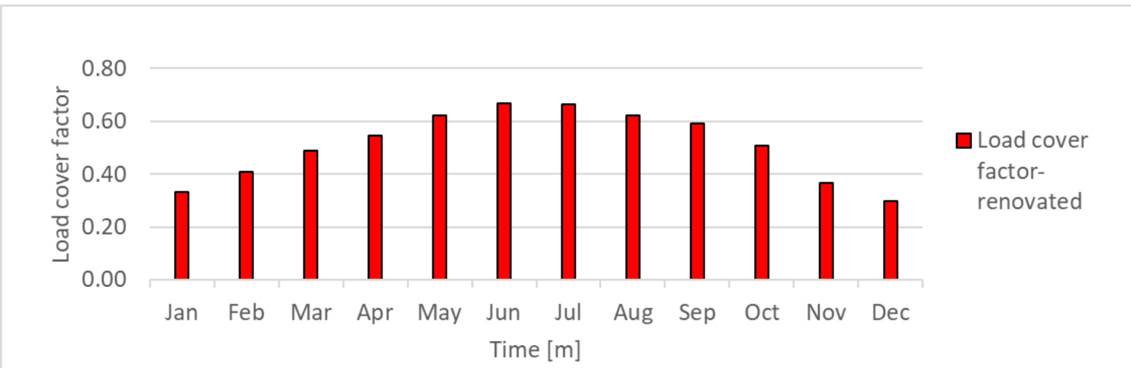


Figure 90 Monthly load cover factor.

The load cover factor peaks during the summer months, with values reaching approximately 0.70 in June and July, indicating that the district can meet 70% of its energy needs from its own renewable or local generation sources during these months. The battery system plays a critical role in enhancing this self-sufficiency by storing excess energy produced during periods of high solar availability and discharging it during periods of lower production or higher demand, particularly at night.

During the winter months the load cover factor drops significantly, with values ranging between 0.30 and 0.50. While the battery system still helps manage the energy flow, the lower production levels from the photovoltaic system limit its ability to significantly cover the district's energy demand during these months.

The next figure illustrates the grid Interaction Index (F_{grid}) for the renovated district, both with and without a battery storage system.

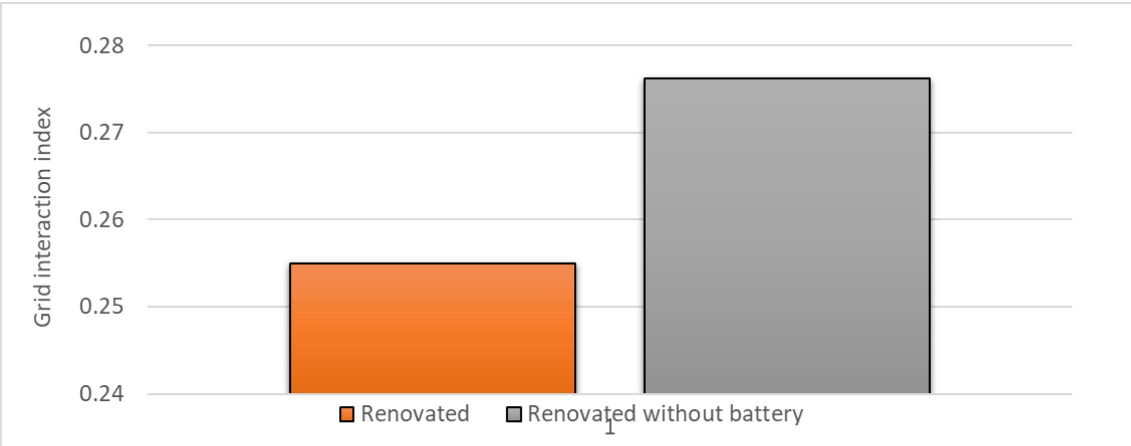


Figure 91 Grid interaction index.

In the graph, the renovated district with a battery displays a lower Grid Interaction Index compared to the scenario without a battery. This indicates that the system operates with greater efficiency and autonomy when a battery is integrated.

The next figure compares the monthly electricity exports for the renovated district, distinguishing between scenarios with and without battery storage.

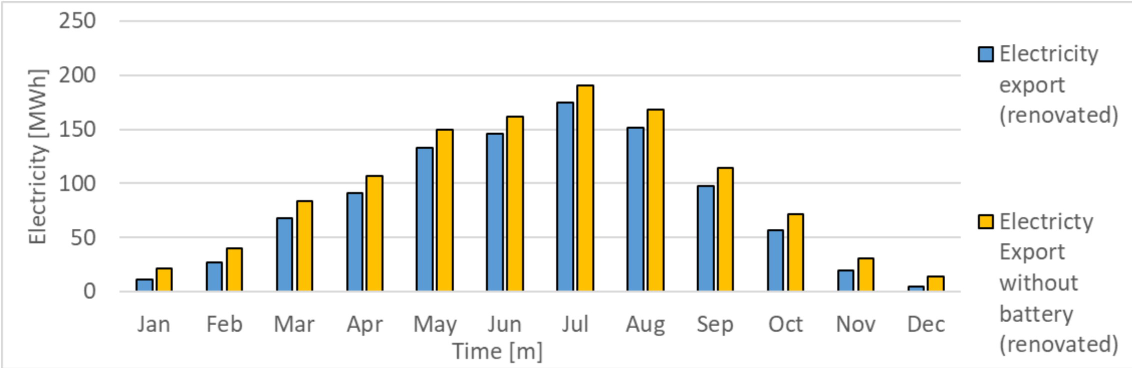


Figure 92 Monthly electricity export comparison with and without battery storage.

The figure shows that due to the disparity between the PV system's large generation capacity and the relatively smaller battery storage, the battery can only store a portion of the energy produced by the PV system. Consequently, although the battery reduces grid interaction, especially during times of lower generation or higher demand, it still cannot fully absorb the excess energy generated during high-production periods.

PED primary balance

The Pamplona district generates 0.34 GWh of renewable energy annually while consuming 0.72 GWh, resulting in a net energy deficit of 0.38 GWh. To compensate for this shortfall, the district imports energy from the grid. However, the presence of an existing 1.1 MW solar installation in the vicinity introduces uncertainty regarding its contribution to the district's energy balance. This situation leads to two hypotheses concerning how the district might achieve a PED status by either increasing the share of renewable energy consumed or enhancing local renewable energy generation.

Hypothesis 1:

If all the energy imported by the district is sourced entirely from renewable energy, specifically from nearby photovoltaic installations, this would inevitably increase the proportion of renewable energy that is self-consumed within the district. Under this scenario, the district enhances its renewable energy consumption without necessarily increasing its local generation capacity. This shift contributes to reducing dependence on non-renewable energy sources and moves the district closer to achieving a PED status.

In this scenario, it is assumed that both the energy generated within the district and the energy imported for consumption have the same primary energy factor of 1. This implies that all imported energy is sourced from renewable energy with no additional primary energy losses. Under this assumption, the PED balance would reflect equal efficiency in both generation and consumption, facilitating a straightforward comparison and highlighting the district's movement towards energy positivity.

Table 51 PED (Primary energy) Balance under Hypothesis 1

Generation of energy [GWh]	Consumption of energy [GWh]	Difference [GWh]
0.34	0.72	-0.38

Hypothesis 2:

Alternatively, the existing 1.1 MW solar installation in the area contributes to an overall increase in renewable energy generation within the region but does not directly affect the district's self-consumption of renewable energy. In this case, while the total amount of renewable energy generated locally increases, the district continues to import energy from the grid without a guaranteed renewable origin. Therefore, unless the additional generated energy is specifically allocated to the district, the district's energy balance remains unchanged. This scenario highlights the need for dedicated measures to ensure that increased local generation translates into increased renewable energy consumption within the district.

In this scenario, the energy imported by the district retains a primary energy factor of 2.5, reflecting the average PEF for electricity from the national grid, which includes non-renewable energy sources and associated losses.

Table 52 PED Balance under Hypothesis 2

Generation of energy [GWh]	Consumption of energy [GWh]	Difference [GWh]
1.39	1.35	0.04

Under this hypothesis, the district generates more renewable energy than it consumes, achieving a net surplus of 0.04 GWh. This means the district meets the criteria for a PED, as it produces more energy from renewable sources than it consumes over the course of a year.

Case Study 2 – Bucharest

The proposed retrofit plan for the district in Bucharest focuses on reducing both heating and cooling demands through the enhancing building insulation in buildings that currently lack it. Given that the heating demand is significantly higher than the cooling demand, a particular importance has been placed on addressing the heating requirements. Since the heating demand is primarily met by the district heating system, a secondary retrofit hypothesis involves improving the efficiency of the district heating network, potentially by replacing it with a more advanced system.

To achieve the PED target, the plan also includes the installation of photovoltaic panels. The aim is to utilize the entire available roof surface area for solar energy generation, ensuring that the district can meet its energy needs sustainably. This approach not only reduces the reliance on external energy sources but also aligns the district with its PED goals by integrating renewable energy solutions.

Insulation

The following tables illustrate the impact of applying 20 cm of EPC insulation to the external walls and roof on both cooling and heating demand for three archetypes in the Bucharest district. This thickness was chosen based on compliance with Ordinul 2641/2017, which sets minimum thermal performance requirements for renovated buildings, including a maximum U-value of 0.56 W/m²K for external walls.

Table 53, Table 54 and Table 55 analyse the overall impact of insulation on each baseline archetype.

Table 53 Impact of insulation on cooling and heating demand for archetype 1 in the Bucharest district

Archetype 1	**Cooling [kWh/m^2]**	**Heating [kWh/m^2]**
Without insulation	47.59	108.19
With insulation	47.96	74.62
Difference	1%	-31%

Table 54 Impact of insulation on cooling and heating demand for archetype 2 in the Bucharest district

Archetype 2	**Cooling [kWh/m^2]**	**Heating [kWh/m^2]**
Without insulation	29.88	110.79
With insulation	24.26	54.16
Difference	-19%	-51%

Table 55 Impact of insulation on cooling and heating demand for archetype 3 in the Bucharest district

Archetype 3	**Cooling [kWh/m^2]**	**Heating [kWh/m^2]**
Without insulation	38.94	129.03
With insulation	37.28	86.47
Difference	-4%	-33%

The next figure illustrates the impact of insulation on the monthly heating and cooling demand for the district.

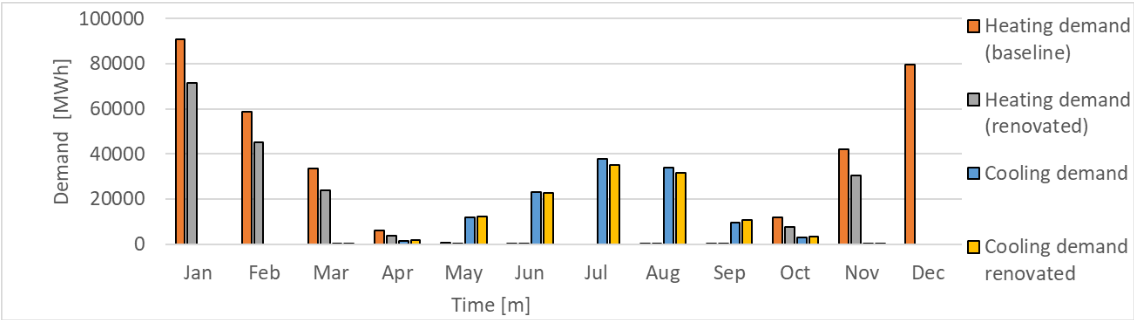


Figure 93 Monthly comparison of thermal demand with and without insulation in Bucharest.

This figure shows in the baseline scenario without insulation the heating demand reaches values of around 90,000 MWh in January and 80,000 in December, indicating significant energy requirements due to considerable heat loss during the coldest months. In contrast, in the renovated scenario with insulation, heating demand is reduced to approximately 50,000 MWh in these months, showing a substantial reduction and highlighting the effectiveness of insulation in retaining heat and reducing the overall energy required for space heating.

Regarding cooling demand, the impact of insulation is evident, though less pronounced. During July and August, the baseline cooling demand reaches around 38,000 MWh, whereas in the renovated scenario, this value drops slightly to around 35,000 MWh. This decrease suggests that insulation also helps reduce the heat entering buildings, thereby minimizing the reliance on cooling systems during warmer months.

Figure 94 illustrates the cumulative effect of the selected EPC insulation on heating demand across the district, aggregating the reductions achieved in individual building archetypes. Similarly, Figure 95 examines the impact on cooling demand, showing how the district's overall energy consumption for cooling is affected by the application of the insulation.

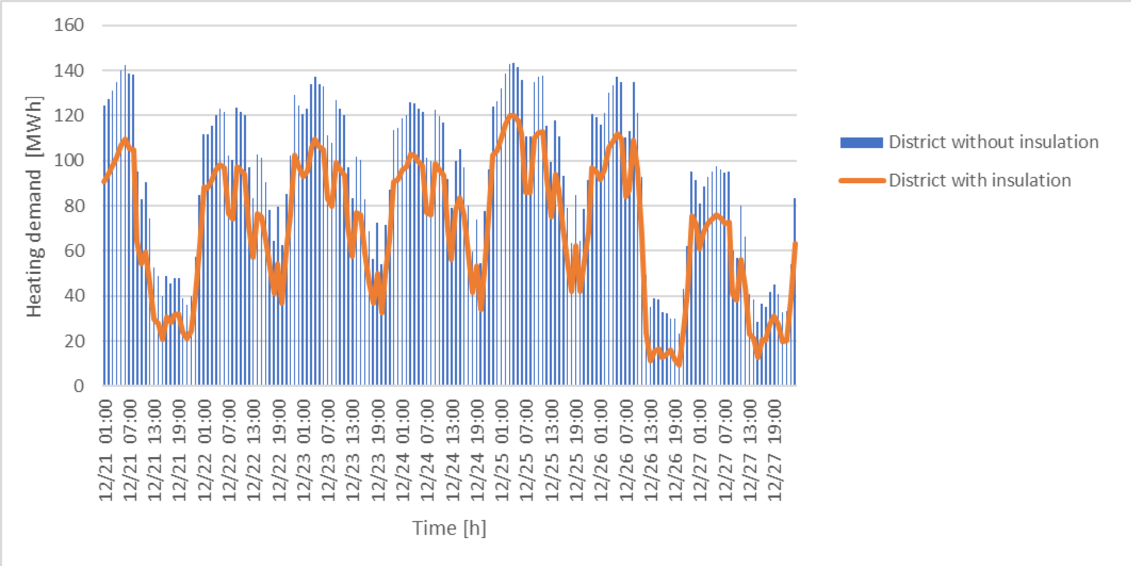


Figure 94 Impact of Insulation on heating demand in the Bucharest District

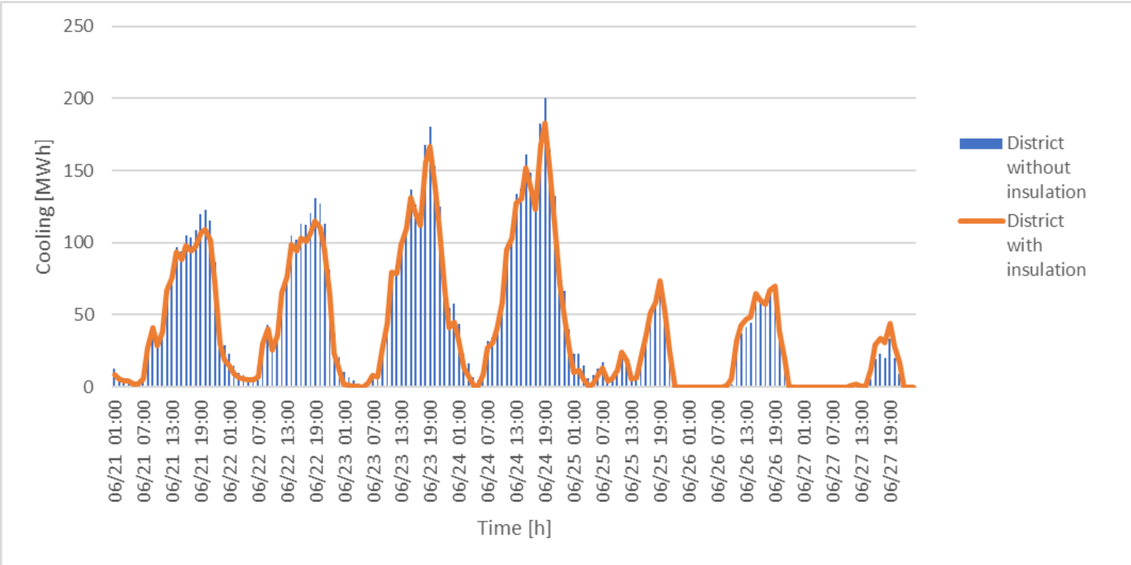


Figure 95 Impact of Insulation on cooling demand in the Bucharest district.

Insulation has a much more pronounced effect on heating demand, with substantial reductions across all archetypes, reaching up to 51% in the case of archetype 2. This aligns with the goal of enhancing energy efficiency during colder months, where heating demand is more significant. These reductions are critical, particularly in climates like Bucharest, where heating represents the dominant portion of energy consumption.

Regarding cooling demand, the impact is less consistent. In archetype 1, insulation leads to a slight increase in cooling demand (+1%), whereas the other two archetypes experience reductions, with a maximum of 19% in archetype 2. This suggests that while insulation is highly effective in lowering heating demand, it can, in some cases, contribute to heat buildup during summer, depending on the building's characteristics and the local climate. However, since heating demand is generally much more predominant than cooling demand, the overall energy savings achieved through insulation are substantial and clearly beneficial.

Figure 96 analyses the monthly reduction in total electricity consumption resulting from the installation of insulation.

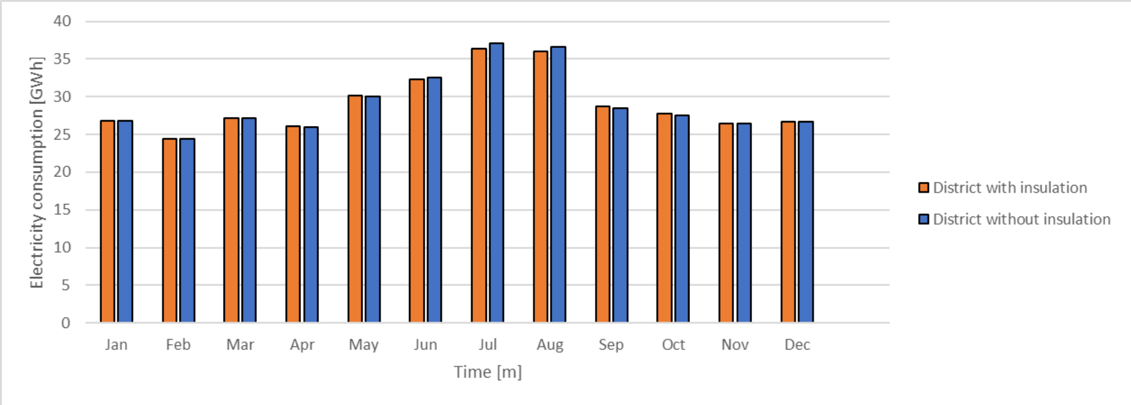


Figure 96 Monthly impact of Insulation on total electricity consumption in the Bucharest district.

The figure indicates that the impact of insulation on electricity consumption (covering both appliances and HVAC systems) is limited. During the winter, the district heating system meets the heating needs, minimizing reliance on electric heating, which reduces the potential effect of insulation. In summer, although insulation helps decrease cooling demand by reducing heat gains, the overall effect remains modest due to the low baseline cooling demand. Furthermore, insulation was applied only to buildings that were previously uninsulated, which further limits its overall impact on energy consumption across the district.

The following table presents the comparative annual analysis of energy demand for heating, cooling and electricity before and after insulation.

Table 56 Impact of insulation on heating, cooling and electricity demand for renovation scenario

	Heating Demand [GWh]	**Cooling Demand [GWh]**	**Electricity Demand [GWh]**
Baseline	323.42	121.64	349.94
Renovated	244.43	118.11	348.93
Difference [%]	-24%	-3%	0.00

The analysis of the results highlights the significant effects of added insulation on energy demands, particularly for heating, representing a 24% reduction. This data demonstrates the effectiveness of insulation in reducing heating needs, especially in climates where thermal losses during the cold season constitute a major component of energy consumption.

Regarding cooling demand, a more modest reduction is observed. In the baseline scenario, the cooling demand decreases after renovation, with a 3% of reduction. This smaller impact can be attributed to insulation primarily addressing thermal losses during the winter season, while it has a less significant effect on cooling needs.
Electricity demand shows no significant decrease. The electricity consumption after insulation remains largely unchanged, primarily due to the reasons mentioned earlier: during winter, the district heating system meets the heating requirements, reducing the role of insulation, while in summer, the cooling demand is already low, minimizing the effect of insulation on energy savings.

Efficiency improvement of the district heating system

To further reduce energy consumption and minimize greenhouse gas emissions, improving the efficiency of district heating systems is essential, particularly in regions like Bucharest, where thermal energy demand remains high even after the application of insulation.
For the district heating system, the retrofit strategy focused solely on replacing the centralized generator, without any intervention on the distribution or emission sections of the system.
In this analysis, the following assumptions were made to estimate the global efficiency of the district heating system after the retrofit:

- Boiler efficiency: Based on existing studies on large, non-condensing boilers in well-maintained systems, an efficiency of 92% [185]was assumed for the central boiler. This value reflects realistic performance under optimal operating conditions for such units.

- Distribution losses: According to a study from the Joint Research Centre (JRC) of the European Commission[186] the average distribution losses in European district heating systems were 8%.

With these assumptions, the estimated global efficiency of the district heating system, combining the boiler efficiency and the distribution network losses, was calculated to be 85%.
Figure 97 presents a monthly comparison of energy fuel consumption before and after the efficiency improvement of the district heating system.

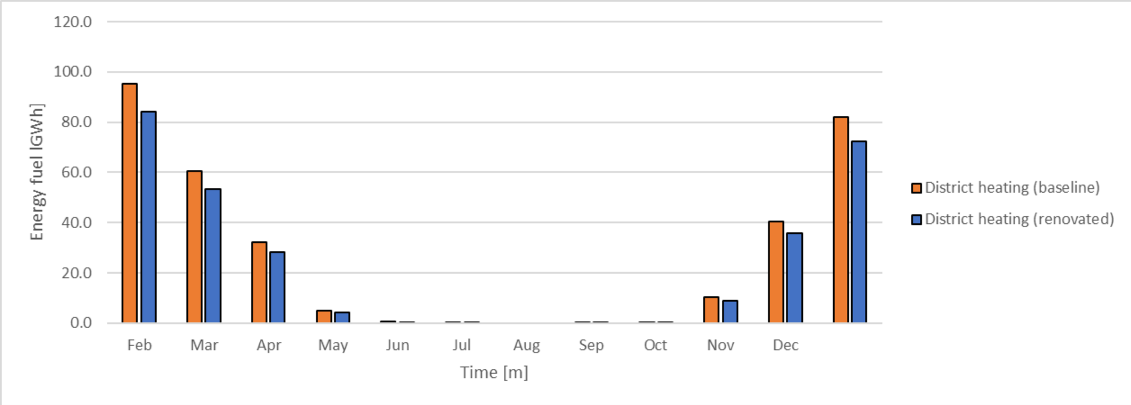


Figure 97 Monthly energy fuel consumption comparison before and after district heating system efficiency improvement in Bucharest.

The renovation demonstrates a reduction in energy fuel consumption after the efficiency improvement of the district heating system. The renovated system consistently shows lower fuel consumption during the peak heating months of February, March, April, November, and December. This reduction is particularly notable in February and December, where energy fuel consumption drops significantly after the renovation.

Overall, the annual energy fuel consumption decreases from 325 GWh to 287 GWh, resulting in a 12% reduction.

Photovoltaic system

To meet the PED goals, it is essential to increase on-site energy generation. Therefore, the installation of photovoltaic systems has been considered, with specific characteristics described in the following table. The energy generation potential of photovoltaic systems has been evaluated, considering the most optimistic scenario assumes the use of the entire available area for the photovoltaic installation, maximizing solar energy production.

In this case, since all roofs are flat, the average ratio between the available area for photovoltaic installation and the installed capacity is approximately 9 square meters per kilowatt peak (kWp). The total installed power amounts to about 41 MW.

The comparison between the energy generated by the photovoltaic systems and the energy demand after retrofitting (specifically insulation measures) allows for assessing whether the PED target can be achieved.

Table 57 Analysis of energy generation and consumption from photovoltaics in Bucharest district

Area available [m^2]	368,606
Total power installed [MW]	40.95
Generation [GWh]	49.34
Electricity consumption [GWh]	348.93
Import [GWh]	299.94

Export [GWh]	0.35
Auto-consumption [GWh]	48.99

In this scenario, a large portion of the generated energy is directly used within the district, helping to reduce reliance on imports. However, to meet the PED goals, this analysis shows that the current photovoltaic installation is insufficient. The following figure provides a monthly breakdown of the district's energy balance, focusing on electricity generation, consumption, imports, exports, and auto-consumption.

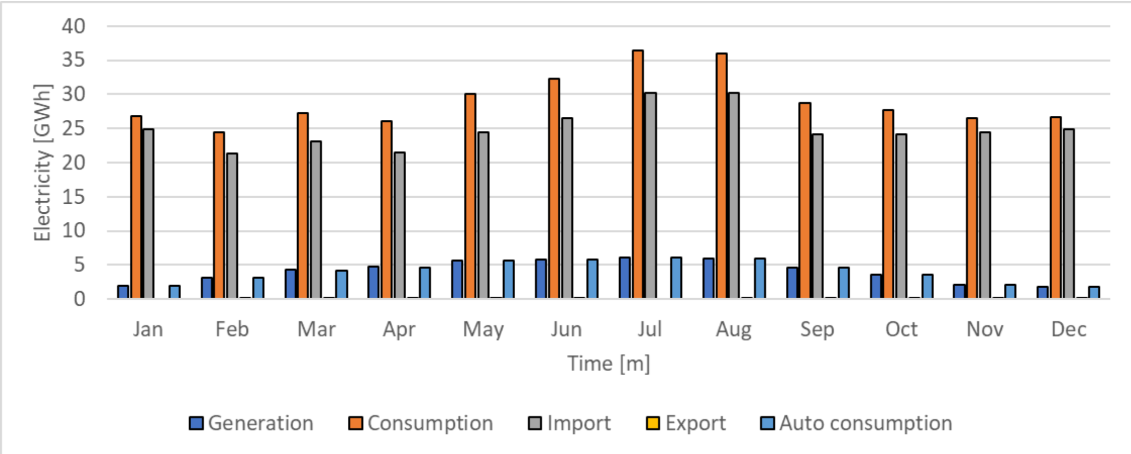


Figure 98 Monthly comparison of energy balance in the Bucharest district.

This figure shows that although a portion of the generated energy is consumed locally, it is not enough to meet the district's total energy demand, and energy exports are minimal, primarily occurring in the summer. Overall, the chart highlights the district's heavy reliance on imported energy and indicates that the current photovoltaic system is insufficient to meet PED targets.

The next figure shows the coverage of electricity consumption throughout the year, highlighting the contribution from Photovoltaic (PV) generation versus the Grid.

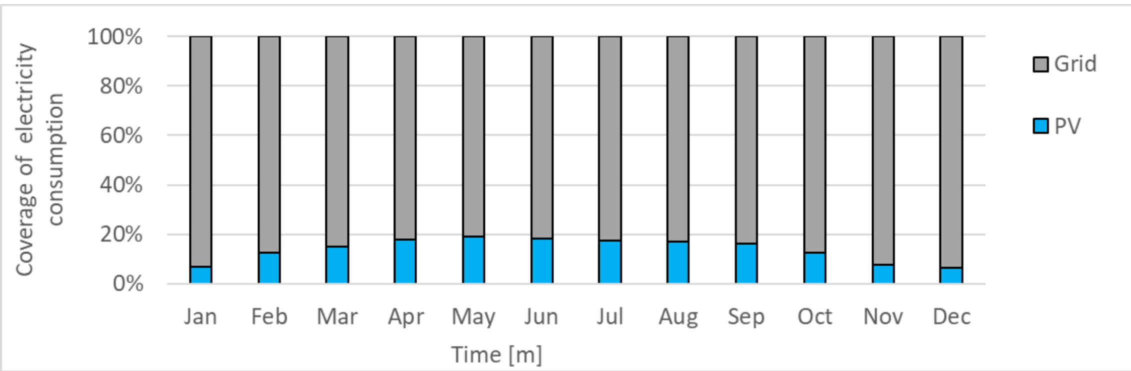


Figure 99 Monthly electricity consumption coverage in Bucharest.

The analysis of the monthly chart suggests that, to move closer to the goals of a PED, additional strategies could be considered. One option would be increasing renewable energy generation by utilizing adjacent areas for additional installations, such as photovoltaic systems or other renewable technologies like wind or solar thermal, to boost overall production and move toward energy self-sufficiency.

PED primary balance

In the Bucharest district, both electricity and methane are used, which adds complexity to the calculation of the PED balance. As a result, the analysis must go beyond the simple electricity balance and include a comprehensive assessment of the total primary energy consumed within the district.

According to Eq 20, the PED balance is determined by comparing the amount of primary energy generated within the district to the energy consumed, considering their respective primary energy conversion factors.

For photovoltaic energy generation, a primary energy factor of 1 has been applied, as per ISO 52000.

For energy consumption, the following factors were used:

- Self-consumption of photovoltaic energy: Primary energy factor of 1 (same as for energy generation).
- Electricity consumption from the grid: Primary energy factor of 2.5, reflecting the grid's conversion efficiency.
- Thermal energy consumption from natural gas (methane): Primary energy factor of 1.1, which accounts for the efficiency of natural gas combustion.

The following table presents the energy balance calculation for the Bucharest district, comparing the generation and consumption of energy in terms of primary energy.

Table 58 Primary energy balance in the Bucharest district

Generation of energy [GWh]	Consumption of energy [GWh]	Difference
49.34	1115.16	-1065.82

The table reveals a substantial deficit in the district's energy balance, with energy consumption significantly outpacing energy generation.

The energy balance according to ISO 52000 assigns a lower primary energy factor (1) to renewable energy generated by photovoltaics, while grid electricity is assigned a higher factor (2.5). However, if the same primary energy factor were applied to both grid electricity and photovoltaic energy (2.5 for both), a more neutral and stringent comparison would emerge between the two energy sources. In this case, the energy balance would actually improve towards meeting the PED target, as applying a higher primary energy factor to photovoltaic energy would increase its contribution in the primary energy balance, making it easier to achieve the target where generation exceeds consumption.

The following table presents a comparison of energy generation, consumption, and balance for both scenarios: the standard energy balance and the adjusted/grid-equivalency energy balance. This comparison illustrates how different primary energy factors impact the ability to meet the PED target.

Table 59 Comparison of primary energy balance in the Bucharest district: applying the same primary energy factor for generation and consumption.

Generation of energy [GWh]	Consumption of energy [GWh]	Difference
123.35	1188.65	-1065.30

In both analyses, energy generation is lower than consumption, preventing the district from achieving the PED target. This lack underscores the necessity for increasing renewable energy generation or implementing additional energy efficiency measures to reduce consumption. Bridging this gap is essential for the district to meet the PED target. Consideration should be given to integrating alternative renewable energy solutions, such as photovoltaic installations on local areas or building facades, as well as transitioning the district heating system to one powered by renewable energy sources, to help close this energy gap and align with PED objectives.

Case Study 3 – Copenhagen

Insulation and windows

In the Copenhagen case study, this strategy was developed in accordance with the guidelines provided in the "Bygningsreglementet 2018" (BR18), which is the Danish Building

Regulations. Specifically, Table 3 of the BR18 outlines the required thermal transmittance (U-value) targets for various building elements, including external walls, roofs, and windows, when conducting building retrofits.

The following U-values were targeted to enhance energy efficiency:

- **External walls and basement walls adjacent to the ground:** 0.18 W/m²K
- **Partition walls adjacent to rooms with temperature differences ≥ 5°C:** 0.40 W/m²K
- **Ground floors, basement floors adjacent to the ground, partition walls towards the exterior or a ventilated space:** 0.10 W/m²K
- **Ceilings and roof structures:** 0.12 W/m²K
- **Roof windows, dormers, and skylights:** 1.40 W/m²K

The following tables present the results of an analysis conducted to assess the effectiveness of enhancing building insulation and upgrading windows. The tables detail the changes in heating and cooling demands for the five building archetypes, both before and after the retrofit.

Table 60 Impact of enhancing building insulation and upgrading windows on cooling and heating demand for archetype 1 in the Copenhagen district.

Archetype 1	**Cooling [kWh/m²]**	**Heating [kWh/m²]**
Without retrofit	18.89	142.34
With retrofit	48.02	96.93
Difference	154.25%	-31.90%

Table 61 Impact of enhancing building insulation and upgrading windows on cooling and heating demand for archetype 2 in the Copenhagen district.

Archetype 2	**Cooling [kWh/m²]**	**Heating [kWh/m²]**
Without retrofit	25.84	70.06
With retrofit	21.61	66.81
Difference	-15.84%	-4.63%

Table 62 Impact of enhancing building insulation and upgrading windows on cooling and heating demand for archetype 3 in the Copenhagen district.

Archetype 3	**Cooling [kWh/m²]**	**Heating [kWh/m²]**
Without retrofit	1.76	128.08

With retrofit	3.30	76.21
Difference	88%	-40.50%

Table 63 Impact of enhancing building insulation and upgrading windows on cooling and heating demand for archetype 4 in the Copenhagen district.

Archetype 4	**Cooling [kWh/m²]**	**Heating [kWh/m²]**
Without retrofit	0.24	194.53
With retrofit	3.62	145.08
Difference	1408%	-25.42%

Table 64 Impact of enhancing building insulation and upgrading windows on cooling and heating demand for archetype 5 in the Copenhagen district.

Archetype 5	**Cooling [kWh/m²]**	**Heating [kWh/m²]**
Without retrofit	3.42	105.18
With retrofit	13.46	61.72
Difference	293%	-41.32%

The results show how the retrofit has significantly reduced heating demand across all the building archetypes analysed. For instance, Archetype 1 experienced a 31.90% reduction in heating demand, while Archetype 3 saw a reduction of 40.50%. However, the impact on cooling demand varied, with some archetypes showing an increase in cooling demand, such as in Archetype 4, where a significant percentage increase was found although in absolute terms the variation was moderate.

The following figure compares the monthly heating and cooling demand before and after the retrofit.

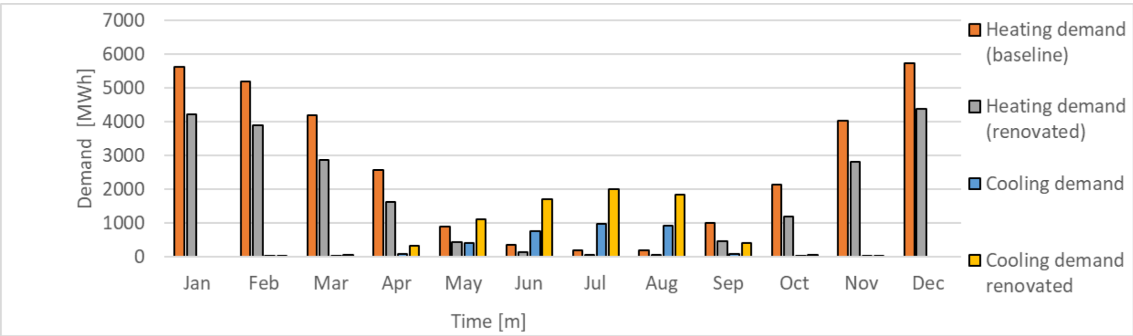


Figure 100 Monthly comparison of thermal demand enhancing building insulation and upgrading windows in Copenhagen.

In the baseline scenario the heating demand is highest particularly in January, February and December, where the demand reaches approximately 6000 MWh. In contrast, after the retrofit, the heating demand decreases significantly in the same months, dropping to around 3500-4000 MWh, indicating a 33-40% reduction in heating energy consumption due to the improved thermal performance.

Regarding the cooling demand, in the baseline scenario the demand peaks at around 1400-1500 MWh in July and August. After the retrofit the cooling demand increases slightly, reaching 2000 MWh in the same peak summer months, representing an increase of about 25-30%.

Figure 101 and Figure 102 illustrate heating and cooling demand for a typical week with and without the retrofit.

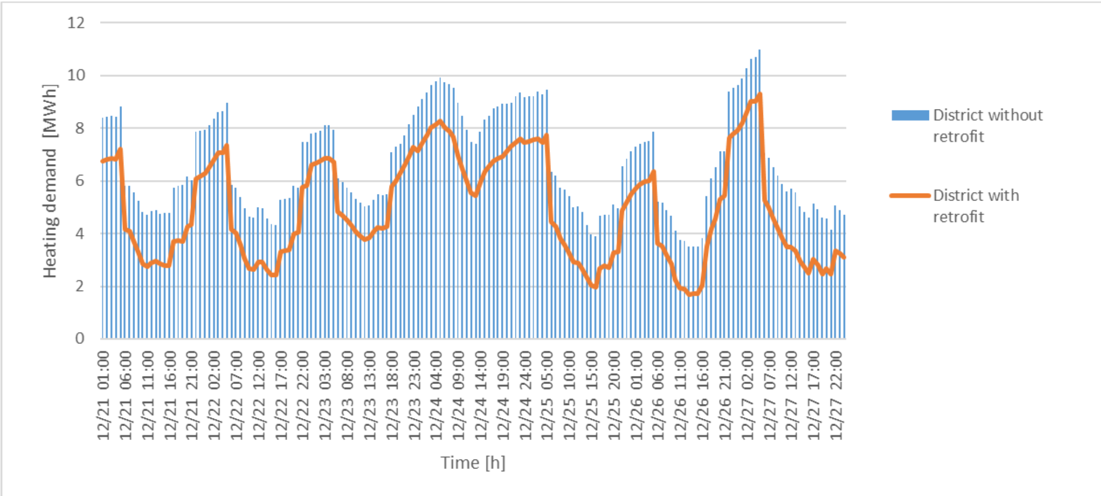


Figure 101 Comparison of heating demand before and after enhancing building insulation and upgrading windows in the Copenhagen district.

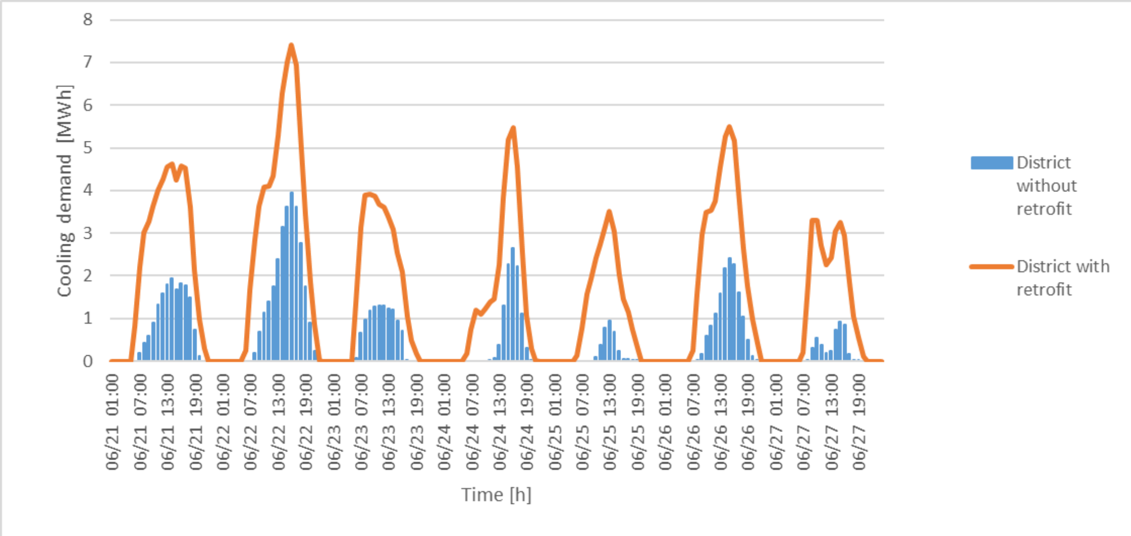


Figure 102 Comparison of cooling demand before and after enhancing building insulation and upgrading windows in the Copenhagen district.

The heating demand after the retrofit, showing a reduction in energy demand, which underscores the effectiveness of the implemented measures. Despite the overall reductions in heating demand, the response in cooling demand is more complex, with variations depending on the building types.

Figure 103 analyses the monthly reduction in total electricity consumption resulting from the enhancing building insulation and upgrading windows.

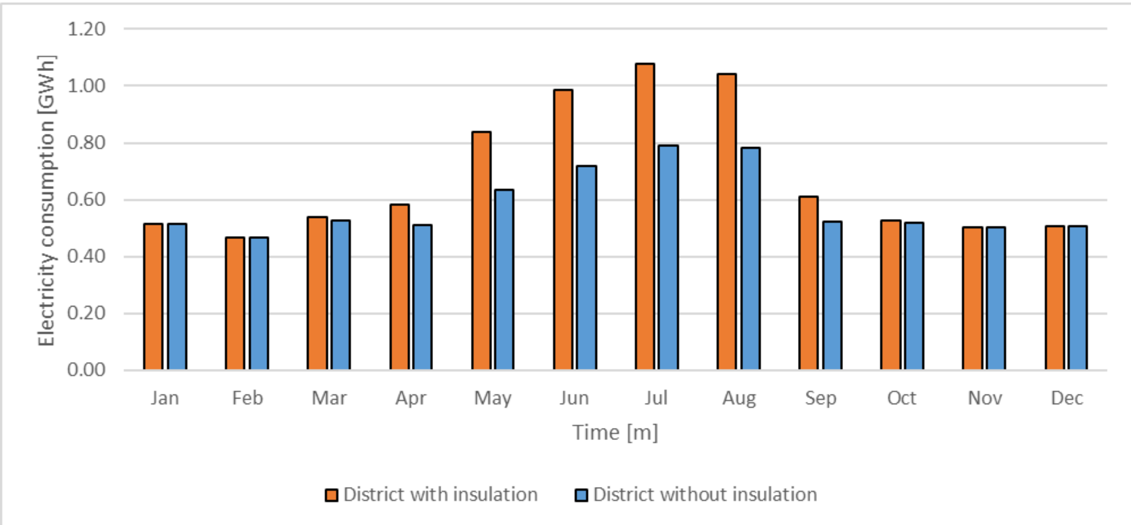


Figure 103 Monthly impact of enhancing building insulation and upgrading windows on total electricity consumption in the Copenhagen district.

This figure indicates that, since electricity consumption is mainly driven by internal loads and summer usage, changes are minimal during the winter months but show significant decreases in energy consumption during the summer.

The table below provides an annual comparative analysis of heating, cooling and electricity demand before and after the renovation.

Table 65 Impact of enhancing building insulation and upgrading windows on heating, cooling and electricity demand for renovation scenario.

	Heating Demand [GWh]	Cooling Demand [GWh]	Electricity Demand [GWh]
Baseline	32.06	3.23	6.99
Renovated	22.07	7.44	8.19
Difference [%]	-31%	130%	17%

While internal loads remain unchanged, electricity consumption has increased due to the higher energy demand for cooling.

The measures results in a substantial reduction in heating demand, decreasing by 31%. This decline is due to the enhanced thermal efficiency of the buildings, which minimizes heat loss during the colder months and reduces the energy required for maintaining comfortable indoor temperatures. Conversely, the cooling demand increases significantly by 130%. Additionally, the overall electricity demand sees an increase of 17%, which is attributed to the higher energy consumption of cooling system.

Photovoltaic system

To achieve the PED objectives, increasing on-site energy generation is crucial. As a result, the installation of photovoltaic systems has been considered, with their specific characteristics outlined in the following table. The energy generation potential of these systems has been assessed, with the most optimistic scenario assuming full utilization of the available area for photovoltaic installation to maximize solar energy production. Some buildings have flat roofs, while the majority have sloped roofs, resulting in various roof orientations for the photovoltaic systems. For the assessment of installable power, the available area is divided by 9 for flat roofs and by 7 for sloped roofs. The energy generated has been compared with the new electricity consumption resulting from the retrofit with enhancing building insulation and upgrading windows, allowing an evaluation of whether the PED target can be met.

It is important to note that, in the calculation of the available surface area, the buildings classified under the prison archetype have not been considered.

Table 66 Analysis of energy generation and consumption from photovoltaics in Copenhagen district

Area available [m²]	69,391
Total power installed [MW]	9.34
Generation [GWh]	6.60
Electricity consumption [GWh]	8.19
Import [GWh]	4.18
Export [GWh]	2.59
Auto-consumption [GWh]	4.01

The analysis indicates that if only electricity generation and consumption were considered, the PED could potentially be achieved. The current photovoltaic systems are generating approximately 80% of the district's electricity consumption. With additional photovoltaic installations, especially on nearby areas, it is likely that electricity generation could fully meet or even exceed the consumption.

The next figure illustrates the district's monthly energy balance, highlighting electricity generation, consumption, imports, exports, and self-consumption.

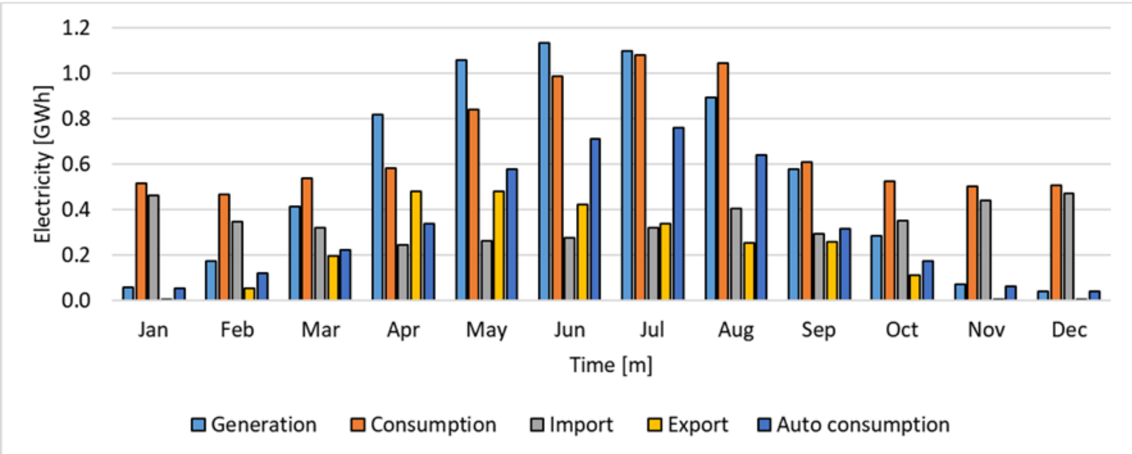


Figure 104 Monthly comparison of energy balance in the Copenhagen district.

The figure shows the high level of energy generation and export during the summer suggesting the possibility of using this excess electricity to power heat pumps, which could help meet the district's substantial thermal demand. Redirecting this exported energy towards heat pumps could improve the overall energy balance, potentially reducing the thermal energy deficit and contributing to a more comprehensive achievement of the PED target.

Photovoltaic system + Heat Pumps

As part of the retrofit strategy, leveraging the excess energy generated by photovoltaic systems to power heat pumps within the district is proposed. By utilizing surplus electricity from PV installations, these heat pumps can produce thermal energy for heating and cooling needs.

Table 67 Energy balance for heat pumps

Parameter	Value
Heating demand covered by photovoltaic-powered heat pumps [GWh]	0.85
Heating demand covered by district heating [GWh]	21.22
Cooling demand covered by photovoltaic-powered heat pumps [GWh]	2.68
Cooling demand covered by grid-powered heat pumps [GWh]	4.76

The following figure shows how much of the heating demand is covered by District Heating versus Photovoltaic-Powered Heat Pumps.

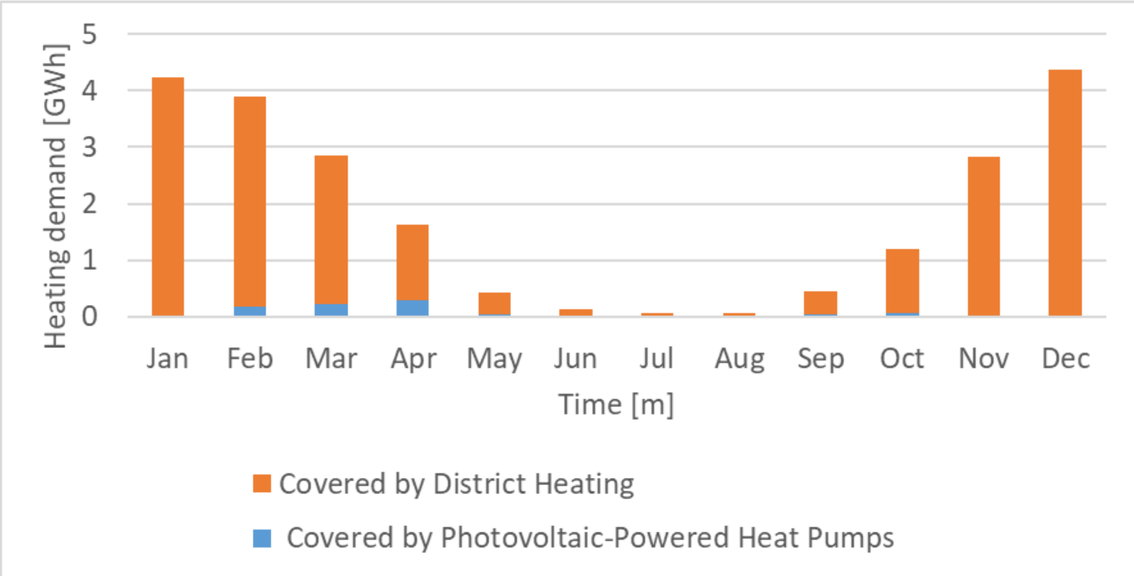


Figure 105 Monthly coverage of heating demand by district heating and photovoltaic-powered heat pumps in the Copenhagen district.

The figure illustrates that during the winter months, heating demand reaches approximately 4 GWh and is predominantly met by the district heating system. Photovoltaic-powered heat pumps contribute only marginally, particularly during the periods of highest energy demand. In the spring and autumn, while heating demand decreases, district heating continues to supply the majority of the required energy, with heat pumps playing a more limited role.

The next figure shows the monthly cooling demand and the respective contributions of grid-powered heat pumps and photovoltaic-powered heat pumps.

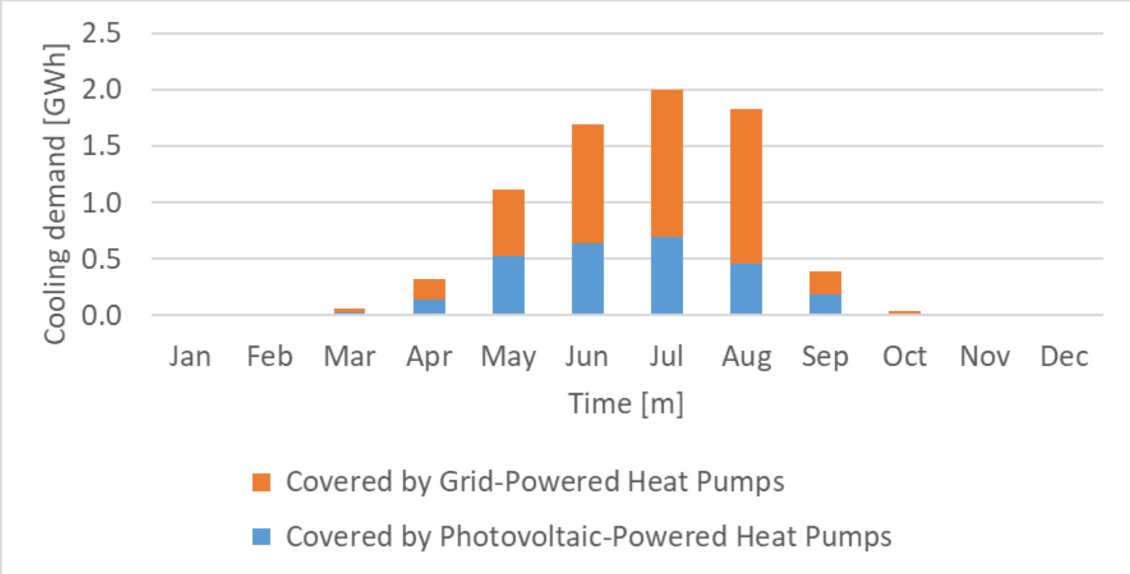


Figure 106 Monthly cooling demand covered by grid-powered and photovoltaic-powered heat pumps in the Copenhagen district.

The figure shows during the warmer months cooling demand peaking at over 2 GWh. The demand during these peak months is met by both grid-powered and photovoltaic-powered heat pumps, with grid-powered systems providing most of the energy.

In May and September, photovoltaic-powered heat pumps can cover a significant portion (47%) of the thermal demand due to higher solar energy availability during these months. However, in the peak summer months—June, July, and August—the reliance shifts towards grid-powered heat pumps. This shift likely occurs because the electricity demand for cooling exceeds the generation capacity of the installed photovoltaic systems during this period, requiring more energy from the grid.

PED primary balance

The table presents a comparative analysis of energy generation, consumption, and the resulting energy balance for the Copenhagen district after retrofit interventions. The energy values are expressed in terms of primary energy, calculated according to the ISO 52000 standard. For photovoltaic energy generation, a primary energy factor of 1 has been applied, as per ISO 52000.

For energy consumption, the following factors were used:

- Self-consumption of photovoltaic energy: Primary energy factor of 1 (same as for energy generation).
- Electricity consumption from the grid: Primary energy factor of 2.5, reflecting the grid's conversion efficiency.

- Thermal energy consumption from natural gas (methane): Primary energy factor of 1.1, which accounts for the efficiency of natural gas combustion.

Table 68 Primary energy balance in the Copenhagen district

Generation of energy [GWh]	Consumption of energy [GWh]	Difference [GWh]
6.60	46.36	-39.76

The results highlight a considerable gap between energy generation and consumption in the Copenhagen district, even after the implementation of retrofit measures. With energy generation at 6.6 GWh and consumption reaching 46.36 GWh, the difference stands at -39.76 GWh, indicating that despite the energy efficiency improvements, the district's energy production remains insufficient to cover its overall needs.

As in the case of Bucharest, for the Copenhagen district, the primary energy balance according to ISO 52000 assigns a lower primary energy factor (1) to photovoltaic energy compared to grid electricity (2.5). However, if the same primary energy factor (2.5) were applied to both photovoltaic and grid electricity, the comparison between the two energy sources would become more stringent. In this scenario, the energy balance would still improve towards achieving the PED target, as a higher primary energy factor would increase the contribution of photovoltaic energy to the overall balance, making it easier to exceed consumption with generation.

The following table presents a comparison between the standard scenario and the adjusted one with a uniform primary energy factor, showing how this adjustment impacts the ability to meet the PED target.

Table 69 Comparison of primary energy balance in the Copenhagen district: applying the same primary energy factor for generation and consumption.

Generation of energy [GWh]	Consumption of energy [GWh]	Difference [GWh]
16.50	46.36	-29.86

When focusing solely on the electricity balance, the analysis shows that the excess of electricity can be exported to the grid, which has been analysed as one of the potential strategies to reduce both the district's electricity demand from the grid and its reliance on district heating (as illustrated in Figure 105 and Figure 106). By optimizing the export of excess photovoltaic energy, it is possible to reduce grid imports and partially offset the energy requirements for heating.

However, when the thermal demand is integrated into the analysis, it becomes clear that the district still does not meet the PED target. While the export of excess electricity helps improve the balance, the heating demand remains a significant challenge. The energy deficit related to district heating, even with the contribution of heat pumps powered by photovoltaics, underscores the continued reliance on external energy sources to meet the thermal needs of the district.

Although the district is nearing electrical self-sufficiency thanks to photovoltaic generation, achieving the PED target requires further efforts, particularly in addressing thermal energy consumption.

Case Study 4 – Parma

Insulation and windows

In the Parma case study, the enhancing of building insulation and upgrading windows strategy was developed by the guidelines provided in the *Decreto Requisiti Minimi*, the Italian regulation for energy performance in buildings. The decree specifies thermal transmittance (U-value) targets that vary based on the building's climate zone. Parma, situated in Climate Zone E, has specific requirements for retrofitting to ensure energy efficiency is maximized according to local climatic conditions.

The following U-values, which represent the maximum allowable limits, were targeted to enhance energy efficiency in the Parma district:

- External walls: 0.28 W/m²K;
- Basement walls adjacent to the ground: 0.29 W/m²K;
- Ground floors and basement floors adjacent to the ground: 0.29 W/m²K;
- Roofs: 0.24 W/m²K;
- Windows: 1.40 W/m²K.

The subsequent tables will present the variations in thermal energy consumption for each building archetype showing the impacts of these interventions on heating and cooling demands.

Table 70 Impact of enhancing building insulation and upgrading windows on cooling and heating demand for archetype 1 in Parma.

Archetype 1	Cooling [kWh/m^2]	Heating [kWh/m^2]
Without retrofit	27.05	130.88
With retrofit	15.85	88.48
Difference	-41%	-32.39%

Table 71 Impact of enhancing building insulation and upgrading windows on cooling and heating demand for archetype 2 in Parma.

Archetype 2	Cooling [kWh/m²]	Heating [kWh/m²]
Without retrofit	21.84	105.25
With retrofit	17.71	73.20
Difference	-19%	-30.45%

Table 72 Impact of enhancing building insulation and upgrading windows on cooling and heating demand for archetype 3 in Parma.

Archetype 3	Cooling [kWh/m²]	Heating [kWh/m²]
Without retrofit	16.12	299.14
With retrofit	17.96	183.12
Difference	11.42%	-38.79%

Table 73 Impact of enhancing building insulation and upgrading windows on cooling and heating demand for archetype 4 in Parma.

Archetype 4	Cooling [kWh/m²]	Heating [kWh/m²]
Without retrofit	34.46	182.08
With retrofit	31.27	112.20
Difference	-9.27%	-38.38%

Table 74 Impact of enhancing building insulation and upgrading windows on cooling and heating demand for archetype 5 in Parma.

Archetype 5	Cooling [kWh/m²]	Heating [kWh/m²]
Without retrofit	63.28	289.13
With retrofit	37.16	211.26
Difference	-41.27%	-26.93%

Table 75 Impact of enhancing building insulation and upgrading windows on cooling and heating demand for archetype 6 in Parma.

Archetype 6	Cooling [kWh/m²]	Heating [kWh/m²]
Without retrofit	49.40	233.75
With retrofit	34.22	172.75
Difference	-30.73%	-26.10%

Table 76 Impact of enhancing building insulation and upgrading windows on cooling and heating demand for archetype 7 in Parma.

Archetype 7	Cooling [kWh/m²]	Heating [kWh/m²]
Without retrofit	56.91	155.67

With retrofit	39.25	87.30
Difference	-31%	-43.92%

The tables reveal how the measure can significantly reduce heating demand, improving the overall energy efficiency of the buildings.

The improvements in energy efficiency vary across different archetypes:

- Heating demand reduction ranges from a minimum of 26.1% (archetype 6) to a maximum of 43.92% (archetype 7);
- Cooling demand reduction varies from 9.27% (archetype 4) to 41.27% (archetype 5).

The next figure presents the monthly effects of the retrofit on the heating and cooling demand for both the baseline and renovated district, tracked over the course of a year.

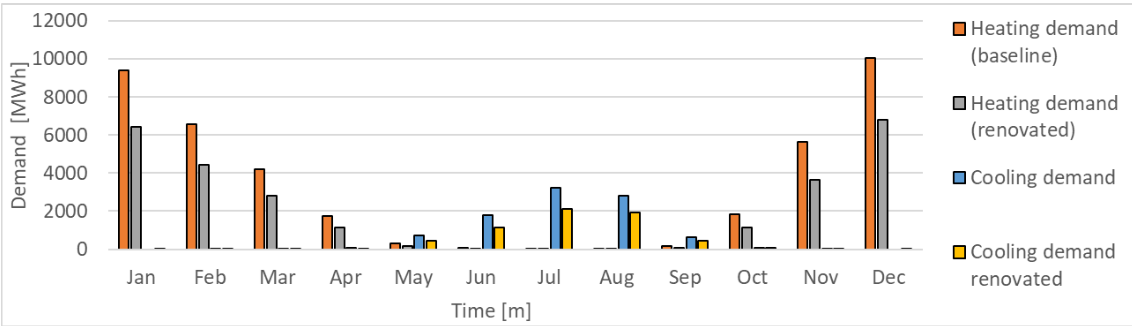


Figure 107 Monthly comparison of thermal demand with and without enhancing building insulation and upgrading windows in Parma.

The measure reduces the heating demand. In the baseline scenario, heating demand peaks at around 10,000 MWh in January and December, with high consumption in February and November as well. After the retrofit, the heating demand drops significantly, falling to approximately 4,000-6,000 MWh during the same months. This reduction highlights the effectiveness of the measure in lowering energy demand for heating, achieving savings of roughly 40-50%.

For cooling demand, the baseline district shows moderate energy use, with July and August peaking at about 2,000-3,000 MWh. After the retrofit, there is a slight increase in cooling demand, reaching around 3,000-4,000 MWh in the same months. This suggests that while the measure improves winter energy efficiency, it retains more heat during the summer, leading to an increased cooling demand.

Figure 108 illustrates the weekly variation in heating demand during a typical winter week for the district, considering the effect of retrofit. Similarly, Figure 109 presents the weekly variation in cooling demand during a typical summer week.

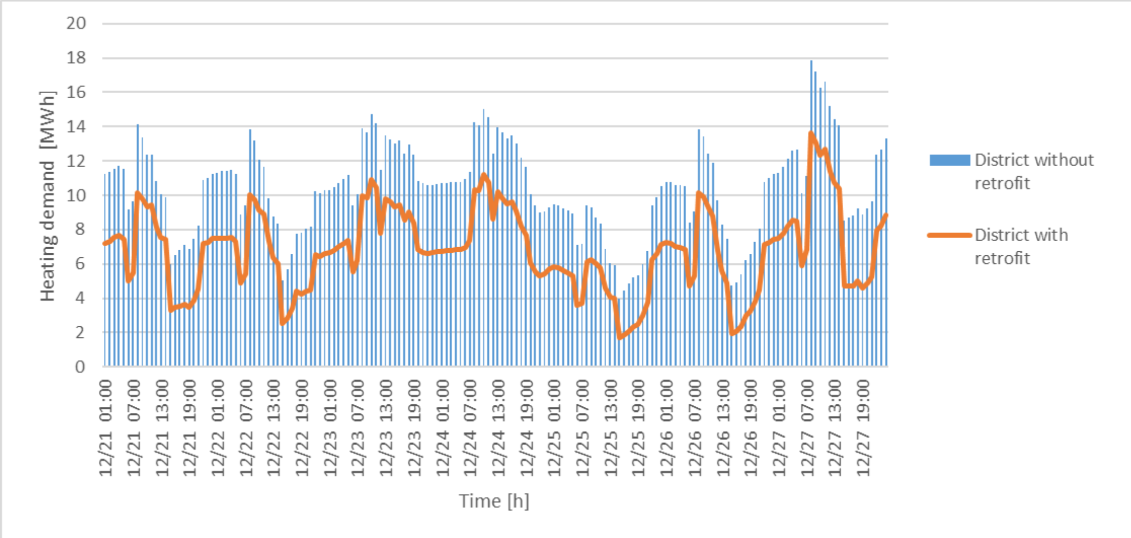


Figure 108 Comparison of heating demand before and after enhancing building insulation and upgrading windows in the Parma district.

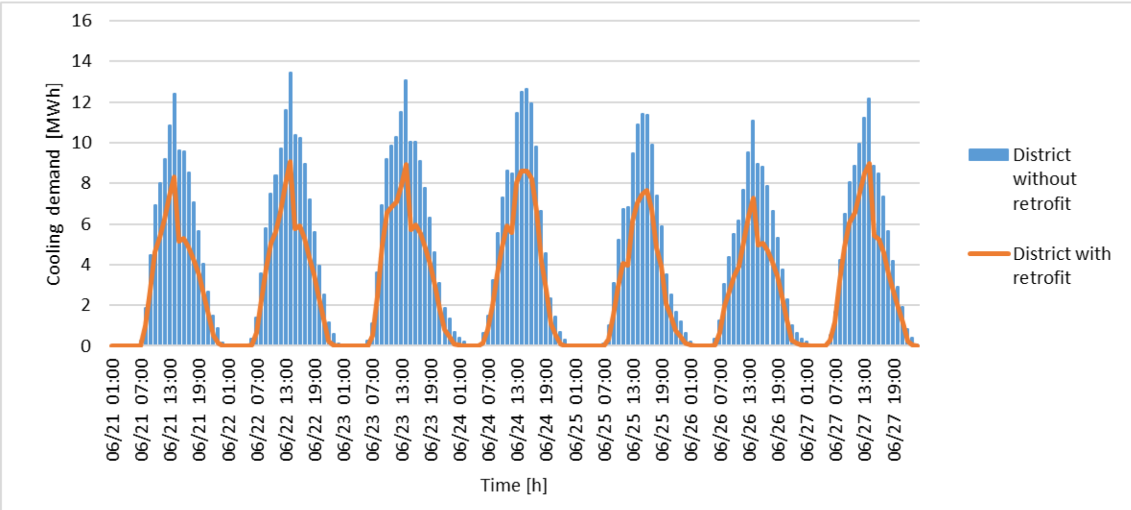


Figure 109 Comparison of cooling demand before and after enhancing building insulation and upgrading windows in the Parma district.

For cooling, the district with retrofit experiences much lower demand, especially during peak hours on the hottest days. This suggests that retrofit effectively limits heat gains, reducing the need for cooling. In the case of heating, the district with retrofit also shows a consistent reduction in energy demand, particularly during colder nighttime hours.

Figure 110 presents an annual analysis of electricity consumption variations due to the application of the measure.

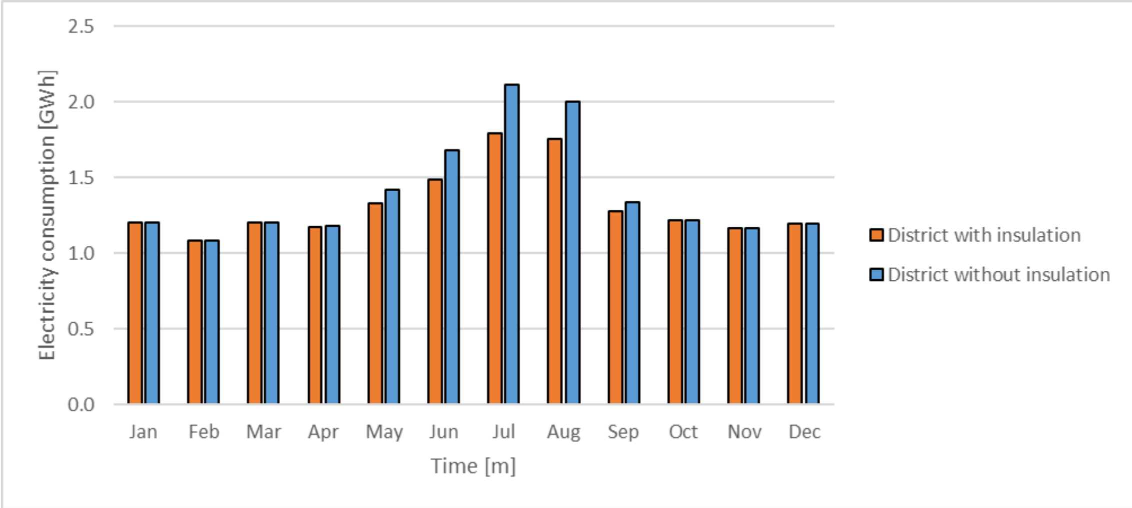


Figure 110 Comparison of electricity demand before and after enhancing building insulation and upgrading windows in the Parma District

The figure shows no reductions during the winter months, as the electric systems considered are used exclusively to cover cooling needs in the summer and not for heating in the winter. The table below provides an annual comparative analysis of heating, cooling and electricity demand before and after the renovation.

Table 77 Impact of enhancing building insulation and upgrading windows on heating, cooling and electricity demand for renovation scenario.

	Heating Demand [GWh]	Cooling Demand [GWh]	Electricity Demand [GWh]
Baseline	40.05	9.34	16.82
Renovated	26.68	6.11	15.90
Difference [%]	-33%	-35%	-5%

After the renovation, heating demand decreases from 40 GWh to 26.7 GWh, representing a 33% reduction. This significant drop highlights the effectiveness of the measure in reducing the energy required to maintain indoor temperatures during colder periods by preventing heat loss.

Cooling demand also sees a reduction from 9.34 GWh to 6.11 GWh, a 35% decrease. Although this reduction is less intense than for heating, it still reflects the benefits on limiting heat gains during warmer months, thus reducing the need for cooling.

The overall electricity demand decreases from 16.82 GWh to 15.90 GWh, a 5% reduction. This smaller change indicates that, while the retrofit has a noticeable effect on reducing heating and cooling demands, other electricity-consuming activities (such as lighting and appliances) contribute to a large portion of the overall electricity use, and their reduction is not directly influenced by the measure.

Photovoltaic system

Achieving the PED targets requires enhancing on-site energy generation. Therefore, three potential scenarios for photovoltaic system installation have been explored: covering 50%, 75%, and 100% of the available area. The table below outlines the details for each scenario, with the most optimistic approach assuming full utilization of the available space to maximize solar energy production.

Table 78 Comparison of potential scenarios for the installation of photovoltaic systems

Area available used [%]	Area used [km^2]	Total power installed [MW]
50%	0.12	17
75%	0.18	25
100%	0.25	34

The following figure illustrates the comparison between monthly energy generation and consumption in the Parma district, considering three scenarios where the area occupied by photovoltaic systems increases from 50% to 100%.

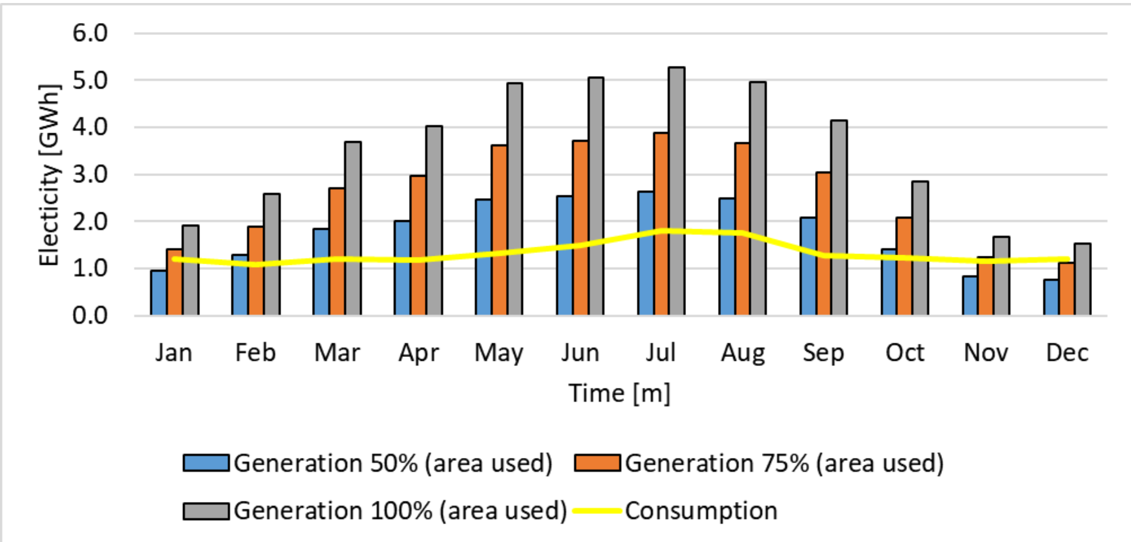


Figure 111 Comparison of monthly energy generation and consumption under different photovoltaic coverage scenarios.

The figure shows that even in the scenario with 50% photovoltaic coverage, energy generation exceeds consumption in most months, and this surplus becomes even more pronounced as the area used for photovoltaic systems expands to 75% and 100%.

However, the apparent energy surplus is also affected by the fact that methane gas boilers are used to meet heating demands during the winter months, reducing the district's electricity consumption in that period.

The following graph represents the monthly analysis of photovoltaic energy generation and consumption for the district of Parma, assuming the maximum utilization of 75% of available area for PV installation. It compares the electricity generated, consumed, imported, and exported each month, while also highlighting auto-consumption.

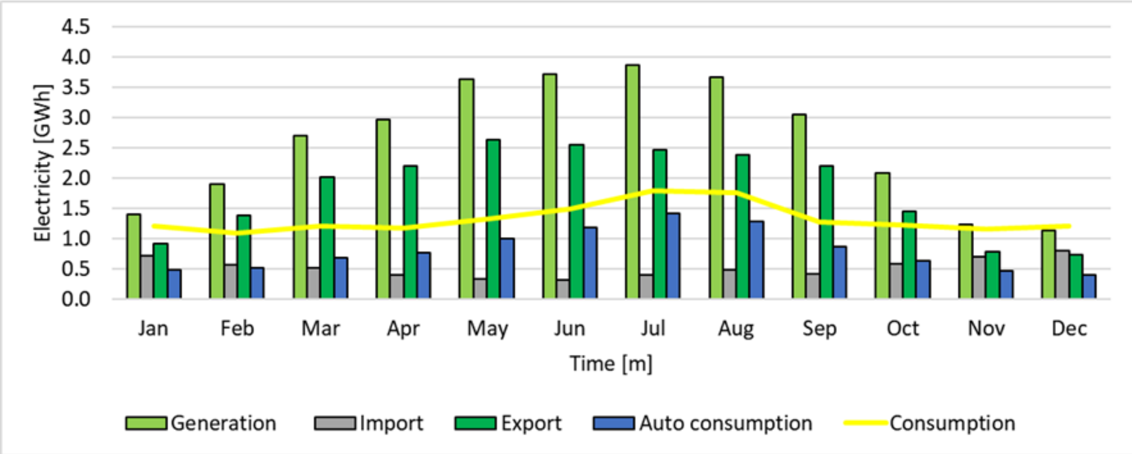


Figure 112 Monthly analysis for Parma: 75% available area scenario.

The graph shows that during the summer months, electricity generation exceeds consumption, leading to significant exports to the grid. In these months, generation reaches a peak of around 7 GWh, while consumption remains relatively stable, resulting in high export values as the surplus electricity is sent back to the grid. Auto-consumption remains consistent, indicating that a portion of the generated electricity is directly used within the district, while the excess is exported.

In contrast, during the winter months electricity leading to increased imports to meet the district's electricity demand. Consumption is generally higher relative to generation, resulting in a net import of energy from the grid to balance the demand.

The next figure illustrates the monthly distribution of electricity coverage by PV systems compared to grid electricity for a given location over a year.

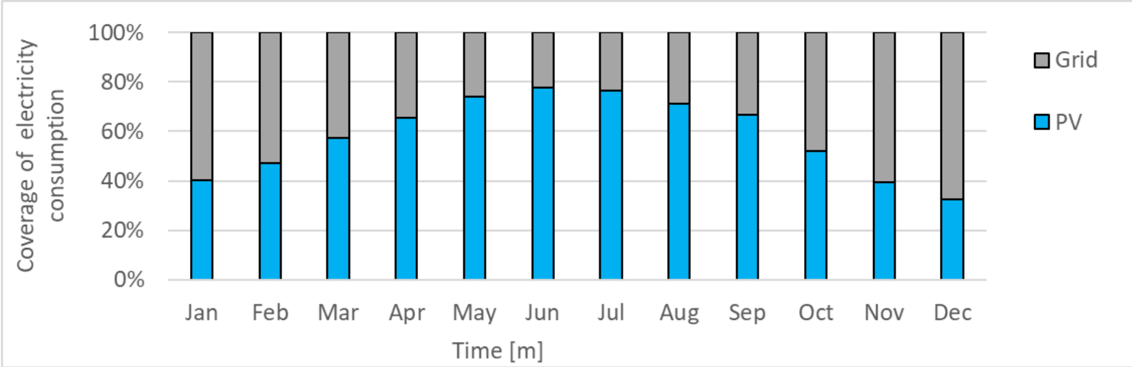


Figure 113 Monthly electricity consumption coverage in Parma.

The highest contributions from PV systems occur in the summer months where it covers a significant portion, ranging from around 70% to nearly 80% of the total electricity demand.

In contrast, during the less sunny months, the contribution from PV systems is lower, providing less than 40% of the total electricity needs. This decrease is due to shorter daylight hours and lower sun intensity, which naturally reduces solar power output.

PED primary balance

The following table summarizes the energy generation, consumption, and resulting primary energy balance for the Parma district after retrofit measures. Calculations follow the ISO 52000 standard, with photovoltaic generation assigned a primary energy factor of 1.

For energy consumption:

Photovoltaic self-consumption shares the same primary energy factor of 1.

Grid electricity is assigned a primary energy factor of 2.5.

Thermal energy from natural gas has a factor of 1.1, accounting for the combustion efficiency of methane.

Table 79 Primary energy balance in the Parma district

Generation of energy [GWh]	Consumption of energy [GWh]	Difference [GWh]
31.35	64.39	-33.04

The data shows that the district generates 31.35 GWh of energy, compared to a total energy consumption of 64.39 GWh, resulting in a deficit of 33.04 GWh. The enhancing building insulation and upgrading windows has played a crucial role in this outcome, significantly reducing the thermal demand for both heating and cooling. By lowering the energy required for temperature regulation, the district has decreased its overall consumption. However, despite these improvements, the district has not yet reached the PED target.

In the following table, energy generation is evaluated using the same primary energy factor of 2.5 as that applied to grid electricity consumption.

Table 80 Comparison of primary energy balance in the Parma district: applying the same primary energy factor for generation and consumption.

Generation of energy [GWh]	Consumption of energy [GWh]	Difference [GWh]
78.37	64.39	13.98

The results indicate that by applying a primary energy factor of 2.5 to both generation and consumption, the contribution of renewable energy is amplified. the district generates 78.37 GWh of energy, while total consumption amounts to 64.39 GWh, leading to a positive balance of 13.98 GWh. This demonstrates that energy generation exceeds consumption, creating a surplus that meets the criteria for a PED.

8. Environmental analysis for case studies

This environmental impact assessment compares for the baseline scenario, only the use phase on an annual basis. For retrofit (renovated district), the assessment includes the entire life cycle-both the operational impacts during the use phase and the environmental impacts associated with the production and end-of-life of new materials and installations required for refurbishment-also assessed on an annual basis. Manufacturing and end-of-life impacts for retrofit are evaluated on a single year basis using the useful life of the equipment or materials, effectively distributing the total impacts equally over each year of their expected useful life. This approach ensures a consistent and fair comparison by considering all environmental impacts on an annual basis.

The next table shows a list of the datasets used for the environmental impacts of the four case studies.

Table 81 Datasets for environmental impacts of the four case studies

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 flat-roof installation, 3kWp, single-Si, on roof {CH}| photovoltaic flat-roof installation, 3kWp, single-Si, on roof | Cut-off, U
		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
	Heat pump	Heat pump, brine-water, 10kW {CH}| heat pump production, brine-water, 10kW | Cut-off, U
	Battery	Self-developed dataset based on [187]
	District heating	Heat, district or industrial, natural gas {Europe without Switzerland} | heat production, natural gas, at industrial furnace >100kW
Use phase	Electricity Import	Electricity low voltage
	Natural gas consumption	Natural gas, burned in boiler modulating >100kW
End of life	Window frame	Disposal, building, window frame, plastic, to final disposal
	Glazing	Disposal, building, glazing 2-IV, U<1.1W/m2K, to final disposal
	Insulation	Disposal, building, polystyrene isolation, flame-retardant, to final disposal
	Photovoltaic system	Calculated based on life cycle inventory data from the Ecoinvent database[188]
	Heat pump	
	District heating[1]	

[1]For the district heating system, the retrofit strategy focused solely on replacing the centralized generator, without any intervention on the distribution or emission sections of the system. As a result, the end-of-life scenario for the retrofit only considers the annual impact of disassembling the existing generator.

Case Study 1 – Pamplona

The figure above presents a comparison of the GWP between the baseline district (scenario 1) and the renovated district (scenario 2).

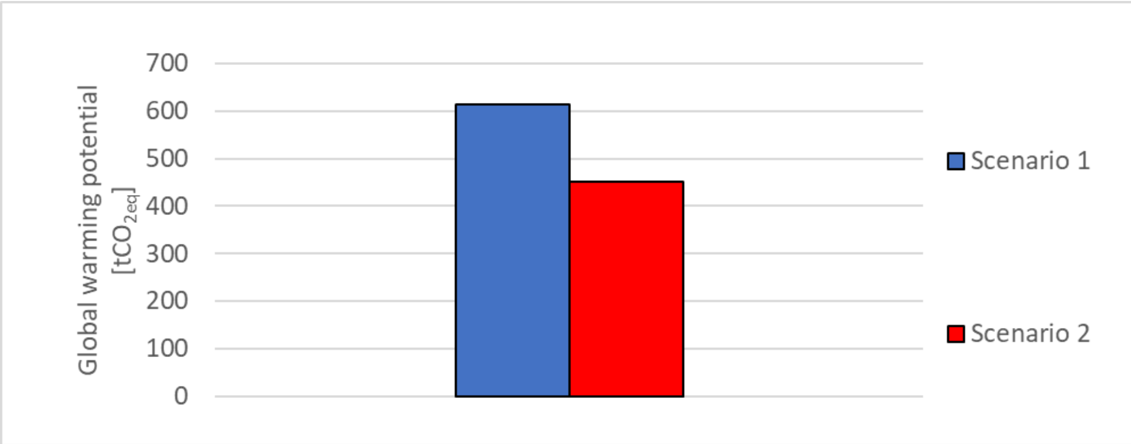


Figure 114 Comparison of GWP between baseline and renovated districts in Pamplona.

The results show that the GWP of the life cycle of the renovated district is approximately 450 tCO_{2eq}, whereas the use phase of the baseline district shows a higher GWP of around 600 tCO_{2eq}.

The figure above presents a breakdown of the GWP for both the baseline (Scenario 1) renovated (Scenario 2) districts during their use phases.

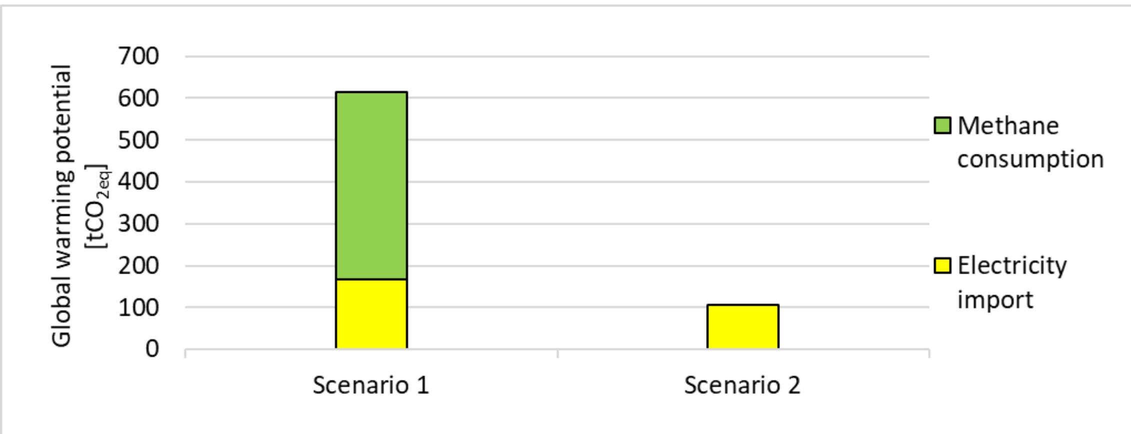


Figure 115 Breakdown of GWP by energy source for use phase in Pamplona.

In the use phase of the renovated district, the GWP is dominated by electricity imports, reaching a value of approximately 100 tCO_{2eq}. There is no contribution from methane consumption in this case, this improvement is attributed to the shift to electricity-based heating systems, particularly using heat pumps. In contrast, the use phase of the baseline district shows a much higher GWP, reaching around 600 tCO_{2eq}. This is largely driven by methane consumption, which contributes most of the emissions, while electricity imports contribute a smaller portion, around 200 CO_{2eq}.

These results highlight the environmental benefits of the renovation in reducing operational carbon emissions, particularly through the transition away from fossil fuels like methane. significant reduction in GWP of the renovated district.

The dominance analysis presented in the following figure indicates the contributions to the GWP across different components of the life cycle of the renovated district.

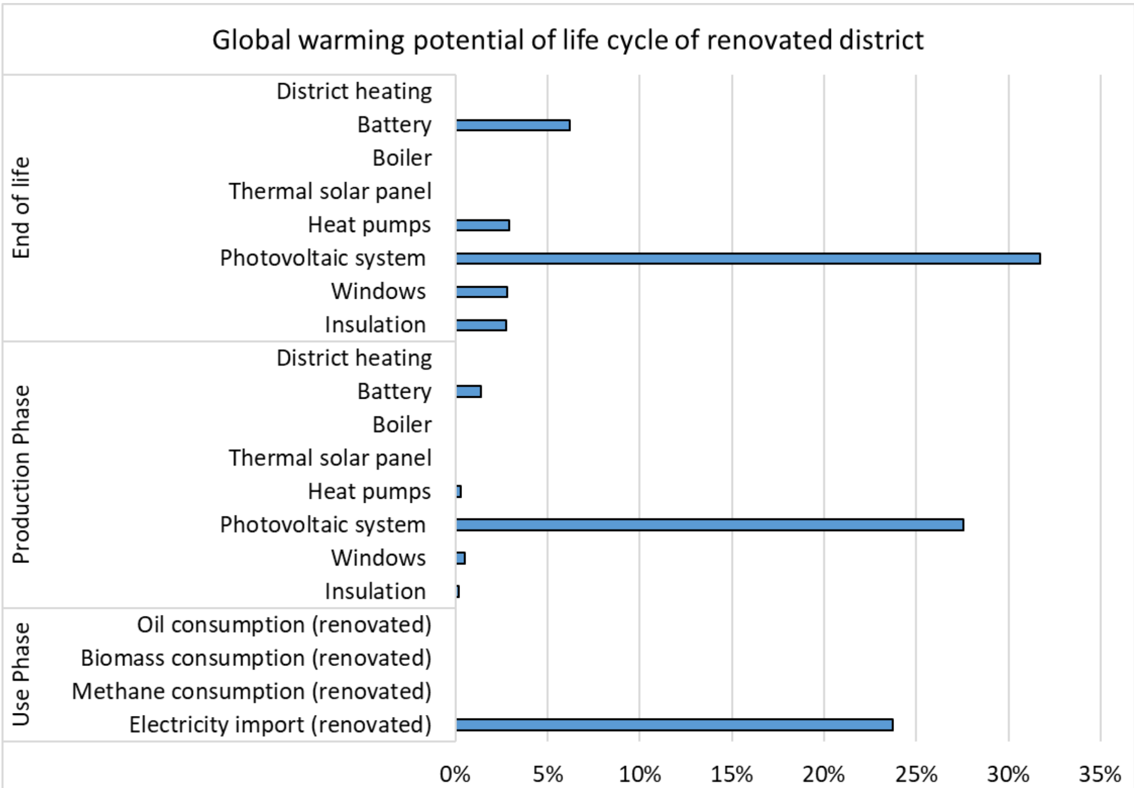


Figure 116 Dominance analysis of GWP for renovated district in Pamplona.

The dominance analysis revealed that the end-of-life phase of the photovoltaic system is the largest contributor to the GWP. Specifically, the photovoltaic system accounts for approximately 30% of the total GWP, making it the most significant factor in the entire life cycle analysis.

In the production phase, the photovoltaic system also plays a key role, contributing around 25% of the total GWP. The battery system and insulation contribute approximately 3% and 1%, respectively.

In the use phase, electricity imports make up around 25% of the total GWP.

The photovoltaic system during its end-of-life phase is the largest single contributor to the GWP, followed by electricity imports in the use phase. This suggests that efforts to improve the recyclability and end-of-life management of the photovoltaic system could significantly reduce the overall environmental impact of the renovated district.

The figure illustrates the comparison of cumulative energy demand between the life cycle of the renovated district (Scenario 2) and the use phase of the baseline district (Scenario 1).

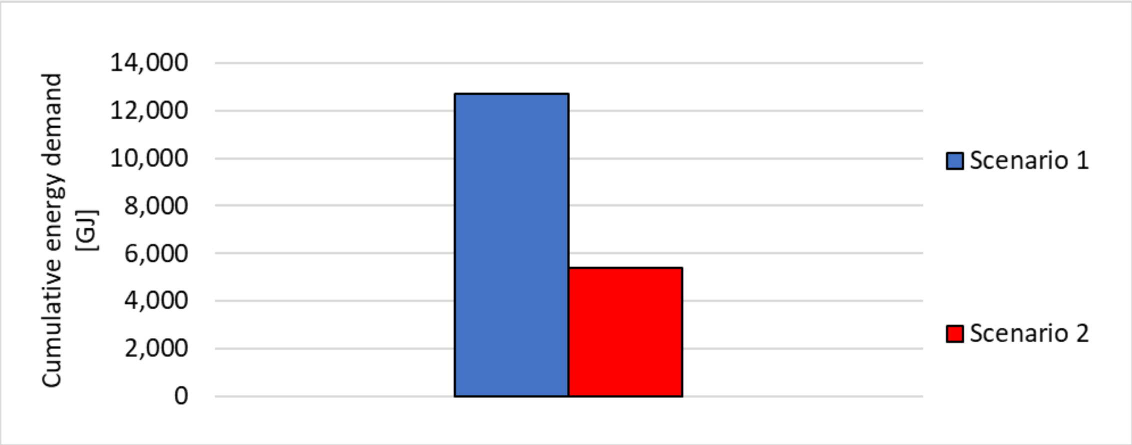


Figure 117 CED of baseline and renovated districts in Pamplona.

The energy demand of the renovated district is approximately 6,000 GJ and is significantly lower compared to the cumulative energy demand of the baseline district that is approximately 13,000 GJ.

The following figure illustrates the cumulative energy demand comparison between the use phase of the renovated district and the use phase of the baseline district. It provides insights into how different energy sources contribute to the overall energy consumption in each scenario.

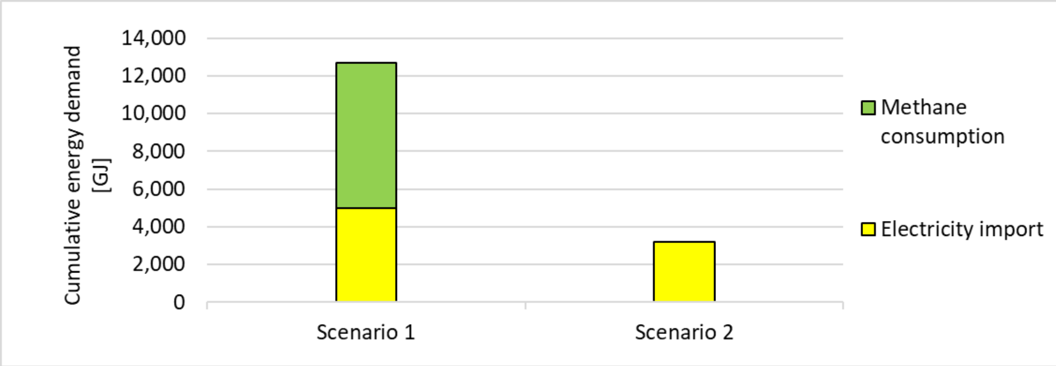


Figure 118 Breakdown of CED by energy source for use phase in Pamplona.

In the use phase of the renovated district, the total energy demand is approximately 3,000 GJ, and it is entirely due to electricity imports, with no methane consumption.

In the use phase of the simulated district, the total energy demand is much higher, around 13,000 GJ. This higher demand is mainly due to methane consumption, which contributes around 8,000 GJ, with electricity imports contributing an additional 5,000 GJ.

The results show that the simulated district has a much higher energy demand compared to the renovated district, primarily due to its reliance on methane. The renovated district, depend on solely on electricity, demonstrates a significant reduction in overall energy consumption during the use phase.

The following figure presents the cumulative energy demand of the renovated district, breaking down the contributions of production and use phases. The chart highlights the relative impact of different elements on the overall energy demand in terms of percentage.

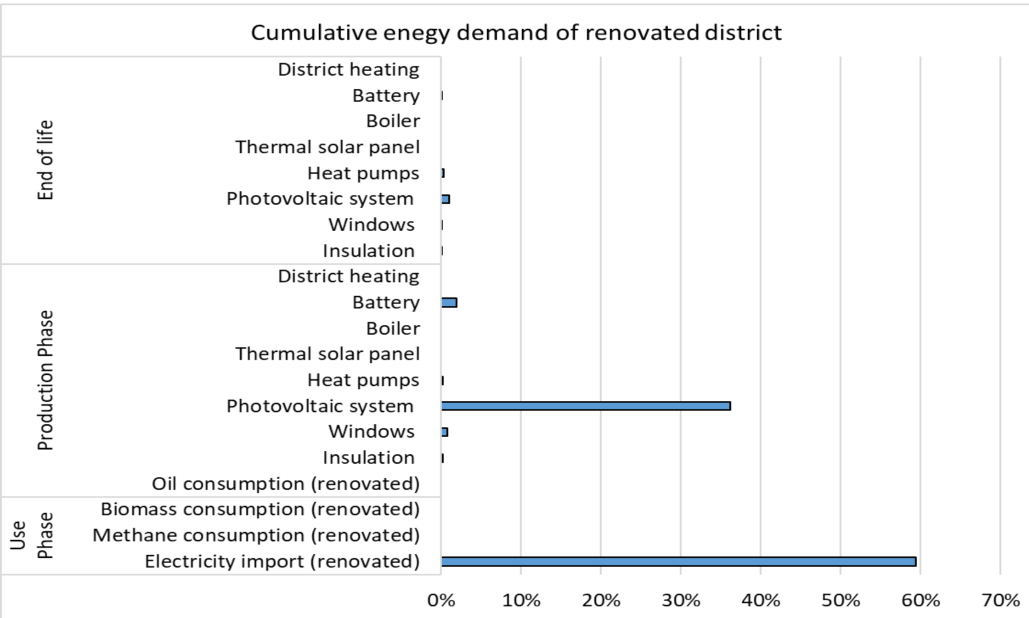


Figure 119 Dominance analysis of CED of renovated district in Pamplona.

The electricity import during the use phase is the largest contributor to the cumulative energy demand of the renovated district, accounting for approximately 60% of the total energy demand. This indicates that despite the energy-efficient measures and the addition of renewable energy systems, the district still relies significantly on grid electricity, which impacts the overall energy balance.

The photovoltaic system in the production phase is the second most significant contributor, accounting for approximately 35% of the cumulative energy demand. While these systems contribute positively to renewable energy generation, their initial production has a notable energy cost.

The next figure illustrates three key environmental indicators: EPT, GWP-PT and EER evaluating the energy and environmental performance of the renovated district compared to the baseline district. These indicators help assess whether the energy and environmental impacts invested in retrofitting the district are compensated by the subsequent energy savings and reduction in emissions over time.

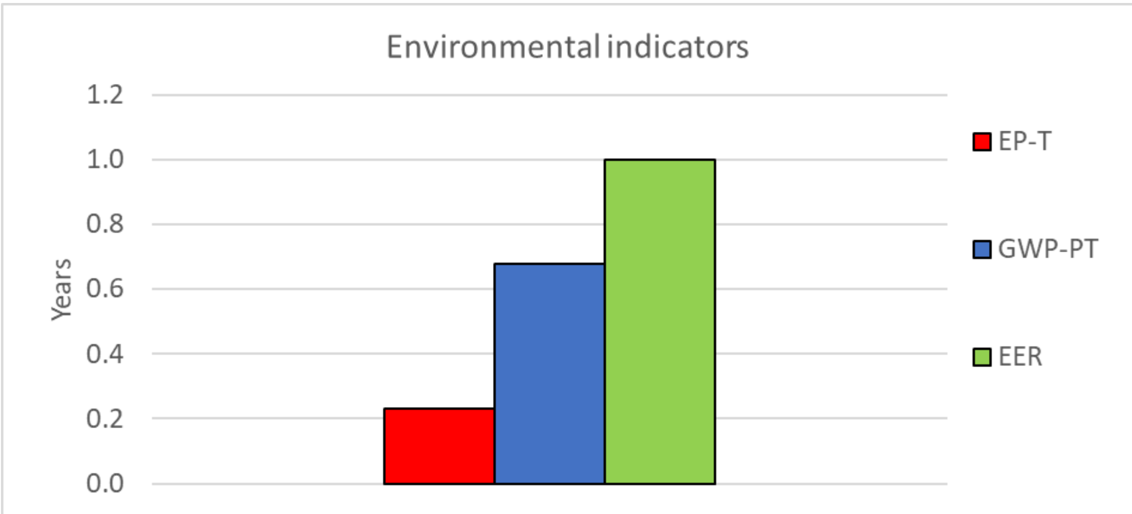


Figure 120 Environmental Indicators for renovated district in Pamplona.

The EP-T is less than 0.3 years, indicating that the energy invested in the renovation is paid back in a relatively short time. This suggests that the renovated district quickly achieves energy savings that offset the initial energy expenditure for its renovation.

The GWP-PT is slightly higher, around 0.6 years, meaning that the global warming impact caused by the renovation is compensated within this time frame. This still represents a quick payback, indicating a relatively strong environmental performance in terms of reducing emissions.

The EER, which is close to 1 year, shows that the overall environmental efficiency of the renovation is favourable. This means that the resources saved, and the benefits gained from the renovation make it an efficient investment from an environmental standpoint.

This case study suggests that the renovated district achieves a quick energy and environmental impact payback. The energy and emissions associated with the renovation are compensated within a short period, and the district shows strong environmental efficiency. This indicates that the renovation delivers significant environmental benefits within a short operational timeframe.

Case Study 2 – Bucharest

The figure above illustrates a comparison of the GWP between the baseline district (scenario 1) and the renovated district (scenario 2).

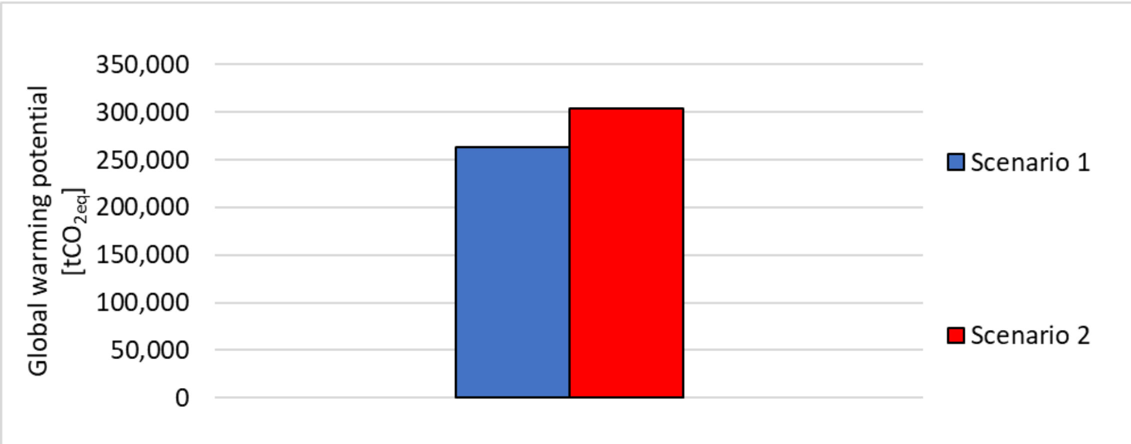


Figure 121 Comparison of GWP between baseline (scenario 1) and renovated districts (scenario 2) in Bucharest.

The results show that the total lifecycle GWP for the renovated district, which includes emissions from production, use, and end-of-life stages, is approximately 300,000 tCO_{2eq}, and is higher than the baseline district while is around 250,000 tCO_{2eq}.

The figure above provides a breakdown of the GWP for both the renovated and baseline districts during their respective use phases.

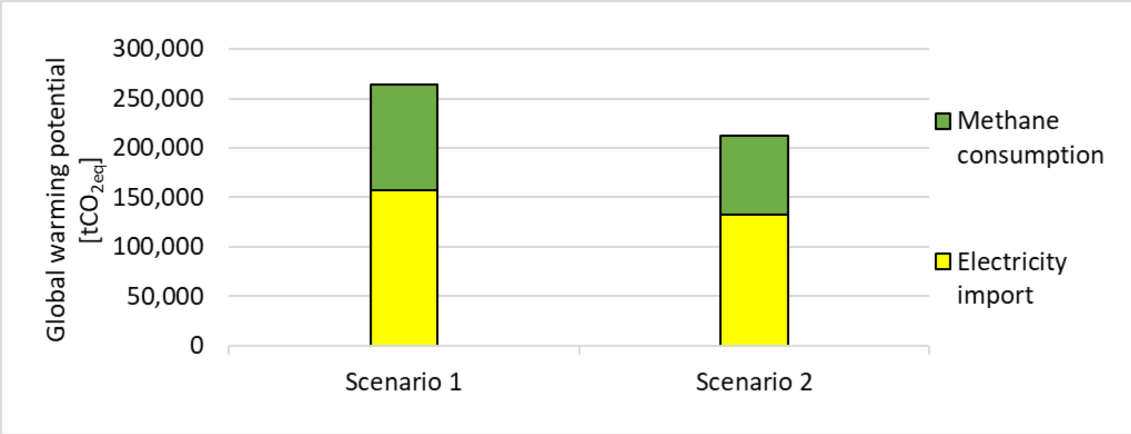


Figure 122 Breakdown of GWP by energy source for use phase in Bucharest

The figure shows that, when focusing solely on the operational phase, the baseline district (Scenario 1) has a GWP of approximately 260,000 tCO_2eq, with methane consumption accounting for around 100,000 tCO_2eq and electricity import contributing approximately 160,000 tCO_2eq. In comparison, the renovated district (Scenario 2) has a significantly lower GWP of approximately 200,000 tCO_2eq, with methane consumption contributing around 70,000 tCO_2eq and electricity import accounting for about 130,000 tCO_2eq

In the baseline district, GWP contributions stem from both methane consumption and electricity imports, with methane consumption accounting for most emissions. This highlighting the reliance on fossil fuels for heating, which leads to high greenhouse gas emissions during operation.

For the renovated district, the figure shows a notable reduction in emissions, primarily due to the reduction of methane consumption. This reduction is indicative of the replacement of the district heating system. Furthermore, the installation of insulation and the integration of photovoltaic panels, have also played critical roles in minimizing the carbon footprint during the operational phase.

The following figure represents a dominance analysis of the GWP over the life cycle of a renovated district.

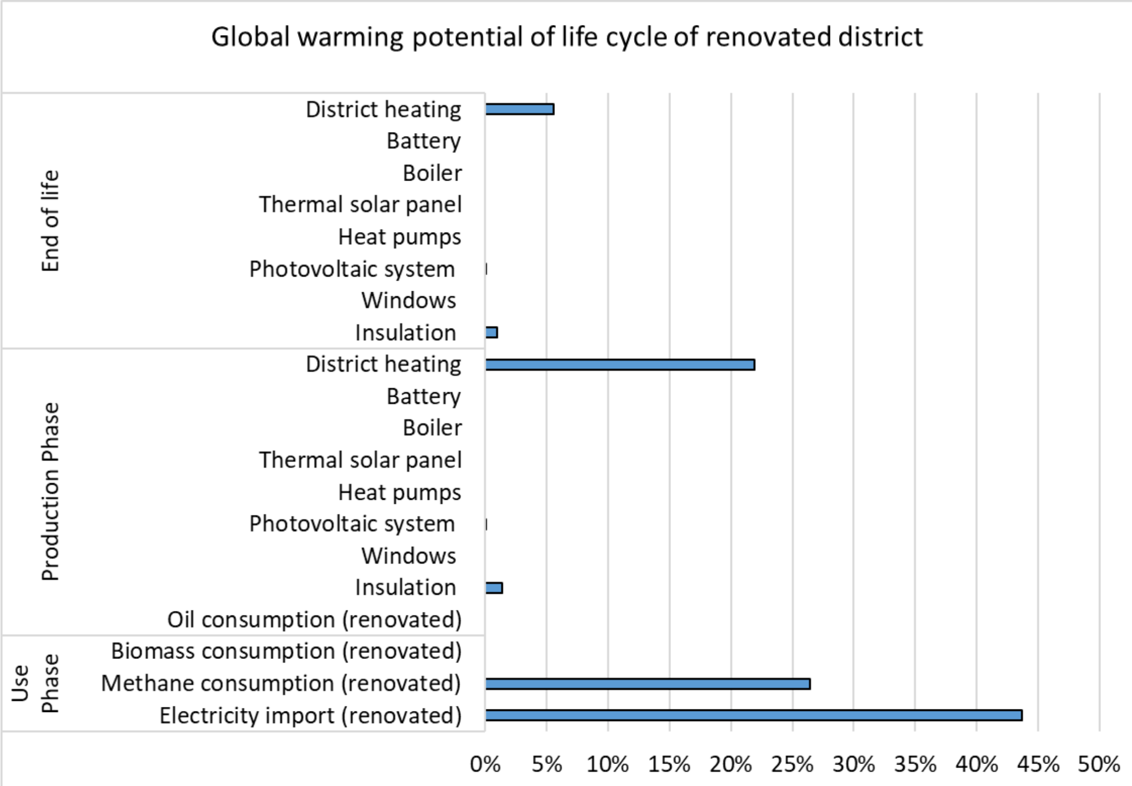


Figure 123 Dominance analysis of GWP for renovated district in Bucharest.

In the end-of-life phase, the district heating system emerges as the largest contributor to GWP, accounting for 5% of the total impact, followed closely by insulation.

In the production phase, the district heating system remains the dominant contributor to GWP, reaching approximately 25% of the total impact while the impact from other elements like insulation remains comparatively low.

During the use phase, electricity imports represent the largest source of GWP, contributing 45% to the total, followed by methane consumption at 25%. These results highlight the critical importance of optimizing energy sourcing, increasing the integration of renewable energy and improving energy efficiency during the operational phase to significantly reduce emissions over the district's life cycle.

The figure presents a comparison of the CED between the life cycle of a renovated district and the use phase of a baseline district.

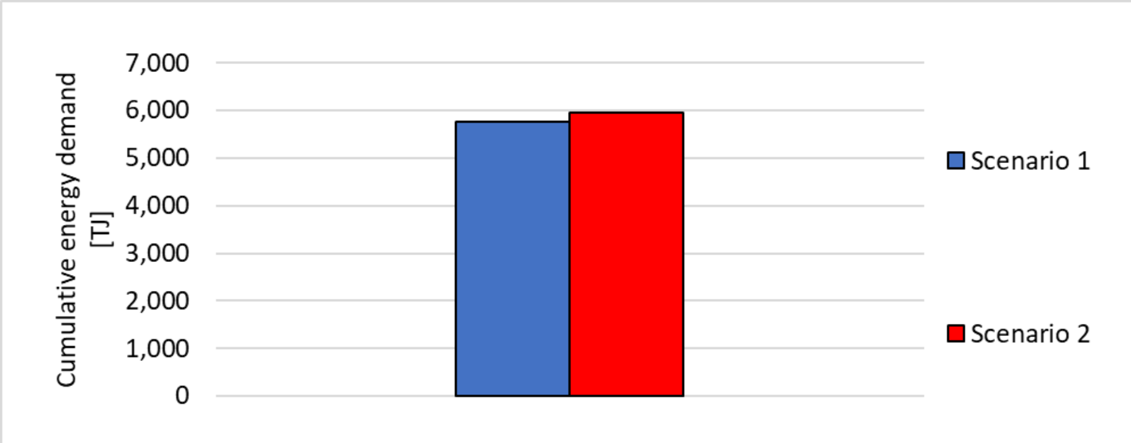


Figure 124 CED of baseline (scenario 1) and renovated (scenario 2) districts in Bucharest.

The life cycle of the renovated district shows a higher CED, reaching approximately 6,000 TJ. On the other hand, the use phase of the baseline district has a significantly lower energy demand, around 5,800 TJ. This lower value reflects only the energy consumption during the use phase of the district without considering other life cycle phases like production or end-of-life.

The following figure presents a comparison of CED during the use phase of the renovated district and the simulated district,

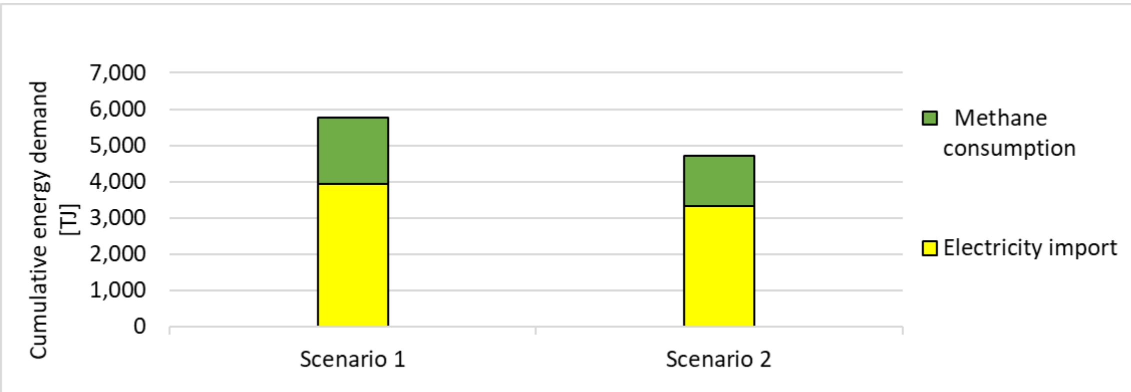


Figure 125 Breakdown of CED by energy source for use phase in Bucharest.

In the renovated district, the total energy demand reaches approximately 5,000 TJ, with electricity imports contributing around 3500 TJ and methane consumption adding 1,500 TJ. In the simulated district, the total energy demand is slightly lower, at about 6,000 TJ, with electricity imports accounting for approximately 4,000 TJ and methane consumption around 2,000 TJ.

The results show that while renovation improve energy efficiency, there remains a significant reliance on external electricity and methane consumption.

The following figure represents a dominance analysis of the CED for the renovated district.

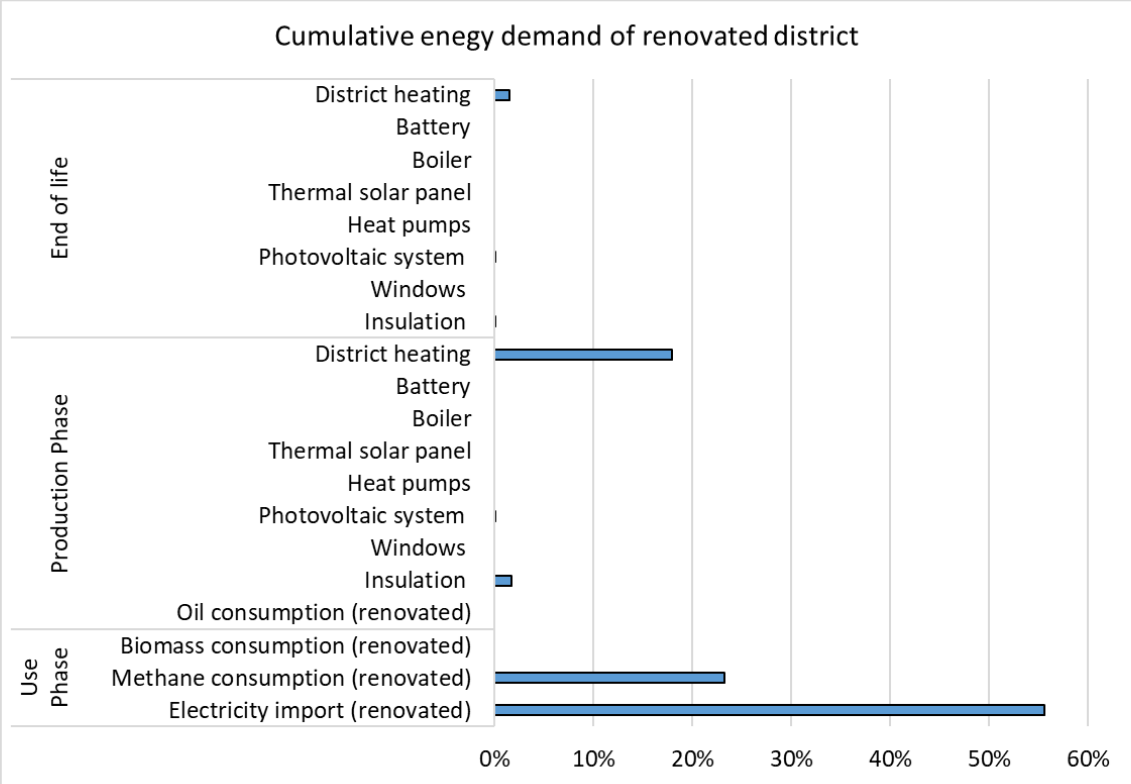


Figure 126 Dominance analysis of CED of renovated district in Bucharest

In the end-of-life phase, the contributions to the CED are minimal and can be considered negligible when compared to the other phases.

In the production phase, the district heating system is the major contributor to CED, reaching the 20% of overall impact. Other elements contribute relatively little in comparison, indicating that production efforts for the district heating infrastructure are energy-intensive.

In the use phase, the most significant contributor to energy demand is electricity imports, which account for approximately 55% of the total CED.

This dominance analysis highlights that while production and end-of-life phases contribute, the use phase, particularly electricity imports, is the largest driver of energy demand in the renovated district. This suggests that efforts to optimize energy sourcing, such as increasing local renewable energy generation, could significantly reduce the CED of the district.

The following figure presents a comparison of three environmental indicators—EP-T, GWP-PT, and EER—expressed in years.

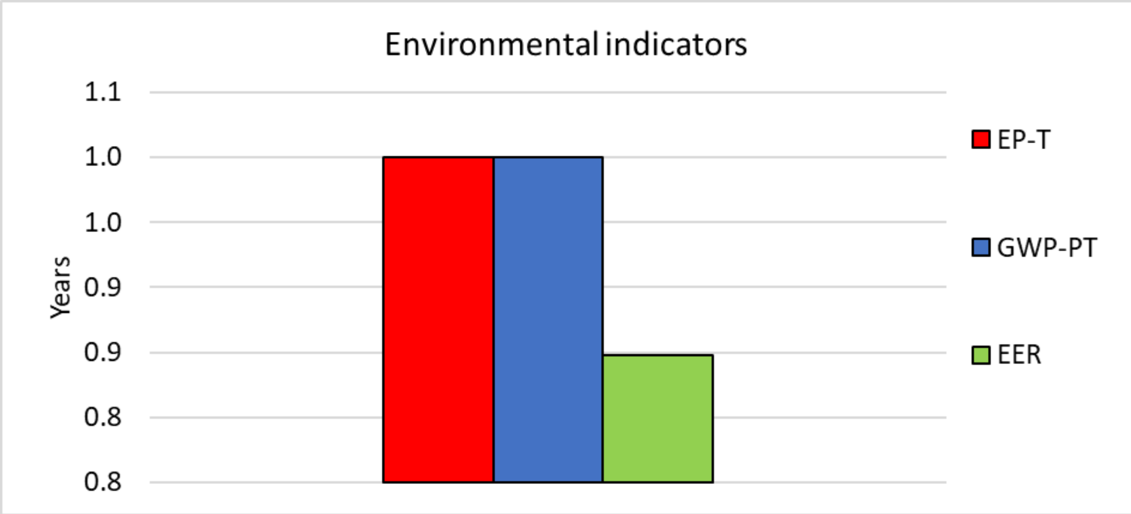


Figure 127 Environmental Indicators for renovated district in Bucharest.

The figure illustrates that both the EP-T and the GWP-PT reach approximately 1 year. If this time frame is considered as the useful lifetime of the renovated district, it indicates that the environmental investment does not yield a substantial return. In fact, the energy and emissions saved during the operational phase merely compensate for the impacts associated with the renovation itself. This suggests that over the one-year lifetime, no net environmental benefits are achieved, as the savings are used solely to offset the initial impacts.

The EER, which is lower than 1, further supports this conclusion. It indicates that the environmental efficiency of the renovation is suboptimal within this time frame, as the ratio of resources saved to the environmental impact is not favourable. This implies that if the life cycle is limited to one year, the investment does not deliver a positive environmental return.

The results suggest that if the analysis is confined to a one-year period—interpreted as the useful lifetime of the project—the renovation fails to generate net environmental gains, with the energy and emissions payback times equalizing the total life span. This underscores the need for either reducing the payback times or extending the lifetime to achieve meaningful environmental benefits.

Case Study 3 – Copenhagen

The figure presents a comparison of the GWP between the life cycle of the renovated district (scenario 2) and the use phase of the baseline district (scenario 1).

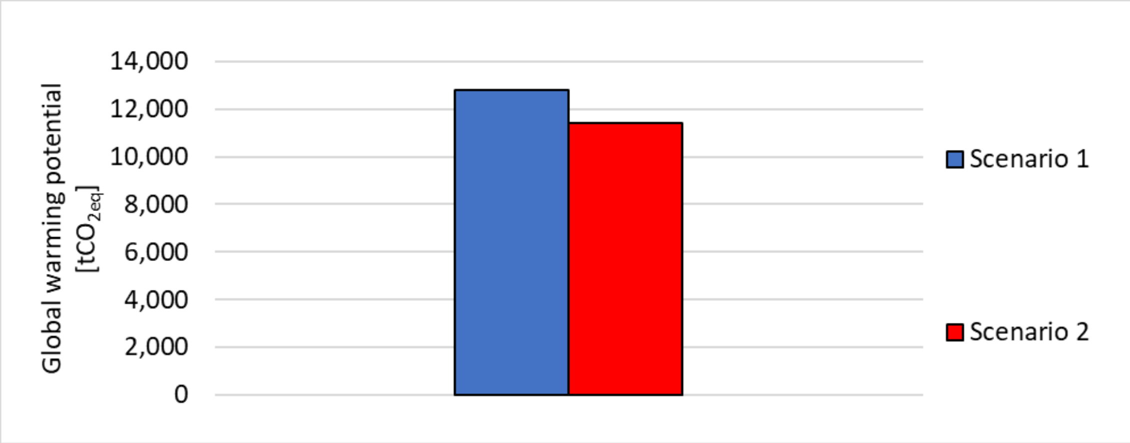


Figure 128 Comparison of GWP between baseline (scenario 1) and renovated (scenario 2) districts in Copenhagen.

The GWP of the renovated district's life cycle reaches 12,000 tCO_{2eq}, representing the total emissions over the entire life cycle, which includes the production, use and end-of-life phases. In comparison, the GWP for the use phase of the baseline district is significantly lower, at approximately 13,000 tCO_{2eq}.

The following figure compares the GWP, during the use phase of the renovated district and the baseline district.

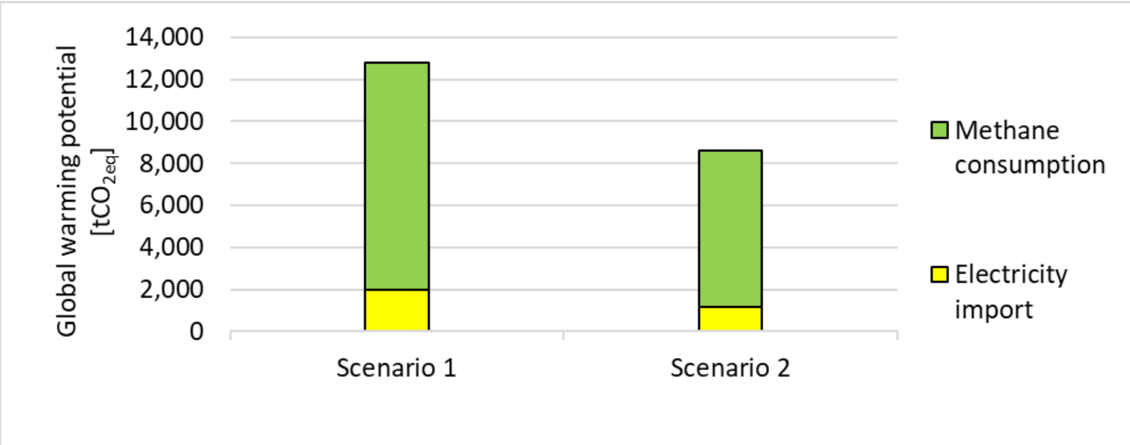


Figure 129 Breakdown of GWP by energy source for use phase in Copenhagen.

The figure shows that the use phase of the renovated district, the total GWP is approximately 9,000 tCO_{2eq}. Most of the emissions come from methane consumption, while electricity imports contribute a smaller portion, representing less than 10% of the total emissions.

In the use phase of the baseline district, the GWP is slightly higher, reaching around 13,000 tCO_{2eq}. Methane consumption is the dominant source of emissions, while electricity imports contribute a smaller but still notable share, making up about 15% of the total GWP.

These results highlight that while both districts depend on methane, the renovated district achieves a lower overall GWP due to reduced methane consumption. The relatively small contribution of electricity imports to the GWP in both cases suggests that reducing methane use would be the most effective strategy for further minimizing the global warming impact. Additionally, the significant reduction in the use phase impacts has offset the environmental burdens of other life cycle phases, leading to an overall improvement in the district's environmental performance.

The next figure represents a dominance analysis of the GWP throughout the life cycle of the renovated district and divided into the phases of end of life, production and use.

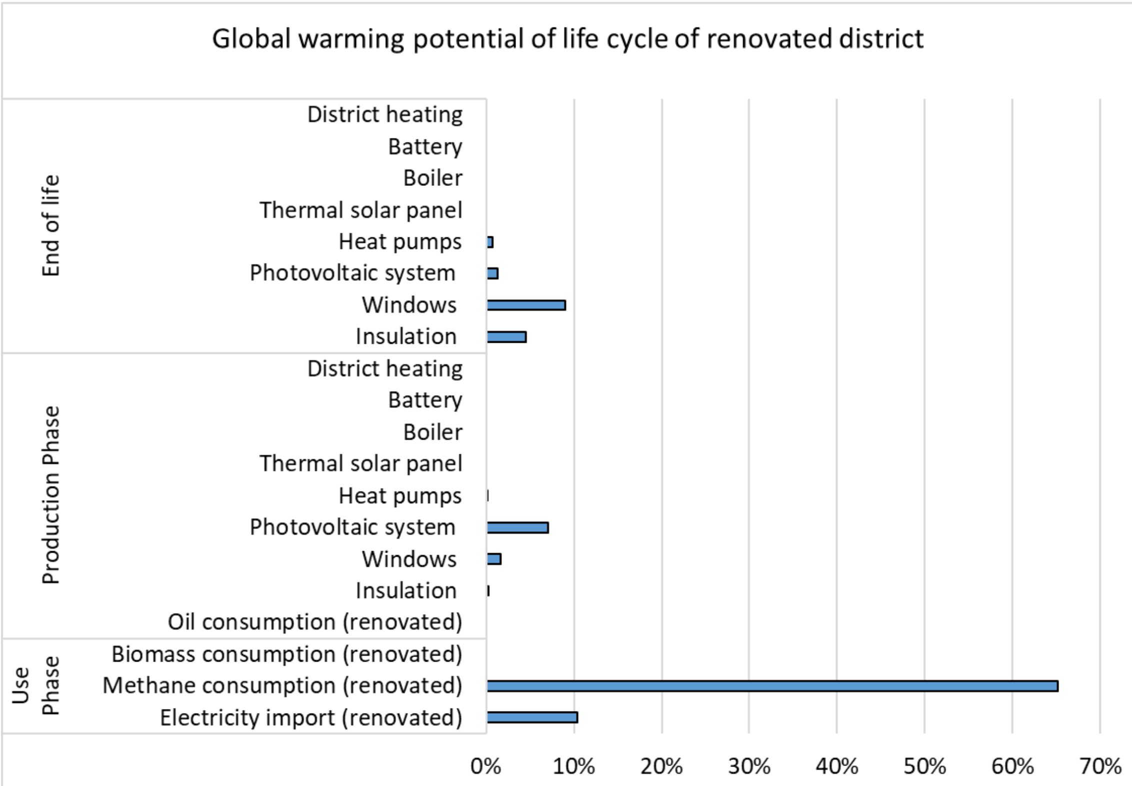


Figure 130 Dominance analysis of GWP for renovated district in Copenhagen.

In the end-of-life phase, windows have the largest impact, contributing approximately 5% to the total GWP, followed by the insulation, which accounts for around 3%. Components like heat pumps and photovoltaic system contribute minimally, around 1-2%.

During the production phase, the photovoltaic system is the dominant contributor, responsible for approximately 10% of the total GWP. Other elements, such as the insulation and windows, each contribute around 1%-3% to the overall impact.

In the use phase, methane consumption is a major driver of emissions, accounting for approximately 65% of the total GWP. This highlights its significant role in the environmental impact of the district during its operational phase, alongside electricity imports, which also play a crucial role.

Overall, the results show that the most substantial contributors to the district's GWP come from methane consumption in the use phase and windows in the end-of-life. Addressing these key areas could lead to significant reductions in the overall carbon footprint of the renovated district.

The following figure compares the CED between the life cycle of the renovated district (scenario 2) and the use phase of the baseline (scenario 1) district.

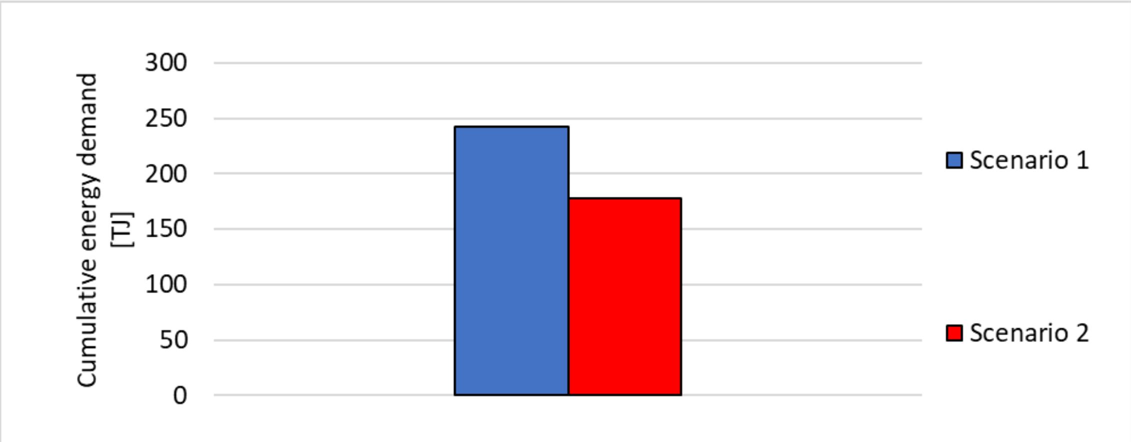


Figure 131 CED of baseline and renovated districts in Copenhagen.

The life cycle of the renovated district shows a total energy demand of approximately 200 TJ, which includes energy consumption during production, use and end-of-life phases. In contrast, the use phase of the baseline district exhibits a lower cumulative energy demand, around 250 TJ, representing only the energy consumed during its operational phase.

The next figure compares the CED during the use phase of the renovated district and the simulated district. The energy demand is broken down into contributions from methane consumption and electricity imports.

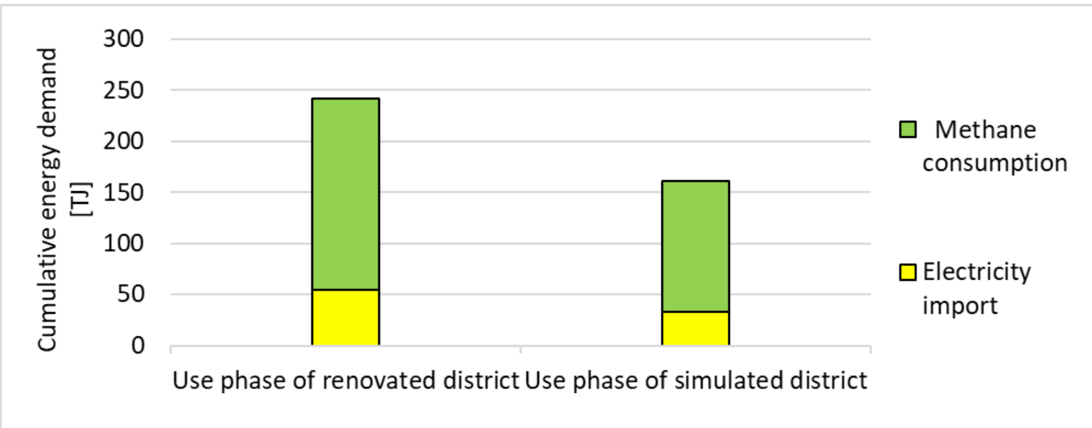


Figure 132 Breakdown of CED by energy source for use phase in Copenhagen.

For the use phase of the renovated district, the total energy demand is approximately 150 TJ, with most of the demand coming from methane consumption. Electricity imports contribute a smaller portion, making up less than 10% of the total energy demand.

In contrast, the use phase of the simulated district shows a higher total energy demand, approximately 250 TJ. Like the renovated district, the methane consumption constitutes most of the energy demand, while electricity imports contribute around 20%.

The comparison shows that the simulated district has a significantly higher energy demand during its use phase, largely due to higher methane consumption. This reduction in the renovated district's overall impact is influenced by several factors, including enhanced energy efficiency measures, the integration of renewable energy sources, and the application of advanced technologies to optimize energy consumption. These improvements have collectively contributed to a lower global warming potential and a more sustainable performance during the district's life cycle.

The following figure displays a dominance analysis of the CED for the renovated district, detailing the contributions across the life cycle phases: end of life, production and use.

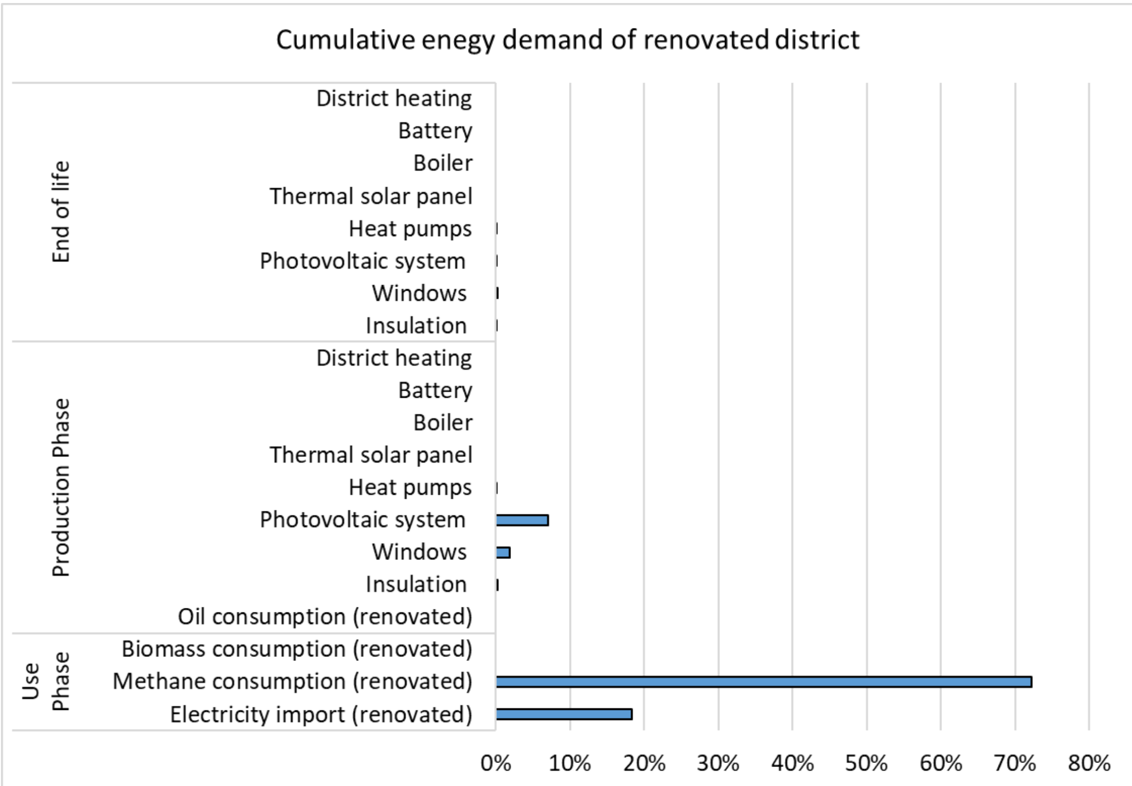


Figure 133 Dominance analysis of CED of renovated district in Copenhagen.

In the end-of-life phase, the contributions from all components including heat pumps photovoltaic systems, windows and insulation are relatively minor, with each accounting for only a small percentage of the overall energy demand.

The production phase sees photovoltaic systems contributing around 5%. In the use phase, methane consumption dominates, contributing close to 70% of the total energy demand, highlighting its significant impact on the district's overall energy profile. Electricity imports are also notable but much less so, contributing around 20%.

The next figure presents three key environmental indicators EP-T, GWP-PT and EER—expressed in years.

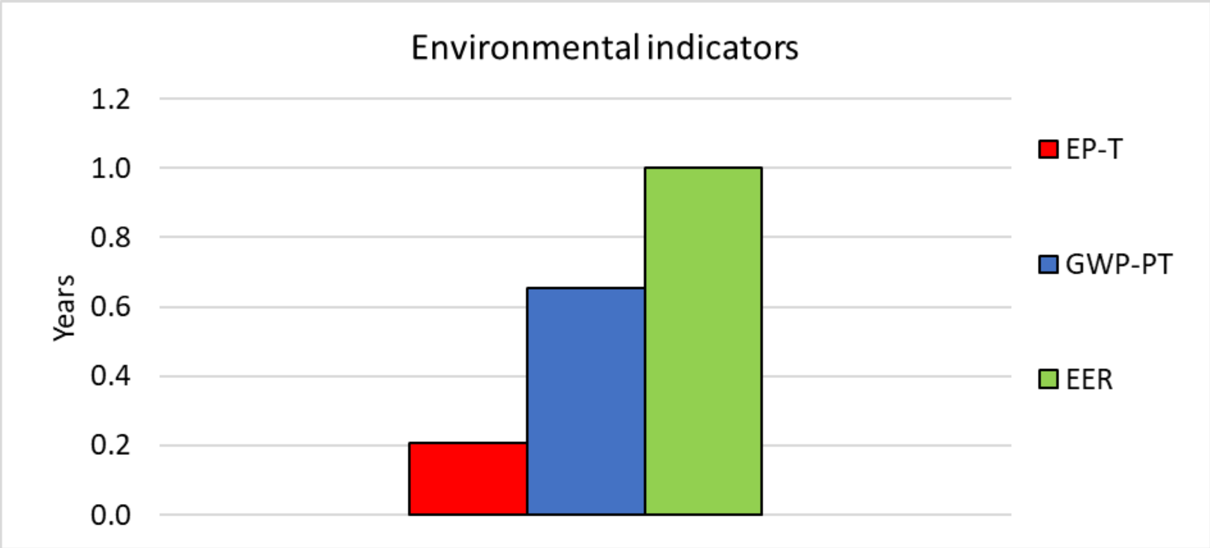


Figure 134 Environmental indicators for renovated district in Copenhagen.

The low value for EP-T suggests that the energy consumed during the production phase is quickly compensated by energy savings during the operational phase. GWP-PT has a moderate value, indicating the time required to offset global warming potential impacts through energy savings or emission reductions. In contrast, the higher value for EER is a positive indicator, signifying that the system operates with a higher energy efficiency, meaning more energy is saved over time compared to the energy invested. A high EER reflects effective energy performance, showing that improvements in energy efficiency have a lasting positive impact.

Case Study 4 – Parma

The next figure compares the GWP between the life cycle of the renovated district (scenario 2) and the use phase of the baseline (scenario 1) district in Parma.

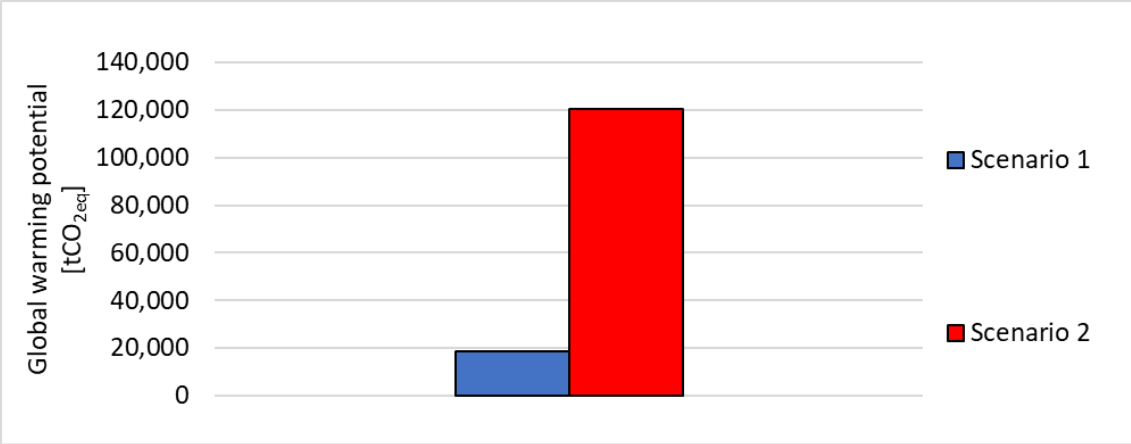


Figure 135 Comparison of GWP between baseline and renovated districts in Parma.

The life cycle of the renovated district shows a significantly higher GWP, reaching around 120,000 tCO_{2eq}. On the other hand, the use phase of the baseline district presents a much lower GWP, around 20,000 tCO_{2eq}.

The following figure compares the GWP during the use phase of the renovated district and the baseline district. The GWP is broken down into two main energy sources: methane consumption and electricity imports.

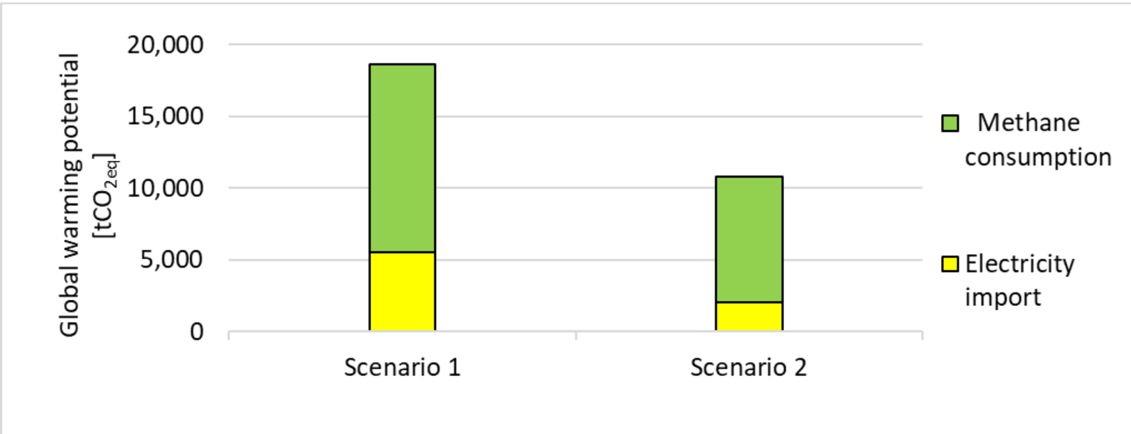


Figure 136 Breakdown of GWP by energy source for use phase in Parma.

For the use phase of the renovated district, the total GWP is around 10,000 tCO_{2eq}, with most of the emissions coming from methane consumption, while electricity imports contribute a smaller portion, accounting for less than 20% of the total.

In contrast, during the use phase of the baseline district, the GWP is significantly higher, reaching approximately 20,000 tCO_{2eq}. Methane consumption is again the dominant contributor to emissions, while electricity imports account for a larger portion compared to the renovated district, contributing about 30% of the total GWP.

In the renovated district, the reduction in methane consumption is a direct result of improved insulation, which lowers the heating demand, thereby reducing reliance on methane for heating. This explains the significantly lower GWP contribution from methane consumption in the renovated scenario. Additionally, the photovoltaic system reduces the district's dependence on electricity imports, further decreasing the GWP during the use phase, as a portion of the energy demand is met by locally generated solar energy.

This comparison highlights that the renovated district has a much lower overall GWP during its use phase, mainly due to a reduction in both methane consumption and electricity imports. The baseline district's higher reliance on both energy sources results in substantially greater emissions during its operational phase. This demonstrates the effectiveness of the renovation in reducing the district's operational carbon footprint, particularly through decreased methane use.

The next figure provides a dominance analysis of the GWP for the life cycle of the renovated district, with contributions from various components during the phases of end of life, production and use.

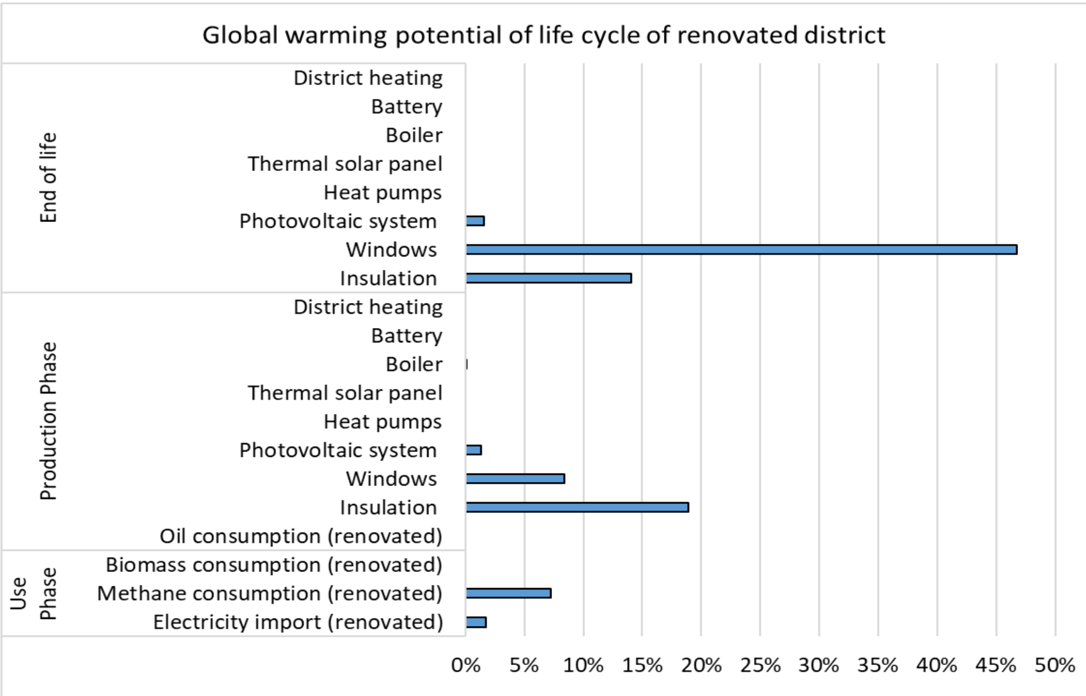


Figure 137 Dominance analysis of GWP for renovated district in Parma.

In the end-of-life phase, windows and insulation are the most significant contributors to the GWP. Windows account for approximately 45% of the total GWP, while insulation contributes around 15%. These two components dominate the environmental impact during this phase, reflecting the challenges associated with their disposal or recycling processes. The photovoltaic system has impact less than 5%.

In the production phase, windows and insulation are the dominant contributors, with insulation alone accounting for nearly 20% of the total GWP. Windows contribute around 10%, while the photovoltaic system contributes close to 5%.

In the use phase, methane consumption is the primary contributor, accounting for approximately 10% of the total GWP, while electricity imports contribute around 5%.

The analysis indicates that windows and insulation are the most significant contributors to the GWP in both the end-of-life and production phases of the renovated district's life cycle.

Thus, windows and insulation play a critical role in the overall environmental impact across both key life cycle phases. Their high GWP impact highlights the importance of selecting more sustainable materials and improving the efficiency of their production and end-of-life processes to reduce the total carbon footprint of the renovated district.

The next figure compares the CED between the life cycle of the renovated district (scenario 2) and the use phase of the baseline (scenario 1) district.

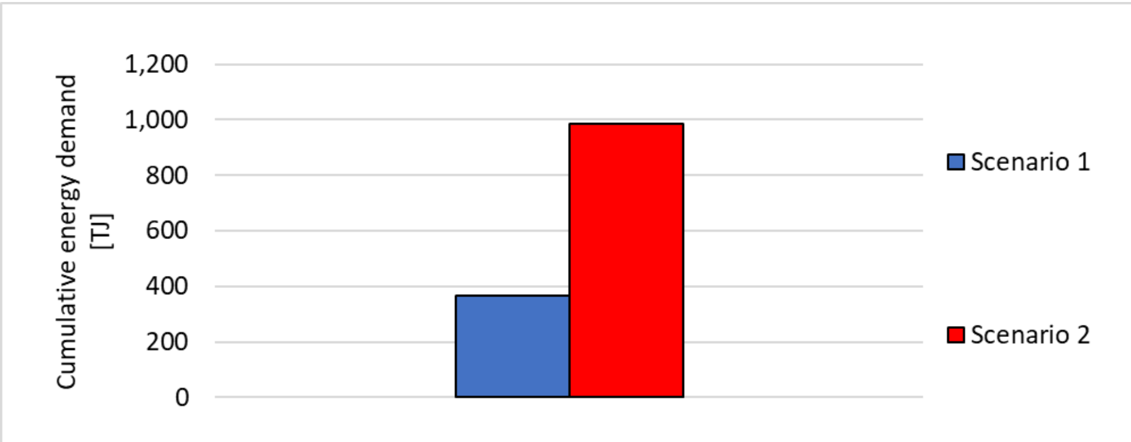


Figure 138 CED of baseline and renovated districts in Parma.

The life cycle of the renovated district has a significantly higher energy demand, reaching approximately 1,000 TJ. In contrast, the use phase of the baseline district has a much lower cumulative energy demand, at around 400 TJ.

The next figure compares the CED during the use phase of the renovated district and the simulated district.

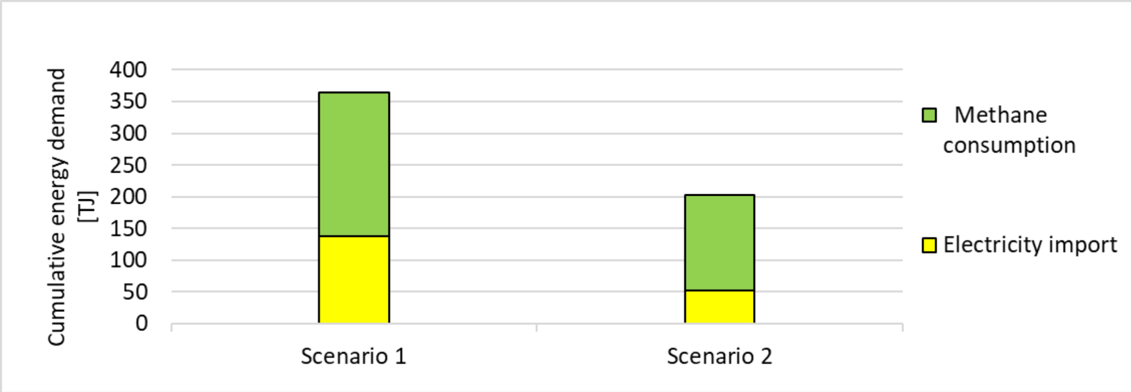


Figure 139 Breakdown of CED by energy source for use phase in Parma.

For the use phase of the renovated district, the total energy demand is around 200 TJ, with methane consumption contributing the majority of the energy demand. Electricity imports account for a smaller portion, representing less than 20% of the total energy demand.

In contrast, the use phase of the simulated district shows a significantly higher energy demand, reaching approximately 350 TJ. Like the renovated district, methane consumption dominates, but the contribution from electricity imports is higher, accounting for about 35% of the total energy demand.

The comparison shows that the simulated district has a much higher overall energy demand during the use phase, primarily due to its higher dependence on both methane and electricity imports. The renovated district, by contrast, demonstrates improved energy efficiency, with a notable reduction in both methane consumption and electricity imports, indicating the positive effects of the renovation measures on energy performance.

The following figure presents a dominance analysis of the CED for the renovated district, divided into the phases of end of life, production and use.

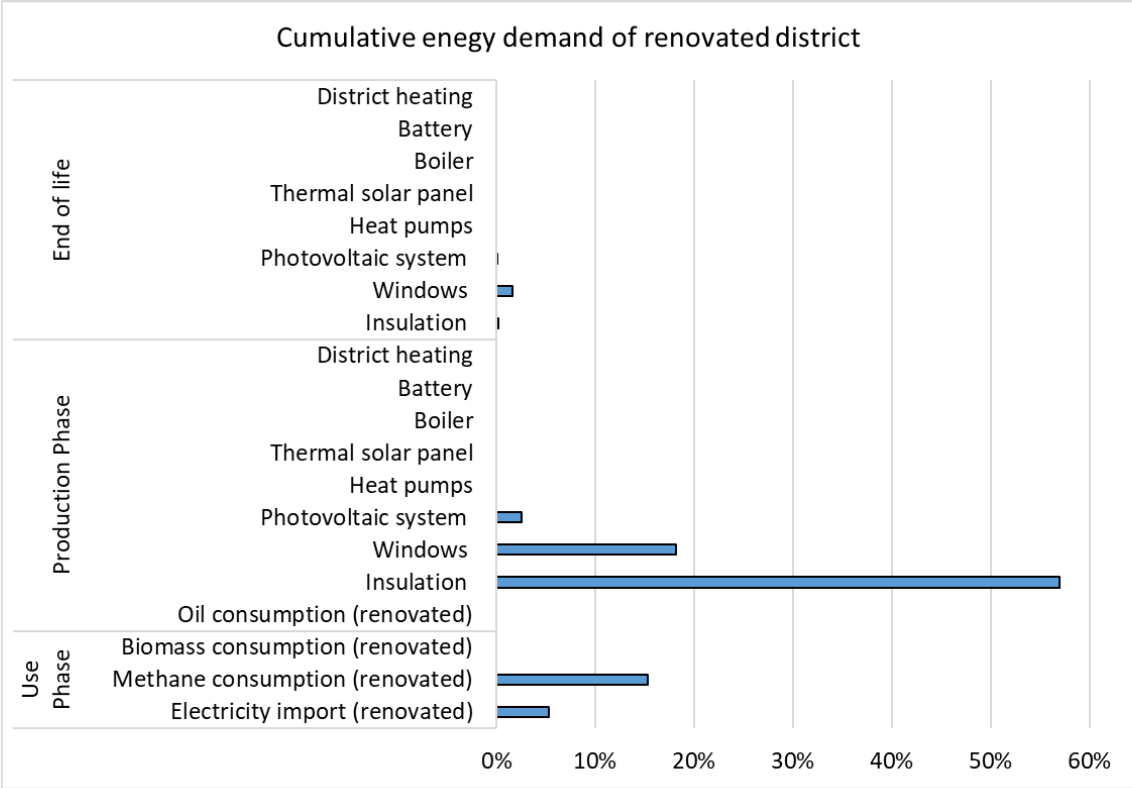


Figure 140 Dominance analysis of CED of renovated district in Parma.

In the end-of-life phase, the contributions from all components photovoltaic systems, windows and insulation—are minimal, each representing a small percentage of the total CED.

In the production phase, insulation is the largest contributor, accounting for nearly 60% of the total CED. Other components, such as windows and the photovoltaic system, also have a notable impact, contributing around 20% and 5% respectively.

In the use phase, methane consumption contributes approximately 15% of the total CED, while electricity imports account for only about 5%.

The results indicate that the production phase of insulation and windows are the largest contributors to the CED. This suggests that improving the energy efficiency of insulation and windows during its production process during its operational phase could result in significant reductions in the overall energy demand of the district. Targeting these two areas offers the most potential for decreasing the district's environmental impact and enhancing sustainability.

The next figure presents three environmental indicators EP-T, GWP-PT and EER expressed in years.

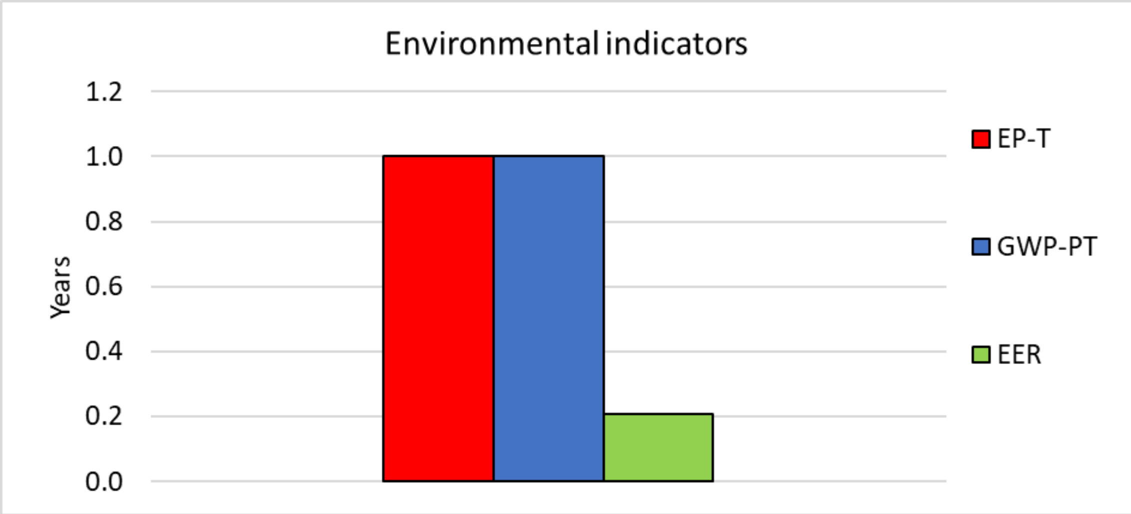


Figure 141 Environmental Indicators for renovated district in Parma.

Both the EP-T and GWP-PT are approximately 1 year, indicating that it takes an entire year for the energy and global warming impacts incurred by the district renovation to be balanced by the operational energy savings and reduced emissions. This represents a negative outcome, as the environmental returns on investment are relatively slow, meaning the renovation does not offer immediate environmental benefits within the first year.

The EER, however, is significantly lower at approximately 0.2 years, highlights the inefficiency of the renovation strategy in yielding quick returns from an energy perspective. Also, the environmental investment takes a long time to become beneficial, as both the EP-T and GWP-PT indicate that the renovation does not yield quick environmental returns. While the renovation improves resource efficiency relatively quickly, the extended payback times for energy and GWP point to the need for further improvements in the renovation strategy to make the environmental benefits more immediate.

9. Conclusions

This research has culminated in the development of an innovative tool tailored to support the early stages of designing PEDs. Addressing significant gaps identified in existing methodologies—particularly their ineffectiveness during preliminary design phases due to complex data requirements and scalability issues—the tool simplifies energy modeling through a modular architecture. By utilizing representative archetypes and focusing on essential parameters, it enables accurate energy and environmental analysis even when input data is scarce or incomplete.

An examination of current PED implementations reveals that the most successful examples are often small, residential districts where technologies like photovoltaic systems and insulation are highly effective. These districts, frequently located in temperate climates, are better equipped to balance energy consumption with renewable energy production, thus more readily achieving strict mathematical positive energy balance However, strategies effective in these contexts are not always transferable to larger urban districts, where increased complexity and data demands pose significant challenges.

To bridge this gap, the developed tool introduces several key features designed to enhance practicality and accessibility:

- Simplified energy modeling: By employing energy archetypes and an optimized set of parameters, the tool evaluates complex energy scenarios with minimal data input. Archetypes reduce the need for detailed building-specific information by representing clusters of buildings with similar characteristics, thus streamlining the analytical process. This approach directly addresses issues related to data availability and accuracy, particularly in large-scale applications where comprehensive datasets are often unavailable. As a result, the tool enables quick and efficient cost-benefit analyses of retrofit strategies, providing consistent insights without the need for extensive preliminary studies.
- Interoperability and adaptability: The tool integrates seamlessly with various data types and models, adapting to different spatial and temporal scales. This feature ensures that the tool remains applicable across diverse district contexts, from small residential areas to complex urban environments. Its adaptability facilitates collaboration between disciplines such as architecture, urban planning and engineering, enabling stakeholders to address multifaceted challenges holistically. By connecting multiple sectors and leveraging diverse data sources, the tool

overcomes traditional technical barriers, creating a more cohesive and integrated framework for PED design.

- User-friendly interface: The intuitive interface is specifically designed to address usability concerns, making the tool accessible to a broad range of users, including urban planners, designers, and policymakers with limited technical expertise. The interface allows users to explore various design options, visualize outcomes in real-time, and modify scenarios interactively. This ease of use not only encourages adoption but also supports informed decision-making by presenting complex data in an understandable and actionable format.
- Rapid iterative analysis: Supporting swift scenario evaluations, the tool facilitates iterative design processes, enabling users to refine strategies effectively and efficiently. The ability to run multiple simulations in a short time frame allows stakeholders to test various retrofit combinations and identify optimal solutions quickly. This capability is particularly critical during early design phases, where time constraints often limit the extent of analysis that can be performed. By providing immediate feedback, the tool empowers users to adapt their strategies dynamically, optimizing outcomes in response to evolving project requirements.
- Life cycle perspective: Incorporating life cycle assessment (LCA) into the tool enables users to evaluate the long-term environmental impacts of retrofit strategies comprehensively. This perspective ensures that operational benefits, such as reduced energy consumption, are balanced against potential increases in impacts during production and end-of-life phases. By highlighting potential shifts in emissions between different life cycle stages, the tool provides a compressive understanding of sustainability, helping stakeholders prioritize interventions that bring long-term benefits. The inclusion of LCA also positions the tool as a forward-looking solution aligned with contemporary sustainability goals.

The tool's effectiveness was validated through its application to four diverse case studies—Pamplona, Bucharest, Copenhagen and Parma—each presenting unique urban contexts, district sizes and building typologies. This comprehensive evaluation demonstrated the tool's versatility and practical utility across various real-world scenarios.

Key Takeaways

- Innovative energy modeling: The tool's simplified architecture and use of energy archetypes making it easy to calculate energy use even when there isn’t much data available.

- Effective retrofit strategies: Combining building envelope retrofits with renewable energy solutions significantly reduces energy demand and environmental impact, particularly in temperate climates.
- Comprehensive LCA: The inclusion of life cycle perspectives ensures that retrofit interventions are evaluated not only for operational efficiency but also for their long-term environmental impacts.
- Adaptability across diverse contexts: The tool successfully adapts to different urban settings, demonstrating its applicability in both small residential districts and larger, more complex urban areas.
- Enhanced decision-making: By providing rapid iterative analysis and a user-friendly interface, the tool empowers designers, urban planners and decision-makers to make informed, sustainability-oriented choices.
- Lifecycle impact awareness: The dominance analysis highlights the importance of considering material production and end-of-life phases to ensure that energy efficiency improvements do not inadvertently increase overall environmental impacts.
- Future-ready enhancements: Plans to incorporate Sustainable Development Goals (SDGs) and expand case studies will further enhance the tool's capability to support multi-objective optimizations and broader sustainability targets.

In the residential district of Pamplona, characterized by 1950s buildings, the analysis showed that insulation improvements and window upgrades led to a 17% reduction in annual heating demand. Though this decrease may not seem as significant compared to cooling, it still represents a meaningful improvement given the high initial heating load. In contrast, the cooling demand experienced a reduction of 84%. Additionally, the integration of a nearby 1.1 MW installation, significantly contributed to meeting the energy requirements.

The lifecycle GWP of the renovated district was significantly reduced to 450 tCO_2eq, compared to 600 tCO_{2eq} for the baseline district. Additionally, the CED in the renovated district showed that 60% of the energy consumption during the lifecycle came from electricity imports during the use phase. This highlights how the combination of insulation, window upgrades and renewable energy integration can substantially lower both energy demand and environmental impact, especially in temperate climates like Pamplona's.

These results demonstrate the effectiveness of combining building envelope retrofits with renewable energy solutions, especially in temperate climates like Pamplona's. The tool's adaptability in fine-tuning photovoltaic sizing based on the load profile further helped the district maximize its renewable energy generation potential.

In the Bucharest district, composed of 1980s residential buildings with centralized heating systems, the energy and environmental results from the retrofit analysis show significant improvements.

The energy results highlight substantial reductions in heating demand, particularly after the application of 20 cm of EPS insulation. Across the three archetypes, the heating demand reduction reaches up to 51% for Archetype 2, while the reduction for Archetypes 1 and 3 is 31% and 33%, respectively. Cooling demand, although not as drastically affected, shows a reduction of up to 19% for Archetype 2, while the other archetypes experience either a slight increase or smaller reductions. On average, the total energy consumption for heating drops by 24%, while cooling demand is reduced by 3%. These results underscore the effectiveness of insulation, particularly for heating, which is the predominant energy need in Bucharest's cold climate.

In terms of environmental impacts, the dominance analysis of GWP indicates that the renovation, while reducing operational phase emissions, increases the overall life-cycle impacts due to the production and end-of-life phases. The total lifecycle GWP of the renovated district reaches approximately 300,000 tCO_2eq, compared to 250,000 tCO_2eq in the baseline scenario. This increase in GWP is primarily due to the environmental burden from material production, particularly the insulation and the district heating system upgrades. During the operational phase, however, emissions related to methane consumption are significantly reduced, reflecting the improvements in the district heating system and the integration of photovoltaic systems. Despite the reduction in impact during the use phase, the environmental benefits of improved energy performance were offset by the increased impact during the production and end-of-life phases of the district heating system. This highlights the need to consider the full lifecycle impacts of retrofitting interventions to avoid undermining energy efficiency improvements.

In the Copenhagen district, composed of residential, prison, and gym archetypes, the energy results for the retrofit interventions show a substantial reduction in heating demand across the analysed archetypes. For instance, heating demand decreased by 40.50% in Archetype 3 and by 31.90% in Archetype 1, primarily due to improved thermal performance resulting from the application of insulation and upgraded windows. However, the cooling demand showed an increase in several archetypes, with Archetype 4 exhibiting a significant percentage increase. This rise in cooling demand is attributed to the improved thermal insulation, which also retains heat during warmer periods, leading to higher cooling needs. The overall electricity consumption also increased by 17%, driven mainly by the rise in cooling demand.

From an environmental perspective, the retrofits resulted in a marked reduction in greenhouse gas emissions during the use phase, primarily due to reduced methane consumption for heating. The GWP for the renovated district's use phase dropped to approximately 9,000 tCO_2eq, compared to 13,000 tCO_2eq in the baseline scenario.

In the retrofit scenario, methane still accounts for approximately 60% of the GWP and 70% of the CED, indicating that despite the retrofit, the use phase remains dominant in terms of environmental impact. However, the overall reduction in methane consumption and the shift towards increased electricity use, particularly through the integration of heat pumps and enhanced insulation, have led to a more balanced energy profile. While electricity consumption has increased, the lower emissions associated with electricity compared to methane have contributed to a net improvement in the district's environmental performance. This shift underscores that, despite methane's continued dominance in the use phase, the retrofit has significantly reduced overall fossil fuel dependency, leading to a more sustainable outcome.

In the Parma district, composed of various building archetypes, including residential and non-residential types, the retrofit interventions—such as insulation improvements and window replacements, have led to significant reductions in both heating and cooling demands. Heating demand saw reductions ranging from approximately 26% to 44%, depending on the building archetype, with the largest reduction in Archetype 7. Cooling demand, while less affected, was reduced by up to 41% in some archetypes, with others showing modest increases or smaller reductions. This highlights the dual benefit of retrofits in improving thermal efficiency during winter, but also indicates some challenges related to increased cooling needs in summer due to improved insulation retaining more heat.

From an environmental perspective, the reduction in energy demand has corresponded with a marked decrease in GWP during the operational phase of the renovated district. The renovated district showed a nearly 50% reduction in GWP during the use phase, with most of the emissions decrease attributed to reduced methane consumption and lower electricity imports, primarily due to the installation of photovoltaic panels. Despite these significant reductions during the use phase, the overall life cycle impact of the district has increased due to the production and end-of-life phases of the new materials, such as windows and insulation, which dominated the environmental impact, accounting for up to 45% and 20% of the total GWP in some phases.

The dominance analysis for the life cycle of the renovated district reveals that insulation and window frames are the largest contributors to both the GWP and CED in the production and end-of-life phases. These materials, while crucial for reducing operational impacts, contribute significantly to the total environmental footprint of the renovation. Methane consumption remains a critical source of emissions during the use phase, though its share is reduced substantially after the retrofit. This suggests that while operational efficiency has improved, the environmental costs associated with retrofitting materials must also be carefully considered to ensure a balanced approach to sustainability.

Comparative analysis across these case studies underscored the influence of factors like climate, building typology, and technology selection on energy and environmental performance. Districts with higher heating demands, such as Pamplona and Copenhagen, showed greater benefits from improvements to the building envelope and the integration of renewable energy systems. In contrast, areas with md rise buildings, like Bucharest and with a mix of building uses Parma, required more nuanced strategies to balance varied energy needs effectively.

Overall, the tool's ability to adapt to different conditions while providing accurate assessments with limited data represents a significant advancement in the field of PED design. Its practical applications demonstrated not only the potential for substantial energy savings and emissions reductions but also the critical importance of solutions tailored to the unique characteristics of each district.

Furthermore, the dominance analysis provides immediate insights into which aspects should be prioritized in subsequent phases to achieve an overall reduction in environmental impacts. It highlights critical areas, such as the materials used for insulation and windows, which, while essential for improving energy performance, contribute significantly to the impacts during the production and end-of-life phases. Focusing on these elements in a second analysis allows for the development of targeted strategies to further reduce the district's overall environmental footprint, considering not only operational efficiency but also the sustainability of materials and solutions across the entire life cycle.

Looking toward future enhancements, plans include expanding case studies and broadening indicators by incorporating the Sustainable Development Goals (SDGs). This expansion will enable the integration of multi-objective optimizations, allowing users to balance energy efficiency, economic considerations, and environmental impacts in alignment with SDG targets.

In conclusion, this thesis contributes to sustainable urban design by introducing a practical and accessible tool that addresses some of the limitations of existing methods. By simplifying the preliminary design process and making it more accessible to a broader range of stakeholders—including designers, urban planners, and decision-makers—the tool empowers users to make informed choices that promote the development of effective and sustainable PEDs.

The research highlights the necessity of adaptable solutions that are sensitive to local conditions, emphasizing that one-size-fits-all approaches are often insufficient in addressing the complex challenges of urban energy systems. The innovation presented here effectively bridges the gap between theoretical models and practical application, offering a scalable and user-friendly solution that can play a pivotal role in global efforts to create more resilient, low-carbon cities.

Future developments of the tool will focus on enhancing its capacity to address the multifaceted challenges of sustainable urban development. By integrating advanced functionalities and considering socio-economic aspects, the tool aims to foster collaboration across disciplines, support the transition toward sustainable urban environments, and contribute meaningfully to combating climate change.

This work underscores the potential for significant energy and environmental benefits when tailored, context-specific strategies are employed. It is hoped that the tool will facilitate the adoption of more informed, sustainability-oriented design practices, ultimately supporting global initiatives aimed at building more sustainable and resilient urban landscapes.

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Annexes

Survey of San Pedro

This chapter contains photos taken by the author to illustrate that all buildings in the district are identical. These images support the decision to use a single archetype to adequately represent the entire district. The photos demonstrate that the essential elements required for segmentation, characterization and defining a reference building are the same, which demonstrates the appropriateness of using one archetype for the analysis.


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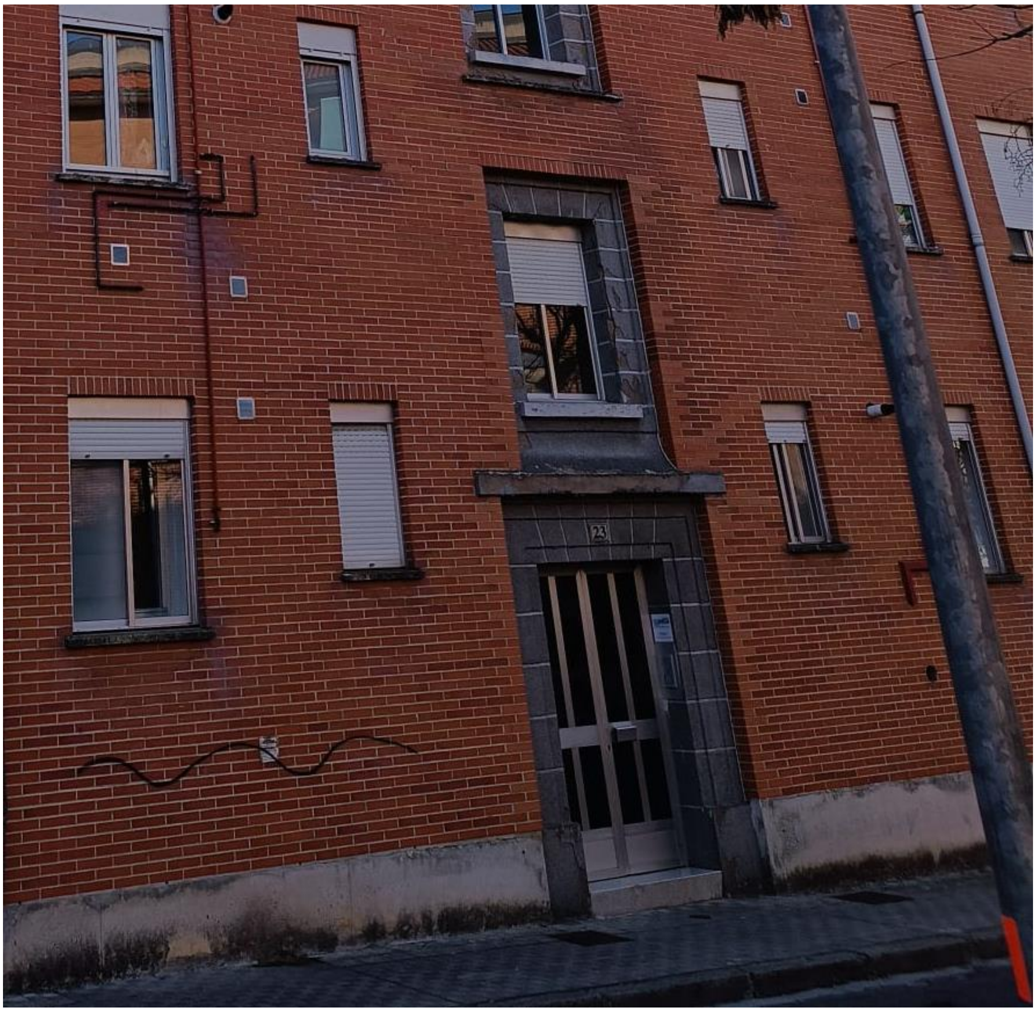
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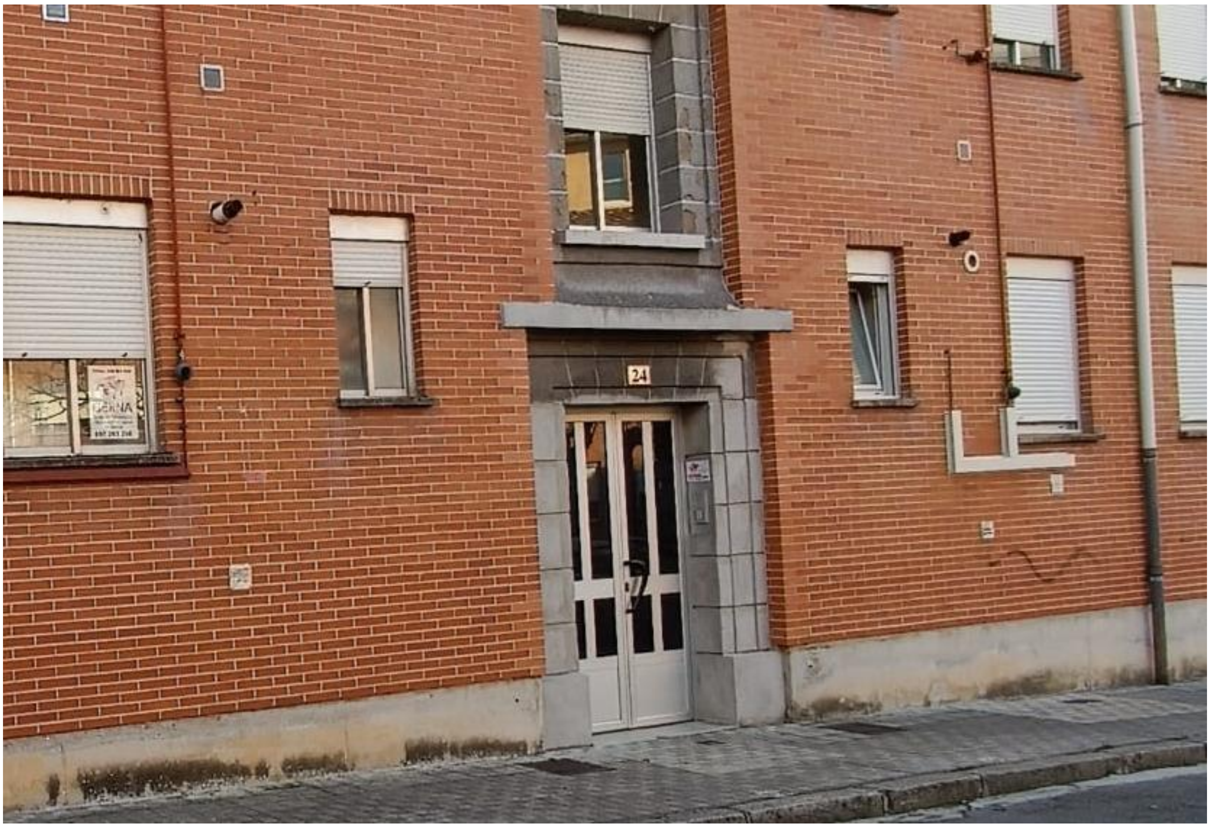
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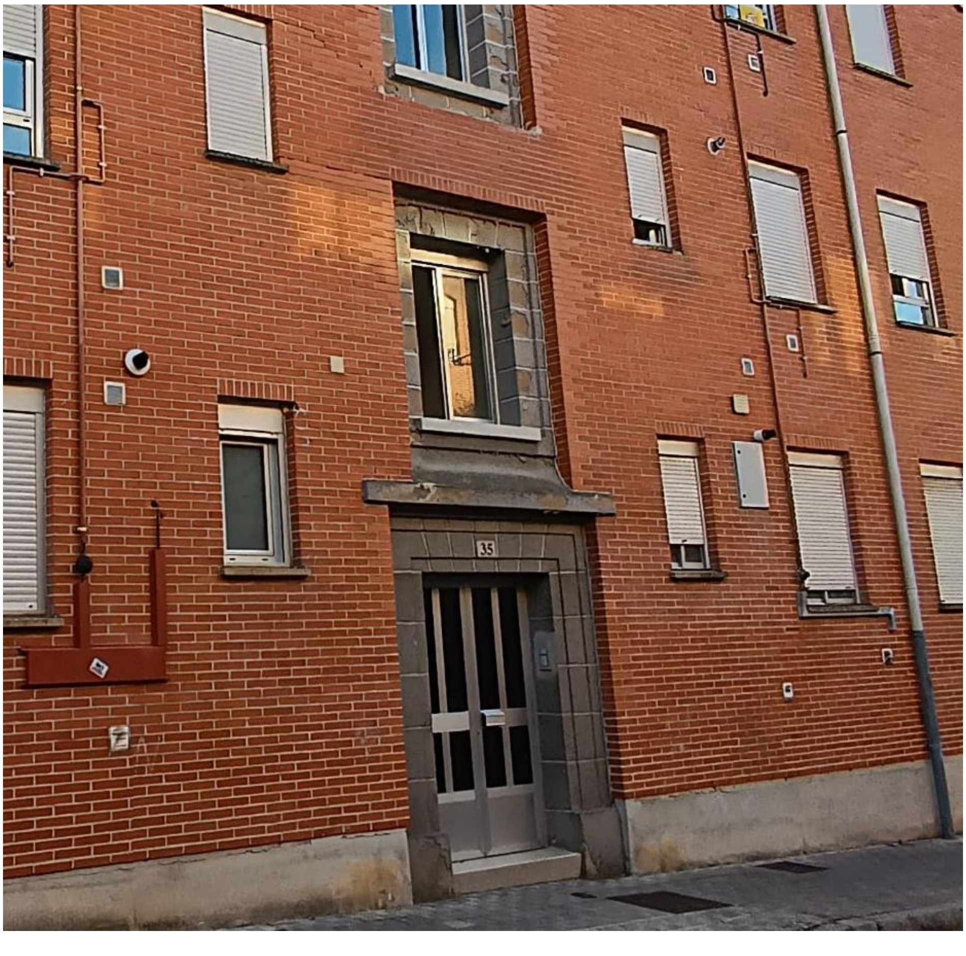
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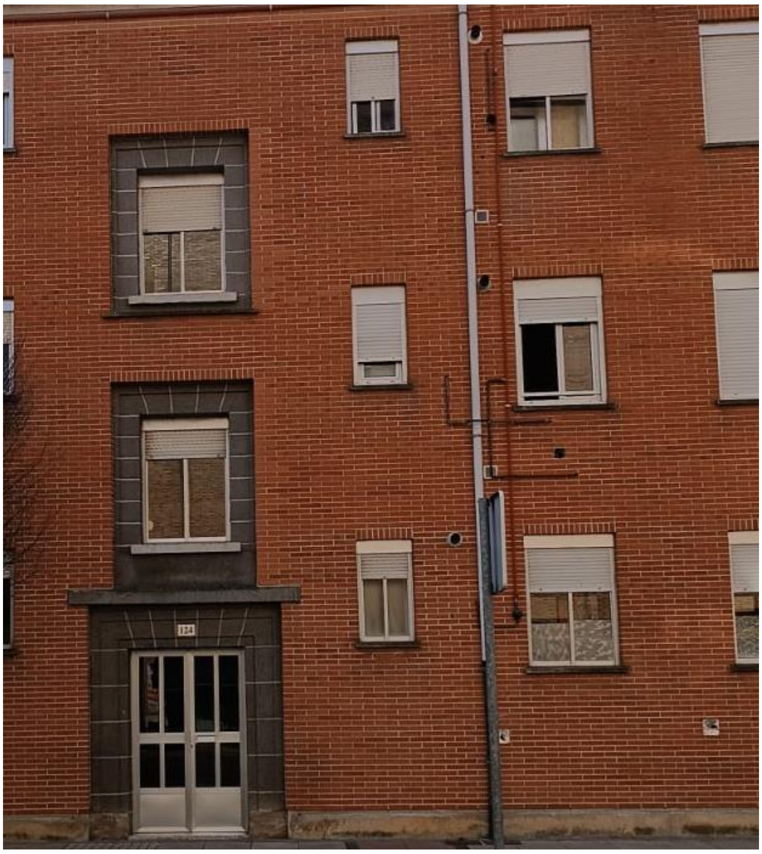
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