ANNEX 83

EBC

Energy in Building and Communities Programme

International Energy Agency

Deliverable 2 - Methods, Tools and Technologies for Realizing Positive Energy Districts

Positive Energy Districts (Annex 83)

Energy in Buildings and Communities Technology Collaboration Programme

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Deliverable 2 - Methods, Tools and Technologies for Realizing Positive Energy Districts

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Energy in Buildings and Communities Technology Collaboration Programme

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 30 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely 'Objectives' and 'Means'. These two groups are distinguished for a better understanding of the different themes.

Objectives - The strategic objectives of the EBC TCP are as follows:

- reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders and promotion of co-benefits;
- improvement of planning, construction and management processes to reduce the performance gap between design stage assessments and real-world operation;
- the creation of 'low tech', robust and affordable technologies;
- the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible;
- the creation of holistic solution sets for district level systems taking into account energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means - The strategic objectives of the EBC TCP will be achieved by the means listed below:

- the creation of tools for supporting design and construction through operations and maintenance, including building energy standards and life cycle analysis (LCA);
- benefitting from 'living labs' to provide experience of and overcome barriers to adoption of energy efficiency measures;
- improving smart control of building services technical installations, including occupant and operator interfaces;
- addressing data issues in buildings, including non-intrusive and secure data collection;
- the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the 'objectives' themes are final goals or solutions (or part of) for an energy efficient built environment, while the 'means' themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)

Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO_2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO_2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (*)

Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)
Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Resilient Public Communities
Annex 74: Competition and Living Lab Platform
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables
Annex 76: ☼ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO_2 Emissions
Annex 77: ☼ Integrated Solutions for Daylight and Electric Lighting
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation
Annex 80: Resilient Cooling
Annex 81: Data-Driven Smart Buildings
Annex 82: Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems
Annex 83: Positive Energy Districts
Annex 84: Demand Management of Buildings in Thermal Networks
Annex 85: Indirect Evaporative Cooling
Annex 86: Energy Efficient Indoor Air Quality Management in Residential Buildings
Annex 87: Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems
Annex 88: Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings
Annex 89: Ways to Implement Net-zero Whole Life Carbon Buildings
Annex 90: Low Carbon, High Comfort Integrated Lighting (EBC Annex 90 / SHC Task 70)
Annex 91: Open BIM for Energy Efficient Buildings
Annex 92: Smart Materials for Energy-Efficient Heating, Cooling and IAQ Control in Residential Buildings
Annex 93: Energy Resilience of the Buildings in Remote Cold Regions
Annex 94: Validation and Verification of In-situ Building Energy Performance Measurement Techniques
Annex 95: Human-centric Building Design and Operation for a Changing Climate
Annex 96: Grid Integrated Control of Buildings
Annex 97: Sustainable Cooling in Cities
Annex 98: Flexibilization and Optimization of Heat Pump Systems in Existing Buildings through Secondary-Side Digitalization
Annex 99: Air Cleaning for Sustainable and Resilient Buildings

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group - Cities and Communities
Working Group - Building Energy Codes

Acronyms

Acronym	Category	Description
DHN	Energy Infrastructure	District Heating Network
HP	Energy System Components	Heat Pumps
CHP	Energy System Components	Combined Heat & Power
EL	Energy System Components	Efficient External Lighting
ST	Renewable Energy Devices	Solar Thermal Collectors
PV	Renewable Energy Devices	Photovoltaic Modules (Private building)
PVI	Renewable Energy Devices	Photovoltaic Modules (Community infrastructures)
PVT	Renewable Energy Devices	Hybrid Collectors
BIPV	Renewable Energy Devices	Building Integrated Photovoltaics
W	Renewable Energy Devices	Wind Power (>30kW)
MW	Renewable Energy Devices	Micro Wind Power (<30kW)
BE	Renewable Energy Devices	Bioenergy (fuels from biomass); includes solid biofuels, biogas and liquid biofuels
WP	Renewable Energy Devices	Tide, Wave, Ocean Power
MHEP	Renewable Energy Devices	Micro Hydroelectric Power
HEP	Renewable Energy Devices	Hydroelectric Power
RMW	Renewable Energy Devices	Renewable Municipal Waste
WH	Renewable Energy Devices	Waste Heat
GDN	Renewable Energy Devices	Geothermal District Network
GB	Renewable Energy Devices	Geothermal Boreholes
GE	Renewable Energy Devices	Geothermal Energy
ATES	Renewable Energy Devices	Aquifer Thermal Energy Storage
MG	Smart Technology Components	Microgrid
VPP	Smart Technology Components	Virtual Power Plant
PA	Smart Technology Components	Phone App for citizens
PLA	Smart Technology Components	ICT platforms
FLEX	Smart Technology Components	Flexibility to grids (demand response, etc.)
ES	Energy Storage	Electric Storage
STES	Energy Storage	Seasonal Thermal Energy Storage
HFC	Energy Storage	Hydrogen Fuel Cell
TSG	Energy Storage	Other thermal storage: water tank, PCM
EM	Mobility	Electric Mobility
V2G	Mobility	Vehicle to Grid
WTH	Other Components	Water Harvesting
CE	Design Parameters	Circular Economy Perspective
SH	Design Parameters	Social Housing
ZEB	Design Parameters	Zero energy building
PH	Design Parameters	Passive House
NZEB	Design Parameters	Nearly Zero Energy Building
REB	Design Parameters	Retrofit Efficient Buildings
O	Fossil fuels	Oil
NG	Fossil fuels	Natural gas
C	Fossil fuels	Carbon

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Summary

The European Union introduced the program "Positive Energy Districts for Sustainable Urban Development" with the goal of planning, deploying, and replicating 100 positive energy neighbourhoods by 2025 (Krangsås et al., 2021a). This initiative is a crucial part of the broader strategy for sustainable urbanisation, addressing various technological, spatial, regulatory, financial, legal, social, and economic aspects (Kozlowska et al., 2024; Krangsås et al., 2021a). Positive Energy Districts (PEDs) represent an innovative urban concept aimed at creating sustainable and energy-efficient urban areas (Krangsås et al., 2021a).

PEDs are urban areas that generate more energy than they consume and are designed to respond flexibly to fluctuations in the energy market. The concept builds on earlier approaches such as Nearly Zero, Net Zero, or Positive Energy Buildings, extending the scope from individual buildings to district-level applications in order to harness synergies and accelerate urban decarbonisation (JPI Urban Europe / SET Plan Action 3.2, 2020).

District-scale energy systems in PEDs offer economic and technical advantages over individual building energy systems. They facilitate local energy exchanges between buildings, support electric mobility using surplus renewable energy, and provide district-scale energy storage solutions. Additionally, PEDs encourage stakeholder participation in energy systems, aligning with the directive on renewable energy communities (Lindholm et al., 2021a). Thus, PEDs aim to minimise the impact on centralised energy networks by increasing onsite load-matching, self-consumption, and providing options for both short- and long-term energy storage (Hedman et al., 2021). PEDs include diverse building types and are integrated with the city's existing energy grid, fostering carbon-neutral communities.

These districts require the integration of different systems and infrastructures, including energy, mobility, and information and communication technology (ICT) systems, to ensure a balanced energy supply and enhance the quality of life for all residents (Krangsås et al., 2021a). The research questions addressed in this report are:

- What are the main technologies applied in PEDs? Are there any barriers to overcome for realising PEDs? See section B1- Technologies and energy systems in Positive Energy Districts.
- How is flexibility being studied in PEDs? See section B2- Energy flexibility, storage and smart grid integration: solutions and applications to PEDs
- What are the methodologies or tools for realising PEDs? See section B3- Energy Modelling of PEDs: a review of tools, modelling techniques and critical approaches to simulation.

To the first question, PEDs require technologies that are crucial for enhancing energy efficiency, flexibility and decarbonising the electricity, heating and cooling services of the districts/cities. PEDs are characterised by a holistic integration of various systems and infrastructures to achieve sustainability goals. The PED areas aim to actively manage an annual local or regional surplus production of renewable energy of urban areas or groups of connected buildings that aim to produce net zero greenhouse gas emissions (JPI Urban Europe / SET Plan Action 3.2, 2020; Kozlowska et al., 2024). The review of technologies begins by emphasizing the specific needs of the European context, particularly within a geopolitically unstable and with low energy security system. It highlights the necessity of effectively managing renewable energy resources and the strategic role of PEDs in this broader energy transition. The analysis includes the impact of the recent gas crisis and examines several initiatives undertaken by cities to overcome energy dependency and accelerate decarbonisation—developments that can directly support the implementation and scaling of PEDs.

It could be assumed that regions with high solar irradiance, solar panels can be a primary source of energy generation, but it has been seen in this report that PV is at foremost, the key technology to achieve PEDs in all the studied regions. This conclusion comes after analysing more than 39 case studies, interviewing six case studies (Gabaldon, 2025) and analysing districts with energy models (see section *B3.3- Modelling district scale case studies*). The reason for the choice could be due to their easy installation, cost and scalability. While wind energy can be effective in certain regions, especially in northern areas, its applicability is more location dependent. Integrating wind energy within virtual PED boundaries can be a strategic move for energy communities aiming to diversify their renewable energy sources. Regarding heating and cooling, heat pumps are indeed central to the transition towards secure and sustainable systems (Gabaldon, 2025). The IEA emphasises that heat pumps, powered by low-emissions electricity, are a key technology in this global shift with the potential of reducing global CO_2 emissions by at least 500 million tons by 2030 (IEA, 2022). District heating and cooling is also found, utilising waste heat sources such as data centers, supermarkets, heat pumps, solar or geothermal which can significantly contribute to the development of energy-positive communities (Gabaldon, 2025).

Also, effective PEDs necessitate the interaction and integration between buildings, users, and the regional energy, mobility, and ICT systems (JPI Urban Europe / SET Plan Action 3.2, 2020) and flexibility is and will be crucial for optimising this integration of assets.

Methodologies and tools vary depending on data availability, or technical expertise of the modeler, as will be seen in the next chapters. PED assessment tools face widespread issues:

- Data acquisition is labor-intensive, and standard datasets often lead to uncertainty.
- Meteorological data integration is limited, undermining local climate accuracy.
- Geometry simplification (e.g., LOD1) reduces model fidelity.
- Energy system modelling lacks detail in Heating, ventilation and air conditioning (HVAC) systems, storage, and control strategies.
- User interfaces are often non-intuitive and require expert use.
- High-resolution simulations impose computational burdens.
- Geospatial integration with energy tools is weak, requiring custom bridges.

The deliverable also reviews known tools[1] such as TRNSYS – Transient System Simulation Tool, City Energy Analyst (CEA), oemof – Open Energy Modelling Framework, CERC Hub[2] and EnergyPlus.

The authors conclude that most tools lack interoperability and flexibility, especially for multi-domain PED analysis. CEA and Hub tools are ideal for urban planning, policy evaluation, and district-level energy assessments. TRNSYS is best for component-level system simulation (e.g., HVAC). Oemof is strong in optimisation and dispatch for multi-energy systems.

Open-source tools (CEA, oemof, Hub) enable better customisation via Python, while TRNSYS is proprietary. Furthermore, ontologies provide a scalable solution to overcome fragmented modelling as they enable semantic alignment between tools (e.g., BIM, climate data, energy models), support multiscale, cross-domain interoperability (buildings, grids, mobility) and facilitate automated reasoning, querying, and co-simulation. Examples like the BIGG Ontology showcase successful harmonisation of building, system, temporal, and spatial data, enabling more robust simulation and KPI analysis for PEDs. Smart control systems, especially Model Predictive Control (MPC), are essential for PED flexibility and optimisation. Their integration remains limited but promising (e.g., SPARCS, MAKING-CITY). Building Management Systems (BMS) and standards like EN15232 offer frameworks to enhance flexibility and automation.

The main lessons learnt from this deliverable are:

- PED boundaries must account for virtual exchanges (e.g., peer-to-peer energy exchanges).
- Local data quality is critical; even replicable tools such as CEA or EnergyPlus fail without it as it will lead to low accurate results.
- PV alone is insufficient for energy positivity—thermal decarbonisation is still a bottleneck.
- Smart controls and ontologies are underused but hold transformative potential.

Modelling, implementing, and scaling PEDs requires a systemic, interoperable approach rooted in structured data and flexible tools. Approaches like co-simulation have been performed to attempt to make tools interoperable and communicate between them, treating tools as black boxes with input and outputs. Ontologies based systems instead allow enabling semantic integration thanks to metadata, and unlocking the ability to simulate, evaluate, and optimise assets across diverse contexts. Due to the natural complexity of PEDs, it is required to use multiple tools to address multiple assets, levels of data availability and actors. To accelerate PED deployment, new demonstrators, open data frameworks, and cross-sector innovation (especially in control and flexibility) are needed.

[1] Only tools known by the authors of this deliverable have been primarily considered

[2] https://pypi.org/project/cerc-hub/ CERC Hub consist of a set of classes (Central data model), importers and exporters to help researchers to create better and more sustainable cities.
Developed at Concordia university in Canada as part of the research group from the Next Generation Cities Institute, our aim among others is to provide a comprehensive set of tools to help researchers and urban developers to make decisions to improve the livability and efficiency of our cities

Subtask B methods

Annex 83 on Positive Energy Districts (PEDs) strengthens international cooperation and research on PEDs by fulfilling different objectives such as mapping stakeholders (O1), co-defining a clear PED framework (O2), and delivering practical guidance on technologies (O3), digital enablers (O4), and planning with impact assessment (O5). Subtask B specifically contributes to objective O3 and O4, coordinating with Subtasks A and C for definitions and KPIs, as well as collecting case studies that can enhanced the delivery of the tasks.

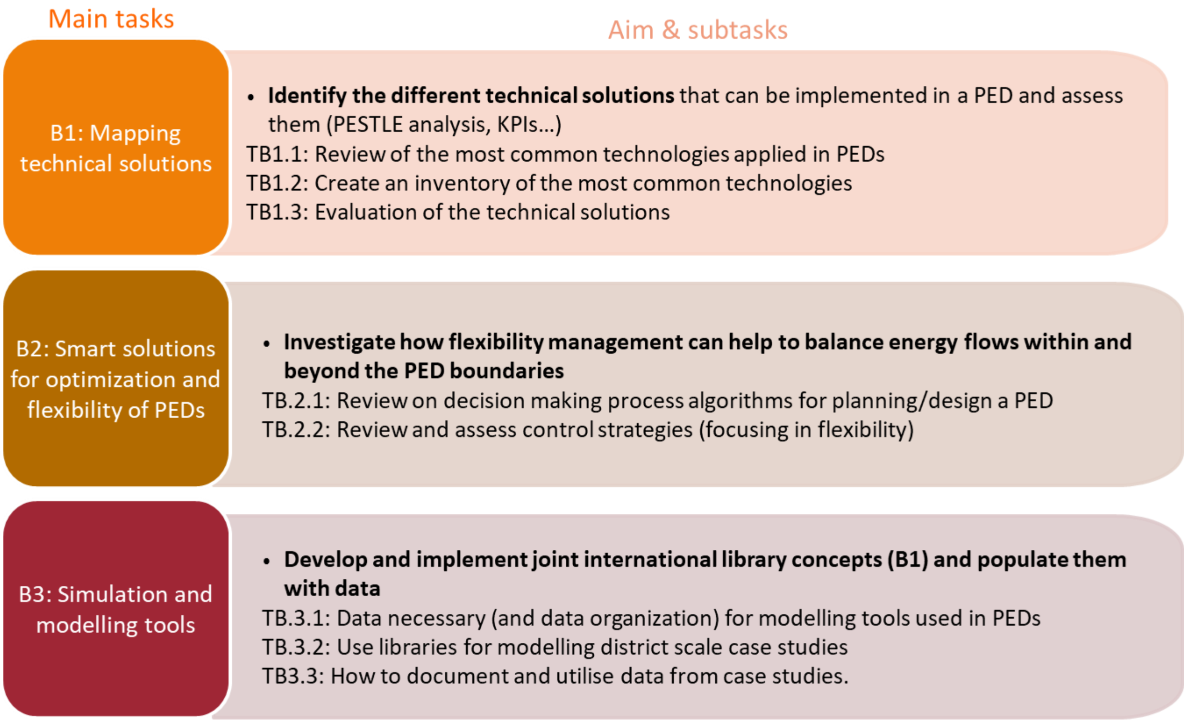


Figure 1: Overview of Subtask B tasks

Subtask B begins with B1, which maps technical solutions available at different scales in Positive Energy Districts. It combines a scan of innovative PED and related technologies (RES/non-RES, storage, networks, monitoring/control) with an inventory from real cases, then evaluates the technologies by topic (heating, cooling, electricity, storage) and its impact to PEDs. The result is a structured database of PED cases with its technologies and socio-economic characteristics to analyse patterns.

Building on B1's content and D's demos, B2 focuses on smart solutions for flexibility and control: it reviews decision-making processes and planning algorithms for stakeholders (planners, architects, citizens, experts) and assesses operational strategies (for forecasting, demand response, load shifting/peak shaving, VPPs, advanced control, data management). Output includes best practices urban-scale and district control strategies to optimise PEDs. In turn, B3 defines standardised data needs and proposes system templates to district-scale cases with subtask B partners tools (e.g., Tools4Cities, City Energy Analyst), and documents how the data and libraries can be used for PED modelling.

B1- Technologies and energy systems in Positive Energy Districts

PED projects originate from the evolution of previous initiatives, mainly innovation projects funded through European research initiatives, particularly Horizon programs (Clerici Maestosi et al., 2024). According to the same author PED implementation is still experimental, with 47% of studies describing real-world cases. (Clerici Maestosi et al., 2024)
PEDs can be categorised into different types based on their operational mode and dependence on the energy grid. Autonomous PEDs are fully self-sufficient, with local renewable energy generation consistently exceeding consumption and minimal or no reliance on the external grid. Dynamic PEDs operate similarly but allow for grid interaction—energy can be imported or exported, provided that the district maintains a net-positive energy balance over a defined period (typically on an annual basis). Finally, Virtual PEDs combine local and off-site renewable energy generation. They operate within virtual boundaries, enabling positive energy performance through remotely located generation assets, if these are managed by stakeholders within the PED (e.g., building owners or operators).

However, PEDs are predominantly developed in Northern and Central Europe, with dynamic PEDs being the most effective and adaptable. Virtual PEDs offer potential for Northern climates due to lower solar availability and higher wind potential. Key technological choices depend on pre-existing regional programs promoting specific technologies (Leone et al., 2023).

The conceptualisation and implementation of PEDs presents numerous uncertainties, both technical and non-technical, that must be addressed to achieve success through the commitment of all stakeholders. This requires an inclusive decision-making process, adopting adaptive approaches to address the challenges that arise (Gohari et al., 2024). However, the deployment of these new models of efficient and sustainable districts in developing countries requires considering characteristics and contexts that differ from those of Europe and North America (UN-Habitat ONU, 2012). To achieve this goal, some international initiatives have been proposed (Emerging Cities Program, 2011; Habitat III Program, 2017), but it is necessary to map the current situation in these countries and identify the specific challenges they must face (Soutullo et al., 2024). The management of these new city models involves the participation and cooperation of all stakeholders at all levels (local, regional and national), through multidimensional and multisectoral solutions.

The development of three PED definitions —autonomous, dynamic, and virtual—provides a practical framework for implementation. Autonomous PEDs promote self-sufficiency and can operate independently from external fossil fuels or the grid. In contrast, dynamic PEDs actively exchange energy with surrounding networks — such as electricity, gas (through hydrogen exports), or district heating grids. Virtual settings, meanwhile, rely on off-site renewable energy sources to reach this positive balance, meaning that energy production is not limited to local generation. All configurations aim to achieve energy positivity, meaning that over the course of a year, they produce more energy than they consume. The proposed "onion model" supports energy sharing between peripheral and central districts to maximise renewable energy use (Lindholm et al., 2021b)
A comparative review of PEDs and related concepts highlights gaps in standardised definitions. The integration of economic, social, and environmental aspects is essential for achieving a comprehensive PED framework (Casamassima et al., 2022). PED definitions must evolve to incorporate urban contextual factors Derkenbaeva et al. argue that the complexity of PEDs—given their multiple interacting components (e.g. buildings, infrastructure, users, energy flows)—cannot be adequately managed using traditional, siloed planning approaches. Managing them effectively requires frameworks like Complex Adaptive System, which can handle complexity, uncertainty, and adaptation, as captured in the Doughnut Model (Derkenbaeva et al., 2022a). Analysis of 60 PED projects revealed diverse spatial scales, with a majority under 0.2 km². Norway and Italy lead in PED implementation, often funded through private investments supplemented by regional grants (Zhang et al., 2021). The adoption of renewable energy solutions substantially mitigates emissions, particularly evident in the stark contrast between gas and renewable heating systems (Castillo-Calzadilla et al., 2024).

The following section provides an overview on how to implement PEDs for decarbonising heating and cooling and how electrification and PEDs play a role in decarbonising cities. It is followed by an overview of PED case studies, its technologies and its main barriers.

B1.1-Decarbonising heating and cooling

The transition to renewable heating and cooling systems—powered by renewable energy sources (RES) such as geothermal, biomass, solar thermal, and photovoltaics—combined with improvements in building energy performance, enables a significant reduction in environmental footprint (Castillo-Calzadilla et al., 2023). This section provides an overview of efforts to accelerate the adoption of RES, a process further reinforced by the current geopolitical context (such as the gas crisis), even though RES had already been prioritised in EU and national energy strategies. It also presents a detailed review of the main RES technologies used for heating, cooling, and electricity generation, with particular emphasis on their role within Positive Energy Districts.

Gas crisis

In 2021, a gas crisis started with combination of factors, including increased demand as economies recovered from the COVID-19 pandemic, lower-than-normal gas storage levels, and geopolitical tensions with Russia, a major gas supplier to Europe. The crisis worsened significantly in 2022 after Russia's invasion of Ukraine, which led to sharp reductions in gas flows to Europe. This triggered a surge in prices and heightened fears of supply shortages. In response, European countries urgently sought alternative gas sources and implemented consumption-reduction measures (Peter Zeniewski et al., 2023).

Despite the volatility, Europe weathered the winters of 2022–2023 and 2023–2024 without major disruptions. This was due to a combination of factors, including mild weather, increased liquified natural gas imports, demand-side reductions, and alternative pipeline supplies. Gas storage levels remained relatively stable. However, as the war in Ukraine and tensions with Russia persist, gas supply continues to represent a strategic risk for the EU (Directorate-General for Energy, 2024c; European Commission, 2021; Fleming & Guérin, 2024). The crisis accelerated the EU's push toward energy sovereignty and decarbonisation, through the development of several initiatives focused on urban heating systems, including the REPowerEU. It was launched in May 2022 and aimed to accelerate the transition to renewable energy and reduce dependence on fossil fuels, including gas. It included measures to promote energy efficiency in buildings and the deployment of renewable heating technologies in cities (European Commission, 2022). The Energy Efficiency Directive was reviewed, and included provisions related to heating and cooling planning, requiring member states to ensure that regional and local authorities prepare heating and cooling plans to guide the transition to sustainable heating solutions in cities (EU, 2023). In addition, the EU set a voluntary target to reduce gas demand by 15% over the winter. This encouraged individuals, businesses, and public institutions, including those in cities, to reduce their gas consumption. The EU also promoted measures to reduce energy consumption in buildings, such as improving energy efficiency through renovations, promoting the use of heat pumps, and optimising heating and cooling systems (European Commission, 2023).

Several member states, particularly in the Baltics, have led the shift away from fossil-based heating. Estonia, Latvia, and Lithuania have set ambitious decarbonisation targets, capitalising on their district heating infrastructures. If modernised and integrated with renewable sources, these systems can significantly reduce emissions. The urgency of this transition has increased following the disruption of Russian gas supplies (Morgan Henley et al., 2022).

Several projects were launched throughout Europe to sustain the decarbonisation of district heating and cooling networks. For instance, the Act!onHeat initiative aimed to broaden the dissemination and uptake of strategic heating and cooling planning concepts and methodologies in over 120 municipalities, enhance their quality, and speed up the development and execution of identified measures (Carsten Rothballer, 2021).
In the framework of district heating, the concept of 'detoxifying' urban heating systems was introduced in Europe, encouraging the renovation, development, and expansion of collective district heating and cooling networks in cities (Directorate-General for Energy, 2024b). In parallel, initiated by the Covenant of Mayors, the 'Cities Heat Detox' campaign highlighted how urban areas are transforming their heating systems to improve air quality, support public health, and drive a sustainable energy transition (Le Corre, 2024). Many cities in Northern Europe are involved in this project, as well as cities in Southern European countries like Italy, Spain and Portugal (EU Mayors, 2024). Berlin has designated citywide heat planning as a central instrument in its transition toward climate neutrality (Gonzalez-Salazar et al., 2020). The goal was to identify the most environmentally sustainable and economically viable heating solutions for each part of the city. Heat planning is carried out in several stages and includes multiple components and aims at providing a spatial overview of areas best suited for different heating approaches, such as centralised district heating systems or local, decentralised solutions. These findings will inform the development of a comprehensive heat strategy for the entire city. The finalised heat plan is scheduled to be submitted to the Berlin Senate for approval in early 2026 (Senate Department for Urban Mobility, 2020). During this time of crisis, many emergency

measures to deal with the 'gas crisis' have been adopted throughout Europe, including at the local level. : Many cities lowered the thermostat in public buildings, such as offices, schools, and libraries, to reduce heating demand. Cities provided energy advice and support services to residents, helping them to identify energy saving opportunities and access available financial assistance. They also launched campaigns to raise awareness about energy saving tips and encourage residents to reduce their energy consumption at home. These measures were often complemented by the use of renewable energy sources or alternative fuels, to provide heating to homes and businesses. In addition, cities provided tailored energy advice and support to vulnerable households, helping them improve energy efficiency and lower their energy costs.

In the US, programs such as the Virginia Energy Assistance Program (EAP) and the Low Income Home Energy Assistance Program (LIHEAP) provide essential support to vulnerable households by offering assistance for heating, cooling, and weatherisation expenses. These programs aim to alleviate the financial burden associated with home energy bills, prevent energy shutoffs, and ensure safe and healthy living conditions.

In summary, both national policies and EU directives are increasingly supporting local, decentralised energy production and energy efficiency measures, laying a solid foundation for the development of PEDs. In fact, the gas crisis exposed the vulnerability of fossil-based and centralised energy conversion systems, prompting cities to:

- adopt renewable heating systems, such as solar thermal, geothermal, biomass, and waste heat recovery (Hille, 2023).
- replace traditional boilers with heat pumps (Huisman & Voswinkel, 2023)
- implement thermal storage to stabilise supply (Gómez-Ramírez et al., 2024).

PEDs became a framework for experimenting with these alternatives, especially in cities with large multi-family housing or public buildings still reliant on gas-fired heating systems. By incorporating diverse local renewable-based plants, PEDs present an effective solution for reducing reliance on external energy networks (Derkenbaeva et al., 2022b). Due to their design, PEDs are inherently more resilient to disruptions in external energy markets, as their dependence on locally generated renewable energy makes them less susceptible to the volatility and high prices of fossil fuel imports. Many PEDs also feature district heating and cooling systems powered by renewable energy, further decreasing reliance on gas-fired boilers and fossil-based, centralised heating solutions (Volpe et al., 2025).
In general, the funding mechanisms introduced by governments and institutions in response to the gas crisis are facilitating the growth of local, renewable-based energy systems, aligning closely with the strategic goals for deploying PEDs. Incentives for heat electrification and building renovation are consistent with PED objectives, encouraging integrated, district-level approaches rather than isolated building improvement.

Heat pump technologies

Heat pumps (HPs) play a pivotal role in PEDs by contributing significantly to energy efficiency and the reduction of CO_2 emissions, due to their high energy efficiency and non-combustion operation, especially when powered by renewable electricity (Ochs et al., 2022). The primary function of a HP is to transfer thermal energy from a heat source at a lower temperature to a heat sink at a higher temperature, enabling efficient heating or cooling. The supplied energy can be used immediately, stored, or distributed via a heating network. Various types of HPs exist, including air-source, ground-source, and water-source models, with air-source HPs being the most used in residential buildings (Ruby Moore-Bloom, 2022).
In PEDs, the efficiency potential can be unlocked by using HPs to harness renewable electricity from distributed and district-based energy systems, thereby reducing fossil energy demand and supporting the achievement of a positive energy balance.

HPs, combined with storage, offer significant potential for adaptation of the loads (if comfort is still met) to fluctuating renewable energy generation, such as photovoltaics and wind power. The flexibility provided by HPs stems from two primary factors. First, heat pumps can store thermal energy in water, particularly in domestic hot water (DHW) systems, allowing energy consumption to be shifted to periods of high renewable energy availability. Second, they enable the optimisation of building heating and cooling by utilising the entire building structure as a thermal storage medium. By operating within a defined temperature range, buildings can act as thermal buffers, absorbing or releasing heat as needed to maintain indoor comfort while synchronising energy demand with renewable energy supply.
As a result, HPs play a crucial role in balancing energy grids with high shares of variable renewable energy. By intelligently managing their operation and storage capabilities, they reduce reliance on fossil fuel-based backup systems, lower overall energy costs, and enhance grid stability. Furthermore, their integration into PEDs maximises the efficient use of locally generated renewable energy, reducing PED instantaneous surplus energy and improving PED independence. Current HP automation and control systems often function

in isolation, limiting their ability to respond to real-time grid conditions and market signals. To address this challenge, aggregators—entities that pool multiple distributed energy resources and optimise their operation—can play a key role. By integrating HPs into demand response programs and virtual power plants, aggregators enable grid-responsive operation of HPs, enhancing flexibility, load shifting, and overall energy efficiency (Müller et al., 2022; IEA, 2023).

District heating and cooling networks

Decarbonising district heating networks is a crucial step toward achieving climate goals. Waste heat, geothermal, solar thermal, and HPs are seen as key drivers for this change.

Electric-driven HPs can replace gas boilers and combined heat and power (CHP) plants in district energy systems, utilising ambient heat, groundwater, or industrial waste heat to provide sustainable heating solutions (Johansen & Werner, 2022). As illustrated in Figure 1, HPs can be integrated at different system levels—building-wise, block-wise, or decentralised flat-wise, allowing flexible provision of space heating (SH) and domestic hot water (DHW). These configurations enable the utilisation of ambient heat sources, such as groundwater or industrial waste heat to higher temperatures, while relying on electricity from renewable generation (e.g., wind, photovoltaics, hydro). Consequently, the interaction between the electricity grid, district heating infrastructure, and end-user loads establishes a coupled energy system that enhances efficiency, supports large-scale integration of renewables, energy source flexibility and reduces carbon emissions.

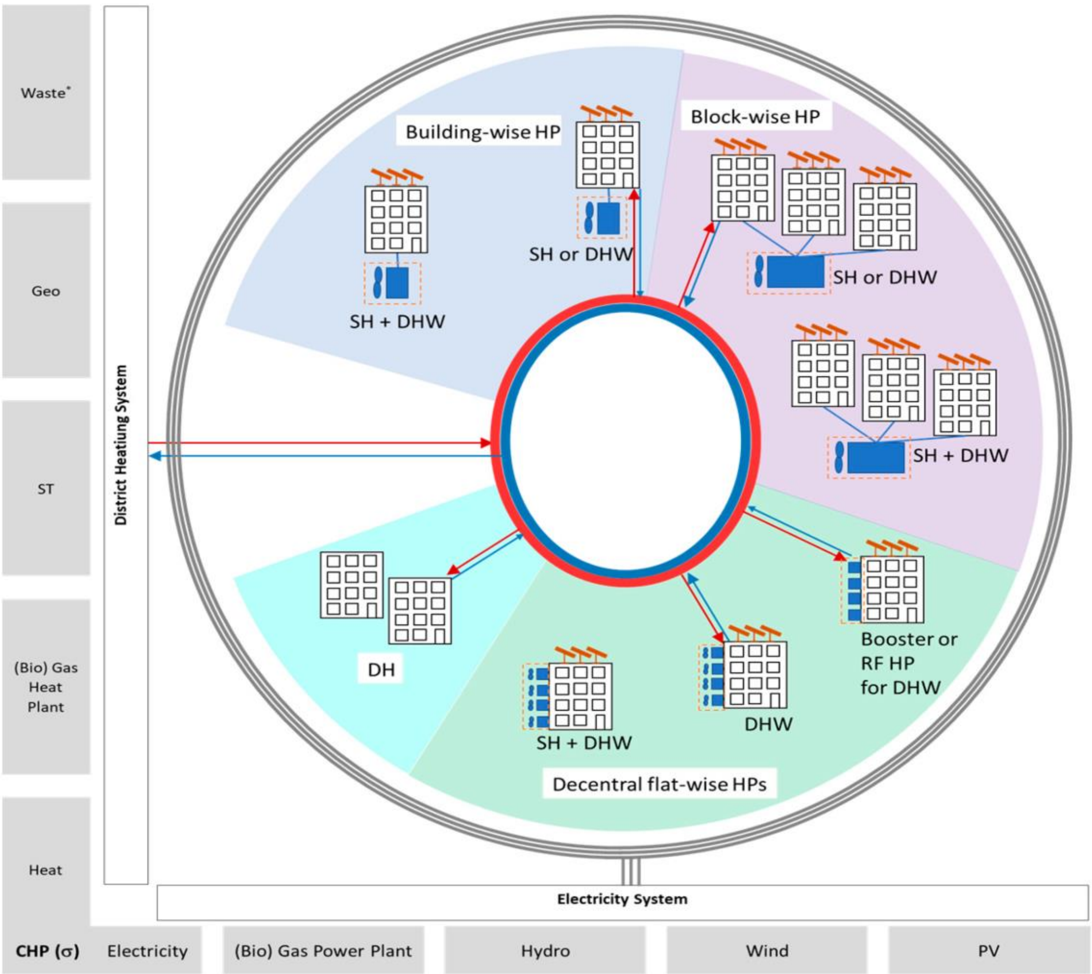


Figure 2: Sketch of the interactions between electric system, DH and loads – IEA Annex 61 (Tosatto et al., 2023)

In fact, waste heat from industrial processes, data centers, supermarkets, metro systems, and wastewater treatment plants can provide a valuable source of low-cost, low-carbon heat. HPs play a key role in upgrading waste heat to useful temperature levels for distribution in district heating networks when needed (Guo et al., 2024). For example, high temperature-HPs can elevate waste heat from around 45°C to as high as 85°C, making access to HPs viable for integration into existing old building infrastructures (of DH and high-energy intensive buildings).

Depending on the typology of the network, for instance, if the network supplies heat at lower temperatures, the upgraded heat can be produced at substation level. Shallow and deep geothermal heat sources can be integrated with heat pumps to provide a stable and renewable heat supply, reducing dependency on fossil fuels (Lund et al., 2022). Coupling district heating networks with short-term (e.g., hot water tanks) and long-term (e.g., borehole or aquifer storage) thermal energy storage systems enhance flexibility and enables better integration of intermittent renewable energy sources (Guo et al., 2024).

District cooling can work together with the district heating, making use of the rejected heat from chillers to drive the latter one. Utilising natural cooling sources such as seawater, lakes, and underground aquifers can significantly reduce energy demand for cooling.

Key technologies available in DH configurations can be seen in Figure 2. Thermal energy storage (TES) technologies, including seasonal storage (e.g., aquifer, borehole, pit, and tank TES) and short-term storage (e.g., network TES and building thermal mass as thermal batteries), provide temporal balancing between supply and demand. Fourth- and fifth-generation district heating (4GDH and 5GDHC) enable bidirectional energy flows and prosumer integration, facilitating efficient use of renewable and waste heat. Depending on how the prosumer is able to provide heat to the DH or the temperature of the heat supply to the user, the substation is of 4GDH generation or 5GDHC. The latter one usually involves cooling and the ability to inject heat from the user to the DH (as prosumers). Low- and ultra-low-temperature networks reduce distribution losses and support the deployment of decentralised heat pumps. Furthermore, DHS can integrate both centralised (CHP, biomass, gas, seawater, lakes and aquifers, geothermal) and decentralised sources (industrial processes, data centers, supermarkets, metro systems, wastewater treatment plants), with waste heat recovery playing a crucial role in enhancing efficiency and sustainability.

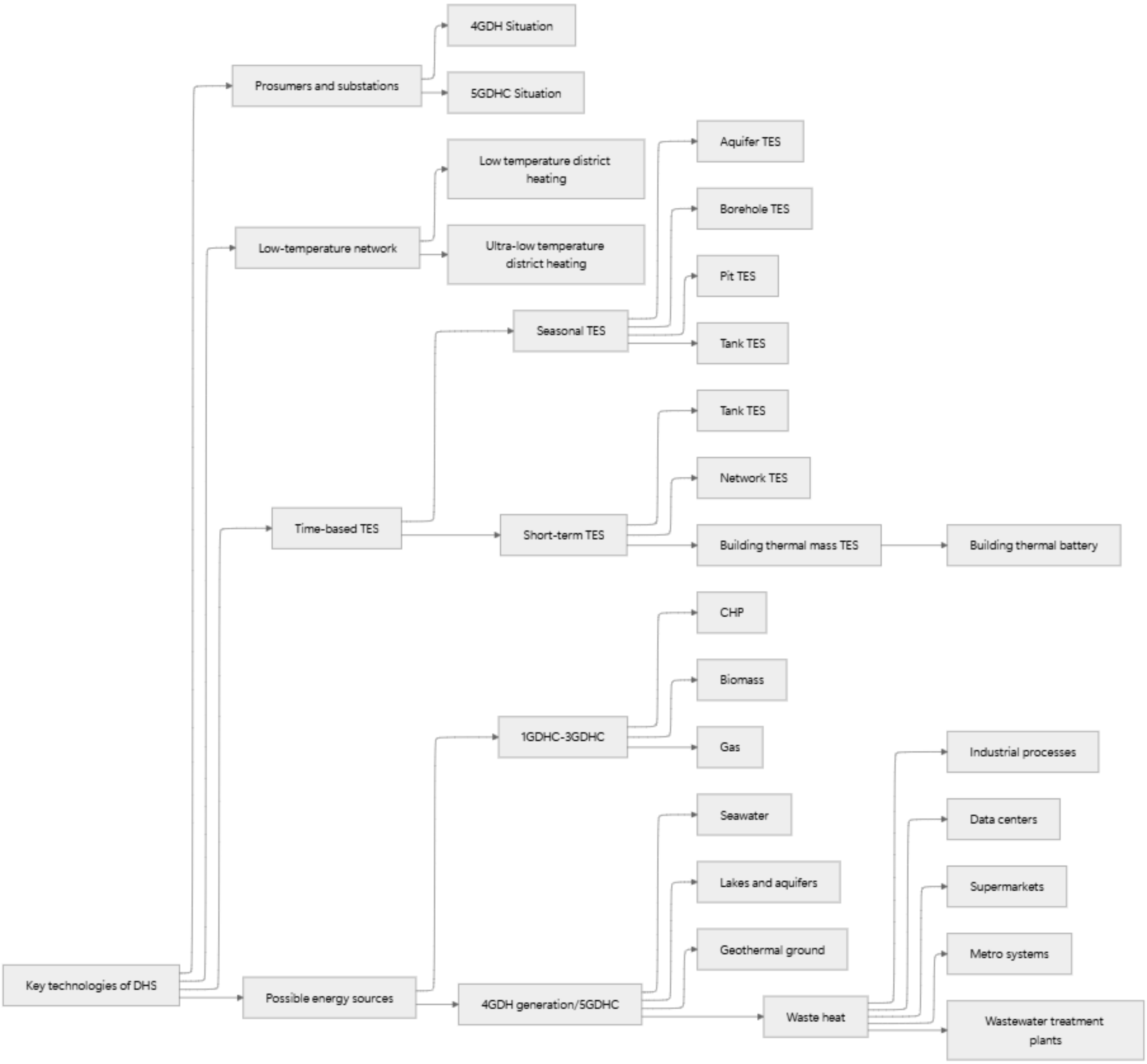


Figure 3: District heating technology options [based on (Guo et al., 2024)]

Low temperature solar thermal

Solar thermal systems play a crucial role in PEDs by harnessing solar energy to provide heating and cooling solutions, thereby reducing the dependency on gas and other fossil fuels. These systems consist of solar thermal collectors that capture sunlight and convert it into heat, which is then stored or directly used for heating purposes or as DHW. In PEDs, solar thermal systems often work in conjunction with heat pumps to optimise energy efficiency and minimise gas consumption for both heating and cooling needs.

In a typical setup, solar thermal collectors supply heat to a district heating network, which distributes the thermal energy across multiple buildings within the district. This shared infrastructure allows for better resource management and energy balancing among the buildings, leading to significant financial and energy savings (NREL et al., 2020).

Additionally, the integration of renewable energy technologies in PEDs, including solar thermal systems, supports urban decarbonisation efforts. Given that cities are responsible for around 70% of global energy consumption and CO_2 emissions, the shift towards renewable energy models like PEDs is essential for meeting climate goals outlined in the Paris Agreement. By fostering such innovative energy solutions, PEDs not only address environmental concerns but also improve the quality of life and access to energy for urban residents.

Biomass

Biomass can utilise waste materials like agricultural residues, forestry thinning, and even municipal waste, turning them into useful energy and potentially reducing landfill burdens. Biomass can be used for various purposes, including electricity generation, heating, and the production of biofuels. In 2021, the European Union accounted for 59% of total renewable energy consumption from biomass (Directorate-General for Energy, 2024a).

In some cases, biomass can be used in existing power plants with modifications, potentially reducing the need for entirely new infrastructure.
The "carbon neutral" claim hinges entirely on sustainable sourcing. If biomass is harvested from unsustainable forestry practices (deforestation, clear-cutting), or if it leads to land-use change (like converting forests to energy crops), it can actually increase greenhouse gas emissions and harm biodiversity.
Burning biomass still releases CO_2, and the full life cycle emissions need to be considered. This includes emissions from harvesting, transporting, processing, and burning the biomass. If these are not carefully managed, biomass can have a higher carbon footprint than initially assumed.
Biomass can compete with other valuable uses for land and resources. For example, using wood for energy might mean less is available for construction or furniture. The EU has introduced stricter rules on the use of primary woody biomass (wood directly from forests) in its Renewable Energy Directive. It limits subsidies for electricity-only plants that use primary woody biomass and emphasises the "cascading principle," prioritising the use of wood for higher-value purposes like construction before energy (EU Science HUB, 2019).
Furthermore, even sustainably sourced biomass releases air pollutants - including particulate matter and nitrogen oxides - when burned, which can have adverse effects on human health (Directorate-General for Energy, 2024a). Still, many cases are reassessing or even restricting the use of biomass as a sustainable source for heating and cooling, often introducing specific limitations or conditions on its use:

- New DH systems with Biomass in several areas of the city of Valladolid, without any limitations in its combustion but promoting local biomass sources
- The Netherlands has banned subsidies for wood pellets that contribute to deforestation, requiring stricter scrutiny of their sourcing
- Slovakia and Portugal only allow subsidies for wood pellets made from forest and lumber mill residues, banning the use of whole trees from native forests

Energy storage systems

TES systems, which include technologies such as ice and chilled water storage, have been integrated into district energy systems for over four decades. These systems help insulate customers from expensive capacity expansions, sudden service interruptions, and volatile rate structures (Sarah Crawford-Theurkauf et al., 2023).

The passage of the Inflation Reduction Act in 2022 further incentivised TES by making new projects eligible for the Investment Tax Credit (ITC), highlighting the increasing value of thermal energy for the decarbonisation and modernisation of the energy grid (Sarah Crawford-Theurkauf et al., 2023).

Additionally, innovative approaches in the field of energy storage play a significant role in enhancing load matching and increasing self-consumption in PEDs. By storing excess energy generated during low-demand periods and releasing it during peak demand, these solutions help balance the load and ensure a steady energy supply. This not only improves the efficiency of the energy systems but also contributes to greater sustainability (Ferrante et al., 2025). Global initiatives and frameworks, such as the 2030 Agenda, New Urban Agenda, Paris Agreement, and the EU's long-term strategy for a climate-neutral EU by 2050, underscore the importance of integrating advanced technologies and energy storage solutions at the district level to achieve climate goals (Fichera et al., 2021). These policies and incentives drive the adoption of required technologies in PEDs, promoting energy resilience and environmental sustainability.

The role of electricity storage is also very relevant in PED context. Storage balances the fluctuating supply of renewables like solar and wind with demand, enables demand-response, and can be used for peak shaving and load shifting, contributing to the district's overall energy flexibility. Further information is found in section B2- Energy flexibility, storage and smart grid integration: solutions and applications to PEDs.

Energy Policy and the Transition to Positive Energy Districts and Thermal Prosumers

The transition towards PEDs and the integration of thermal prosumers are essential components in addressing the gas heating and cooling crisis while promoting decarbonisation. Current energy policies play a crucial role in supporting these initiatives by fostering an environment conducive to sustainable urban development.

The European Union (EU) has set ambitious goals to become the first climate-neutral continent by 2050, which align with the United Nations Sustainable Development Goals (SDGs). This commitment is reflected in the EU Framework Program for Research and Innovation, which channels significant investments towards achieving sustainability, with a notable focus on PEDs and thermal prosumers (Clerici Maestosi, 2021; Krangsås et al., 2021b).

By prioritising these areas, the EU aims to modernise its economy and society, thereby reducing greenhouse gas emissions and promoting cleaner energy solutions. To effectively support the development of PEDs, energy policies need to address various aspects, including technological, spatial, regulatory, financial, legal, social, and economic factors (Krangsås et al., 2021b).
The transition management process involves setting the scene by exploring local dynamics, engaging key stakeholders, and implementing preliminary experimental transformations (Turci et al., 2024).

This holistic approach ensures that short-term and long-term goals are aligned, fostering a sustainable and resilient energy system. The concept of the prosumer, which refers to consumers who both produce and consume energy, is integral to this transition. Policies must encourage the adoption of renewable energy technologies and support the diffusion of innovations in energy management. This includes promoting smart grids, microgrids, and peer-to-peer energy sharing systems, which enhance the efficiency and sustainability of energy use (Kotilainen & Saari, 2018; Parra-Domínguez et al., 2023).

Adapting energy policies to support thermal prosumers involves considering the unique energy demands, resource availability, and priorities of different regions. Strategies such as electrification with renewable power, the use of renewable-based gases, sustainable bioenergy, and the direct use of solar and geothermal heat are essential pathways to achieving a renewable-based, energy-efficient heating and cooling system (IRENA et al., 2020).

B1.2 - The role of PEDs in the electrification of the energy sector

Electrification is a crucial component of the EU's strategy to achieve its climate goals and enhance energy security (Rinaldi, 2024).

Electrification enables the integration of renewable energy sources, such as wind and solar power, into the energy system. This reduces dependence on fossil fuels and promotes the transition to a more sustainable energy system. The main challenges for electrification in cities are:

- Infrastructure development: significant investments are needed in electricity grids and charging infrastructure to support widespread electrification. For instance, in the Netherlands the grid congestion can cause significant challenges for PED projects, reducing its economic viability due to the no possibility to export energy when the grid is congested. Thus, energy storage and funds to support the transition are needed.
- Grid stability: integrating large amounts of renewable energy into the grid can pose challenges to grid stability, requiring innovative solutions and grid modernisation.
- Cost of electrification: the upfront costs of switching to electric technologies, such as electric vehicles and heat pumps, can be a barrier for some consumers.

For instance, retrofitting Lisbon's Alfama historic district was challenging due to its heritage protection rules as well as lack of space. The retrofitting made by the district has reduced space heating and cooling demands by 84% and 19%, respectively. Rooftop organic PV integration can generate up to 60 GWh/year, with significant social benefits, including enhanced climate resilience and air quality (Gouveia et al., 2021). In other cases, for instance in Innsbruck Campagne district, the integration of heat pumps and PV systems reduced the seasonal energy generation-demand imbalances. High efficiency building standards were essential to address the "winter gap," enabling PEDs to achieve positive energy balances (Ochs et al., 2024). In fact, energy storage technologies, particularly batteries, heat storage, and chemical storage, are critical for urban PEDs to match energy supply and demand optimising the positive energy balance and, at the same time, making it profitable. However, regulatory and cost barriers limit their deployment and integration (Anastasovski et al., 2024).

The key advantages of electrification at the district level, and more broadly, in building clusters rather than in individual buildings, stem from several interrelated factors, summarised as follows:

- Load aggregation at the district or community level brings together diverse load profiles from different end-user types. This load-sharing approach supports peak shaving by producing an overall load profile that is not only higher, but also more stable and flattened (Angrisani et al., 2015)
- Smoother load profiles help mitigate inefficiencies related to partial load operation of plants (e.g., cycling losses), increase annual operating hours, and enable the deployment of larger, more efficient energy conversion systems (Ceglia et al., 2022).
- Improved alignment with renewable energy availability enables maximised on-site consumption of renewable energy and reduces grid congestion, particularly when integrated with short- or long-term energy storage systems (Marrasso et al., 2024a).
- Centralised, large-scale district energy systems, such as electric-driven chillers or heat pumps, serving multiple users in shared configurations benefit from economies of scale, leading to reduced capital and operational costs (Xu et al., 2024).
- Electric energy conversion systems can support multi-vector energy solutions, where electric, thermal, and cooling demands are met simultaneously through an integrated and holistic approach (Ceglia et al., 2023).

In this context, energy-sharing schemes at the district or community level serve as catalysts for realising the full energy and environmental benefits of electrification strategies.
Moreover, the adoption of participatory and democratic management models can enhance public acceptance of renewable energy systems and help address social challenges such as energy poverty, ultimately improving the overall sustainability of energy-sharing.

Energy sharing between buildings, combined with storage systems, enhances self-sufficiency and carbon neutrality in districts. However, balancing individual energy autonomy with shared resources remains challenging. PEDs offer a structured framework that transforms conventional districts into collaborative ecosystems. By enabling multiple stakeholders (residential, commercial, municipal, etc.) to jointly produce more renewable energy than they consume, PEDs allow surplus energy to be redistributed to nearby areas lacking sufficient resources or space for renewable energy installations. In practice, PEDs often deploy heat pumps and photovoltaic systems alongside high energy-efficiency standards to achieve net-positive energy performance (as will be seen in section B1.3 - Overview of case studies).
Through electrification, smart control systems (see section B2.2 - Overview of), and mechanisms for energy and financial exchange among stakeholders, PEDs create both environmental and economic benefits.

Figure 4 illustrates the multi-level energy interactions in PEDs, from building-level PV and smart appliances, through district-level shared storage and heat pumps, up to city-level renewable energy generation and grid interactions.
This hierarchical approach highlights how energy can be generated, stored, shared, and monetised across scales, enabling PEDs and both technical and economic optimisation.

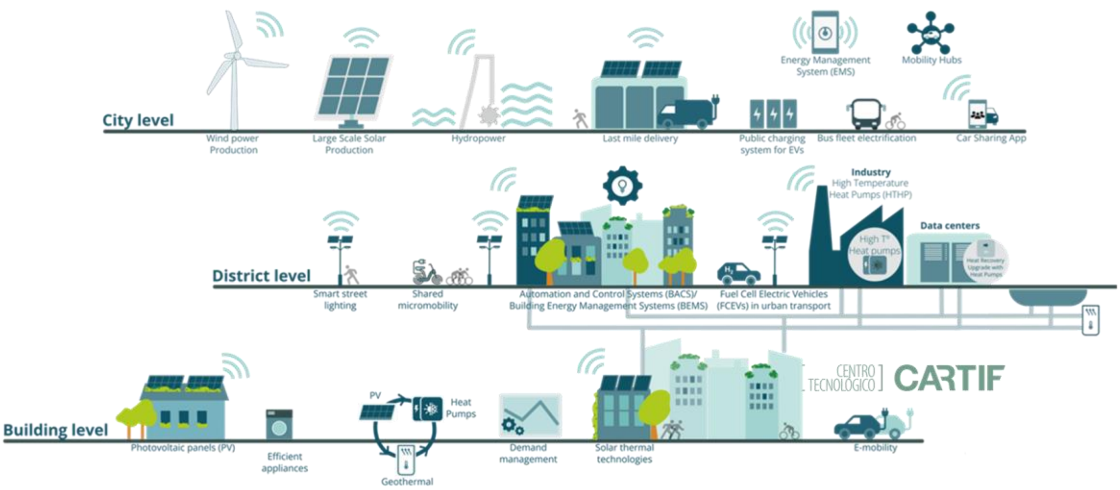


Figure 4: Electrification in cities with positive energy district technologies (Net Zero Cities Solution Bundles, Gabaldon, de Lama, Belen Gomez, and Pastor, 2023)

B1.3 - Overview of case studies

Subtask B gathered data from EU projects (e.g., Cordis database) and grey literature and came up with 39 case studies collected. From it, based on connections of the authors to different case studies, 6 cases were analysed, to extract data regarding barriers and enablers for implementing certain technologies in the case study contexts. The aim is to answer:

- *Which are the most common technologies applied in PEDs?*
- *Why are they being chosen?*
- *Are flexibility, smart solutions, or citizen engagement tools supporting the process?*

The methodology is explained further in Gabaldon, et al. 2025. An analysis of the cases is performed also in this deliverable, mapping the technologies listed in project website and project deliverables, and mapping the Köppen climate zones.

(Krangsås et al., 2021a)

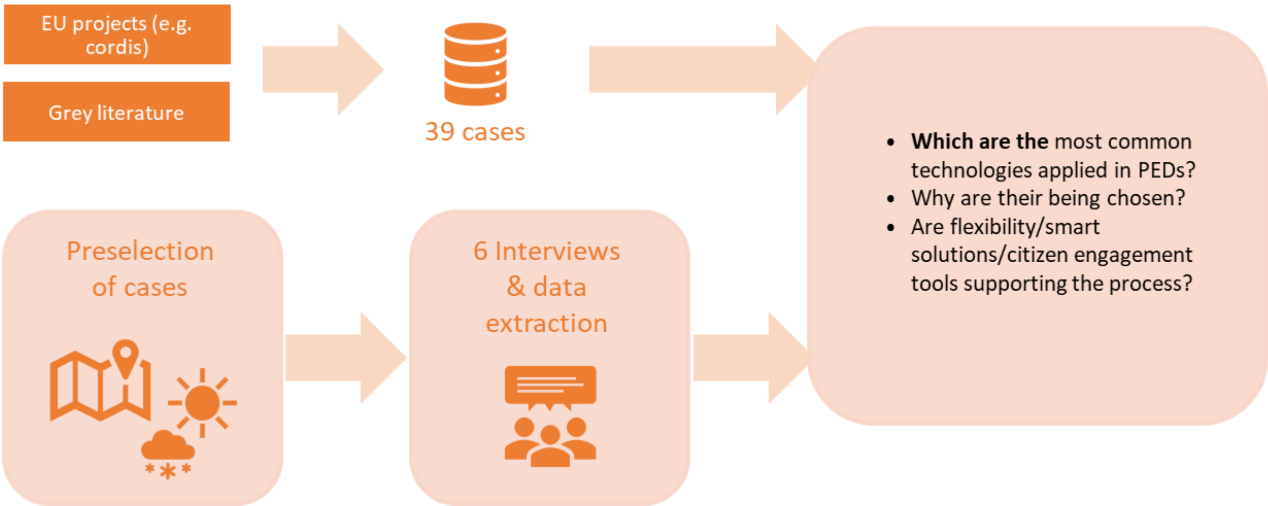


Figure 5: Methodology followed in subtask B1

As a result of the analysis Photovoltaics (PV), District Heating Networks (DHN), and Heat Pumps (HP) are the three most referenced technologies in the case studies—highlighting their centrality to PED design across diverse contexts. Other recurring technologies include Energy Mobility (EM), Energy Storage (ES), Smart Technologies (ST), Waste Heat (WH), and Circular Economy (CE) solutions. Less commonly referenced but still relevant technologies include V2G (Vehicle-to-Grid), ATES (Aquifer Thermal Energy Storage), and Microgrids (MG).

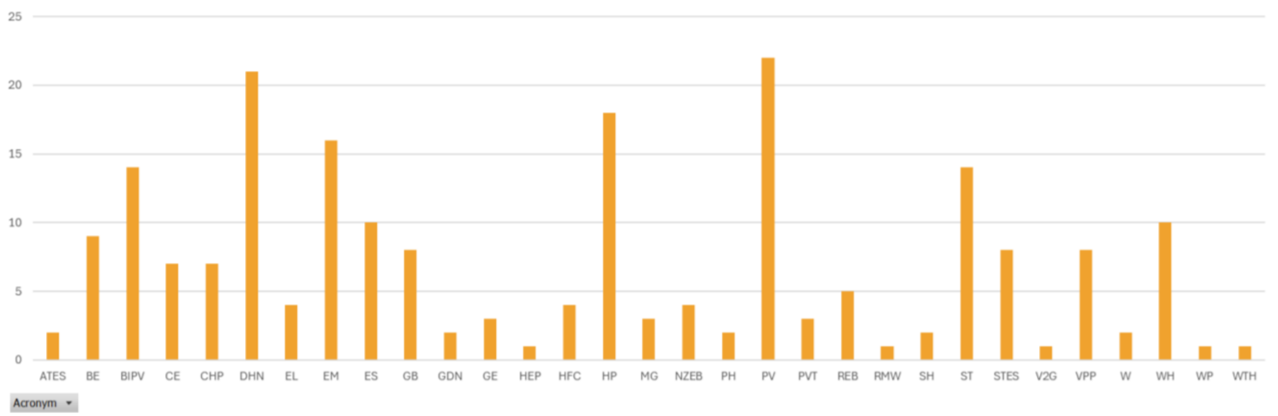


Figure 6: 38 cases results of technologies list

A widely used system for classifying cities according to climate is used to map patterns of climate against technologies. Climate Köppen classification categorises the world's climates based on vegetation, temperature, and precipitation patterns. Each code (like Cfb, Dfb, Csa) represents a specific climate type using a combination of letters, each with a precise meaning.

Table 1: Climate Köppen classification categories used

Code	Major climate	Precipitation pattern	Temperature characteristic
Cfb	Temperate (mild)	No dry season (f)	Warm summer (b)
Dfc	Subarctic climate (cold)	No dry season (f)	Cool summer (c)
Dfb	Continental (cold)	No dry season (f)	Warm summer (b)
Csa	Temperate (mild)	Dry summer (s)	Hot summer (a)
Af	Tropical rainforest climate	No dry season (f)	-
Bsk	Cold semi-arid (steppe)	Dry summer (s)	Cold or warm (k)

As a result of the analysis of, the following patterns have been formulated:

- PV and HP dominate, with wide implementation across all major climates, especially in Cfb (temperate oceanic) and Dfb (humid continental) zones.
- DHN are most prominent in Cfb climates, where population density and existing infrastructure support centralised systems.
- EM and ES show a strong presence in Cfb as well, aligning with needs for flexibility and load balancing in urbanised areas.
- ST and WH also feature across multiple climates but are particularly relevant in cooler zones like Dfb and Dfc, where heating demand is higher.
- BIPV is mainly adopted in Cfb and Csa climates where solar potential and urban design integration are favorable.
- BE is relatively balanced but more prominent in Dfb and Cfb, likely due to local biomass availability.

The Cfb climate zone appears as the most diversified and intensive in technology deployment, possibly due to its urban infrastructure, policy maturity, and moderate weather conditions.

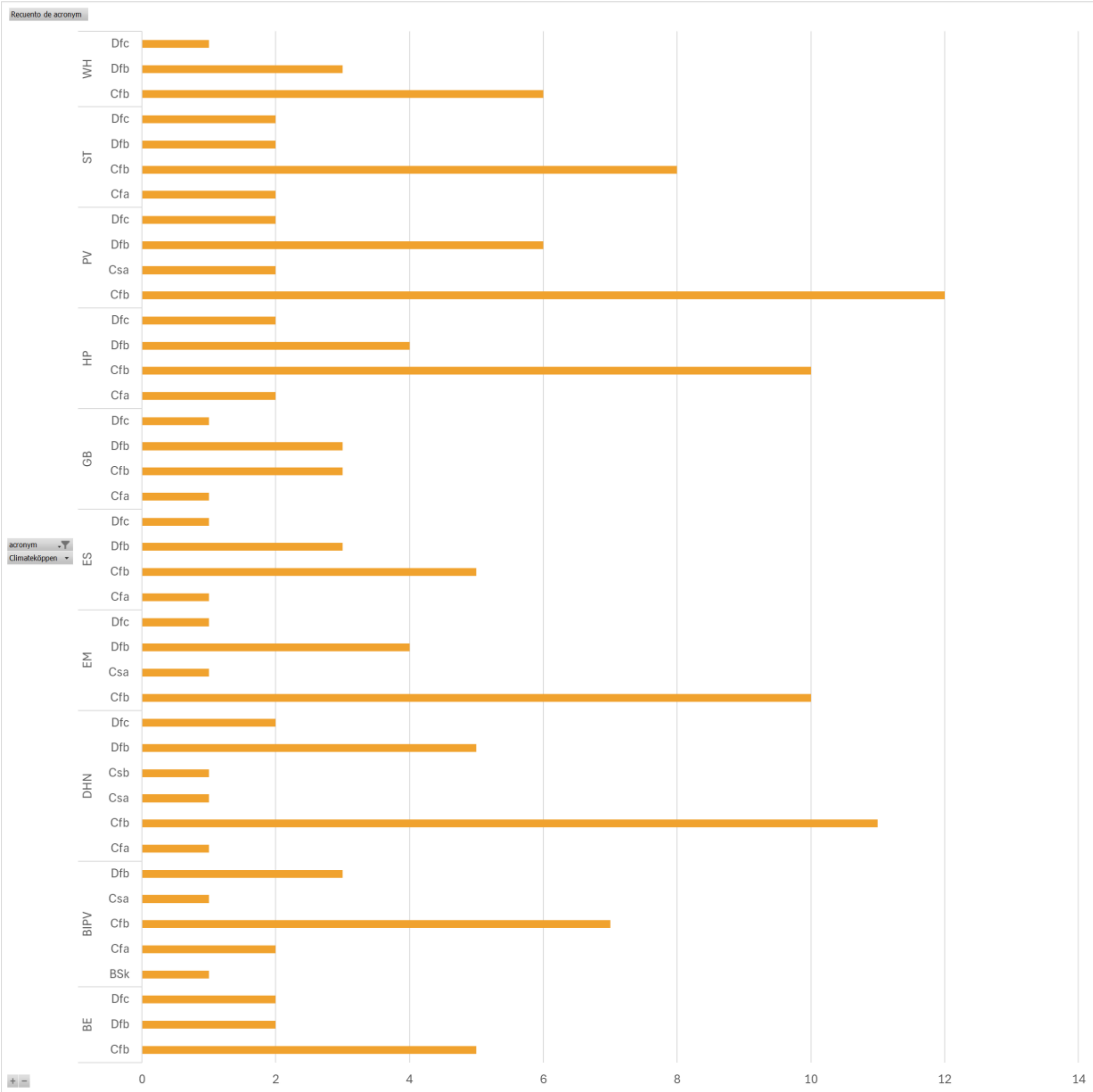


Figure 7: 10 most repeated technologies and its climate appearance

The study is expanded including interviews regarding barriers and technologies implemented [Gabaldon, et al. 2025]. From the literature, seven key challenges to PED implementation which are governance, incentives, social factors, processes, markets, technology, and context, are highly interdependent. Governance and social dimensions rank as the most critical barriers (Krangsås et al., 2021a).
From the interviews, a wide diversity of PED or PED-related approaches emerges, shaped by distinct climatic, spatial, political, and infrastructural contexts. Singapore, Trondheim, and Amsterdam implement PV, HP, ES, and passive design strategies for PED implementation. Singapore's tropical climate necessitates advanced humidity and temperature control, while Trondheim's ZEB Laboratory illustrates a research-driven, integrative model emphasising lifecycle emissions and innovative contracting. Amsterdam's Buiksloterham PED exemplifies circularity and dense urban redevelopment, constrained by space but enabled by unique legal exemptions for managing the energy surpluses and peer-to-peer energy. All three highlight the importance of institutional coordination, community engagement, and performance monitoring. Åland focuses on theoretical models for full RES self-sufficiency in a low-density island context, facing storage and flexibility challenges while leveraging strong political will and cross-sector coordination. Évora integrates PEDs into a historic urban fabric, balancing heritage conservation with smart infrastructure (building integrated organic PV, PV solar farms, community-owned installations, energy management systems, etc.), citizen engagement, and digital tools. Barriers across all cases include regulatory rigidity, infrastructure incompatibilities, and limited financing mechanisms. However, strong enablers such as community involvement, public-private partnerships, and targeted innovation policies have proven crucial.
Together, these cases underline that successful PED implementation relies not only on technological deployment but also on adaptive governance, contextual planning, and active societal participation.

Detailed analysis

Figure 8 visually ranks technologies by how frequently they appear across case studies. Photovoltaics (PV) is the most widely implemented technology (7 occurrences[3]), underscoring its foundational role in PEDs across diverse contexts. This is followed by heat pumps (HP) (5 cases), and flexibility mechanisms (FLEX), district heating networks (DHN), and programmable logic automation (PLA) with 4 instances each. Other common technologies include energy storage (ES), efficient lighting (EL), circular economy practices (CE), and net-zero energy building (NZEB) standards, each appearing in 3 projects.

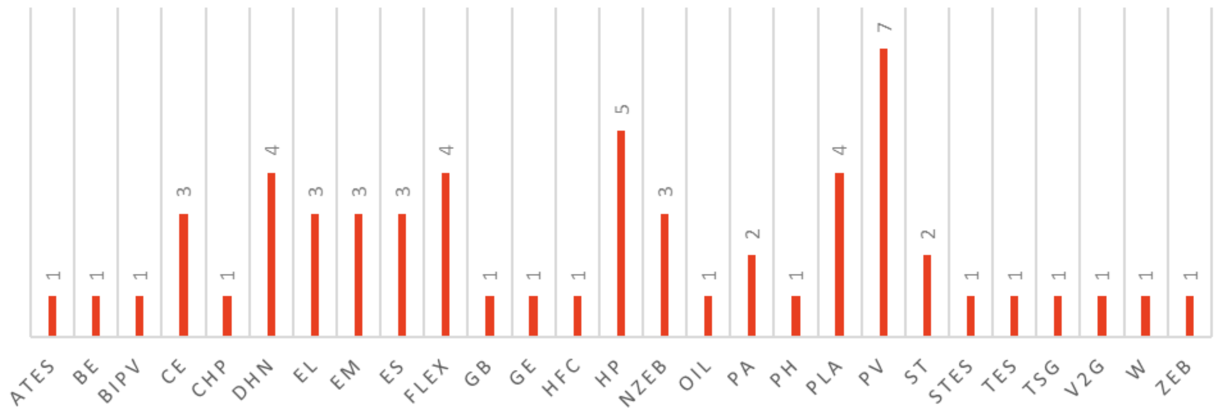


Figure 8: Technology preferences in the case studies

When these data are analysed and compared to the climate, they show that:

- Dfb (warm-summer humid continental) and Cfb (temperate oceanic) climates show the broadest variety of technologies, often integrating HP, DHN, PV, and ES.
- Csa (Mediterranean) climates tend to emphasise PV and HPs, but also flexible systems (FLEX), energy mobility (EM), and circularity (CE).
- Af (tropical) regions focus on high-efficiency systems like NZEB and EL, alongside PV and HP.
- Dfc (subarctic), represented solely by Trondheim, includes HP, PV, and advanced control/storage technologies like TSG and ZEB.

While PV and HP are widely used regardless of climate, technological preferences slightly shift depending on regional challenges—such as flexibility in Csa climates or integrated heating in Dfb zones—highlighting the need for climate-sensitive PED strategies.

Figure 9 displays the distribution of all reported barriers across all case studies. The most cited barrier is "Complexity of actors/not all in the same agenda" (13%), underlining the importance of coordination and stakeholder alignment. “Political commitment to innovation” and “Other” barriers follows closely at 9% each, indicating systemic and context-specific challenges.
Barriers such as “Regulation hinders implementation”, “Limited budget constraints”, “Infrastructure inadequacies”, and “Access to diverse funding sources” each represent 7% of cases. A range of additional barriers (e.g., lack of skilled workforce, acceptance, technical limitations) each account for around 4%, pointing to a wide but shallow distribution of challenges.

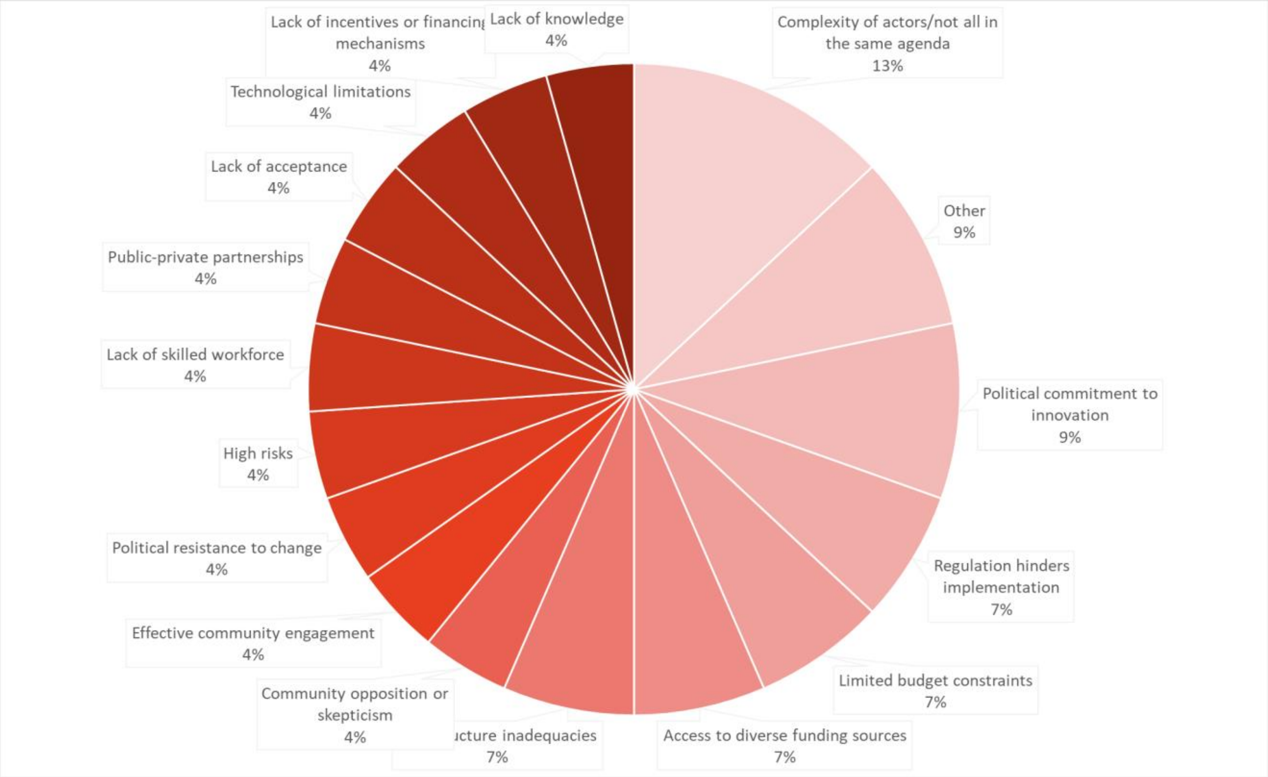


Figure 9: Distribution of all reported barriers across all case studies

Figure 10 shows the relative frequency of key barriers across different Köppen climate zones where PEDs are implemented. It includes only those barriers that appear in more than two case studies. For instance, "Complexity of actors/not all in the same agenda" is a prominent barrier in Af (tropical) and Cfb (temperate oceanic) climates. "Political commitment to innovation" appears significantly in Af and Cfb climates. "Other" barriers, which include context-specific challenges such as regulatory issues or performance gaps, are especially prevalent in Cfb and dominate in Dfc (subarctic climates). "Limited budget constraints" appear only in Dfb and Dfc, suggesting financial limitations are more pronounced in colder or lower-density regions. "Access to diverse funding sources" is noted as a barrier especially in Dfb zones.

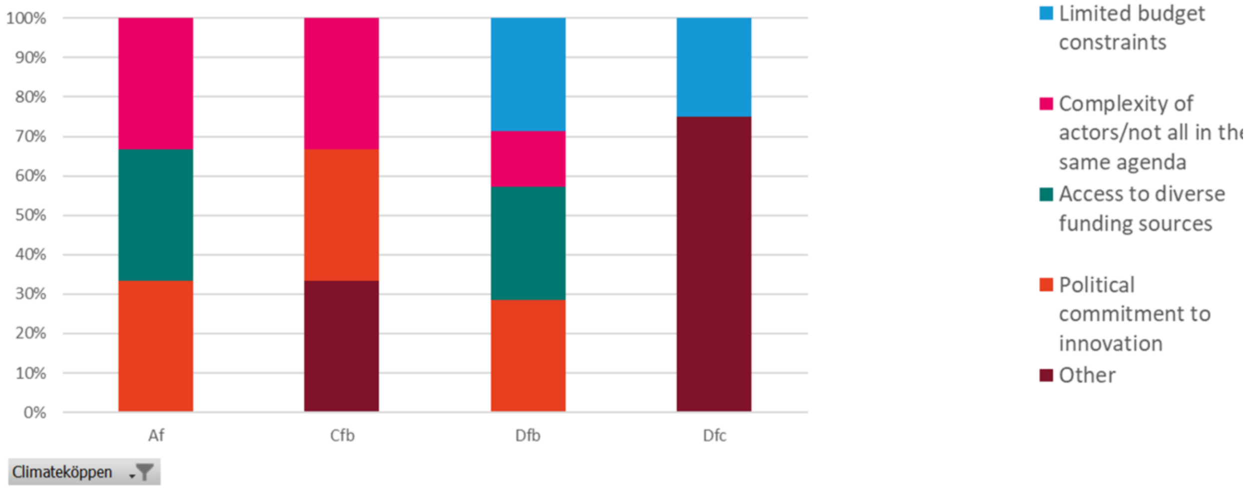


Figure 10: Frequency of key barriers across different Köppen climate zones

Note that this analysis is based on a limited selection of case studies and climate contexts. While it provides valuable insights into common technologies and barriers in PED implementation, the findings should not be considered exhaustive.

Case study details

Hereafter, the case studies and results from the interviews are explained one by one. Each case study is presented in a standardised format, starting with general information about the location, socio-economic and climatic context, followed by a short description of the project objectives, technologies implemented, and outcomes achieved. In addition, the main barriers and enablers identified during the development and implementation phases are summarised in a dedicated table, distinguishing between barriers (B) and enablers (E).

CASE STUDY NAME: DRAKE LANDING

City: Okotoks
Country: Canada
Density: 1,753.3 inhabitants/km²
GDP area/region: 60,747 Million USD, constant prices, constant PPP, base year 2015
Climate classification: Dfb (Humid continental climate, warm summer)

Description: Drake landing was aiming to achieve a high solar fraction (and it succeeded achieving 90% and even 93% in some years). They started a project federal funded to test district heating and seasonal thermal storage using solar thermal in the area.
Some 2,295 m² of hydronic flat-plate collectors cover the roofs of the 52 houses' detached garages. The seasonal borehole thermal energy storage (BTES) is comprised of a grid of 144 boreholes with single u-tube heat exchangers within approximately 34,022 m³ of earth. Short-term thermal storage (STTS) consisting of 240 m³ of water is used to interconnect the collection, distribution and seasonal heat storage subsystems and to act as a buffer to accept and release heat at rates considerably higher than are available through the BTES.

Barriers list:

Type		Explanation
B	Uncertain return on investment	The developer bore all financial risk and required substantial funding due to a misalignment between incurred costs and expected benefits.
B	Limited financial resources	Project relied heavily on external federal and provincial funding due to insufficient internal budget.
B	High perceived risk	Uncertainties associated with seasonal thermal storage and the feasibility of a district heating network created major risk concerns.
B	Technological unfamiliarity	District heating networks are uncommon in Canada, which limited technical confidence and implementation experience.
B	Market resistance to innovation	Radiant floor heating was perceived as too novel by developers, potentially deterring adoption which led to decide to install fan coils instead.
E	Political support for innovation	Strong backing from regional government helped legitimize and promote innovative energy solutions.
E	Access to diversified funding sources	The project secured substantial funding from multiple sources, mitigating financial barriers.
E	Stakeholder commitment to innovation	While formal public-private partnerships were absent, key stakeholders showed strong interest in exploring and supporting novel concepts.

Building typologies: RESIDENTIAL.
Average building year: 2007.
Technologies list: DHN (based on geothermal), ST (DHW), BTES, and STTS. Possible future: PV and HPs.

CASE STUDY NAME: SDE4
City: Singapore
Country: Singapore
Density: 7,966 inhabitants/km²
GDP area/region: 34,9820 Million USD, constant prices, constant PPP, base year 2015
Climate classification: Af (Tropical rainforest climate)

Description: The School of Design & Environment 4 (SDE4), completed in 2019, is Singapore's first new-build net-zero-energy building and a key example of climate-conscious tropical architecture. Developed by Serie Architects and Multiply Architects following a 2013 competition, the project formed part of a broader university campus redevelopment. Designed as a "living lab" for students and faculty, SDE4 promotes sustainability through a mix of flexible spaces, including studios, workshops, labs, public areas, and a library. It accommodates around 600 occupants and prioritizes health, comfort, and inspiration while achieving a net-positive energy balance through efficient systems and on-site PV generation.

This integrated design process emphasized user-centered planning, conflict-resolution, and interdisciplinary collaboration. The building generated 619,345 kWh and consumed 470,750 kWh during its performance period, achieving a net energy use of -148,595 kWh. With an EUI of 55.4 kWh/m²/year, it has been recognized internationally for its performance. The project embraces the challenges of tropical climates with nature-based passive solutions, and it serves as a national benchmark for sustainable educational facilities.

Barriers list:

Type	Explanation
B	Lack of skilled workforce: insufficient training in innovation and performance integration.
B	Complexity of actors: different stakeholders not aligned; required breaking down silos in education and design.
B	Lack of coordination among departments overcame institutional silos through integrated design.
B	Political commitment to innovation: supported as a living lab and model for tropical architecture.
E	Access to diverse funding sources: project received sufficient funding
E	Promote healthier and more attractive lifestyles.
E	Improve air quality.
E	Enhance city attractiveness and climate adaptation.

https://cde.nus.edu.sg/arch/special-projects/special-projects-sde-4/
Building typologies: Campus buildings (offices, classrooms, labs, workshops, library, café)
Average building year: 2019. NZEB: with humidity and temperature controls and nature-based passive design.

Technologies list:

- PV: 1,200 panels implemented.
- HP, EL, CE (Circular Economy practices).

CASE STUDY NAME: Åland
City: Åland
Country: Finland
Density: 18.3 inhabitants/km²
GDP area/region: 1,389 Million USD, constant prices, constant PPP, base year 2015
Climate classification: Dfb (Humid continental climate, warm summer)

Description: Åland, an autonomous archipelago between Finland and Sweden, comprises over 6,700 islands (around 60 inhabited) and about 30,000 residents. The region is a pioneer in renewable energy, particularly wind power, and benefits from better solar conditions than mainland Finland. With strong interconnections to Sweden and Finland and a progressive sustainable agenda, Åland has set an ambitious goal: to explore how a society could operate with 100% renewable energy. The Positive Energy District initiative acts as a catalyst, enabling multi-stakeholder collaboration, though the responsibility does not lie solely with the PED actors.
The island faces unique challenges: a carbon-emitting heating sector reliant on wood chips and oil, no real-time frequency control, and low-density, spread-out communities. Electrification of heating and mobility, including future hydrogen ferries and electric vehicles, is key. Efforts toward 100% RES require sector coupling and flexibility solutions. Theoretical models indicate the feasibility, though practical implementation of storage and infrastructure remains constrained by economics and technological maturity. Åland's PED focus is supported by community forums and partnerships and serves as a testbed for RES transformation at scale.

Barriers list:

Type	Explanation
B	Technological advancements: needed especially for long-term storage and hydrogen technologies.
B	Infrastructure inadequacies: current systems not built for full RES integration.
B	Complexity of actors: multiple stakeholders with differing agendas.
B	Community opposition or skepticism: resistance from some citizens regarding changes.
B	Lack of acceptance: some reluctance to adopt innovations.
B	Political resistance to change e.g., reluctance to shift from wood chips for heating.
B	Limited budget constraints: initial subsidies no longer available.
B	High risks: innovative tech like long-term storage is costly and uncertain.
B	Lack of incentives or financing mechanisms: particularly for future energy tech.
E	Effective community engagement: both online platforms and in-person forums.
E	Building strong stakeholder relationships: use of public-private partnerships.
E	Political commitment to innovation: clear ambition to achieve net positive energy status.
E	Strong advocacy for change: strong local efforts and political will.
E	Consistent political leadership: benefits from self-governance.
E	Access to diverse funding sources: a combination of public, private, and grassroots funding.

Building typologies: Residential (single-family houses, apartments), Educational buildings, Agricultural facilities (potato, dairy), Light industrial (chip factory, medical manufacturing, butchery), Tourism-related buildings (hotels). Average building year: Varies widely; no specific average provided.
Technologies list: DHN, HP, CHP, EL ST, PV Oil, W, BE, PLA, ES. Future: HFC, EM GE, V2G, FLEX.

CASE STUDY NAME: Trondheim
City: Trondheim
Country: Norway
Density: 44 inhabitants/km²
GDP area/region: 14,395 Million USD, constant prices, constant PPP, base year 2015
Climate classification: Dfc (Subarctic climate, no dry season, cool summer)

Description: The ZEB Laboratory in Trondheim, located on the NTNU campus, is a Zero Emission Building (ZEB) designed as a research, education, and office facility. Completed in 2020/21, it exemplifies cutting-edge approaches to sustainability through the ZEB-COM framework—achieving zero emissions throughout construction (C), operation (O), and materials (M). The lab features a suite of advanced technologies, including high insulation, PV panels, low-temperature heating, and heat recovery systems. Though a single building, its scalable technologies and active integration into the university campus made it a relevant case for Positive Energy Districts, particularly through its ability to supply surplus energy to neighbouring buildings.
Innovative aspects include a collaborative contract model that involved contractors from the design phase, sharing financial risk and allowing customized solutions. However, performance gaps emerged during operation - such as underperforming PV generation, inefficient heat pump COPs, thermal storage control issues, and district heating losses. These issues are being addressed through ongoing monitoring and research. The building remains a dynamic living lab, supported by public outreach, real-time data transparency, and continuous reassessment.

Barriers list:

Type	Explanation
B	Lack of political/city governance: no central urban planning commitment.
B	Political resistance to change limited support at local political level.
B	Lack of political will or support: municipality not fully engaged.
B	Lack of incentives or financing mechanisms: high investment costs, no clear business models.
B	Limited budget constraints: required new business models due to high ambition. And lack of funding
B	Lack of knowledge and skilled workforce: unfamiliarity with solutions and implementation.
B	Infrastructure inadequacies: difficulty integrating with existing infrastructure.
B	Regulation hinders implementation: legal compliance slowed innovation.
B	Stakeholder conflicts of interest: roles and responsibilities were unclear.
B	Complex permitting processes: special authorizations needed for new technologies.
B	Other: need to adapt solutions to diverse users and situations.
B	Other: managing operational performance gaps in real time.
B	Other: new technical solutions required regulatory approval.

Building typologies: University research and office building (lab, offices, classrooms).
Average building year: 2020/21.
Technologies list: HP, TSG, ZEB, PV.
** It should be noted that ZEB received public funding as a national research infrastructure

CASE STUDY NAME: Buiksloterham
City: Amsterdam
Country: Netherlands
Density: 864 inhabitants/km²
GDP area/region: 20,9154 Million USD, constant prices, constant PPP, base year 2015
Climate classification: Cfb (Temperate oceanic climate)

Description: The Amsterdam PED is located in Buiksloterham, a former industrial harbor in the Amsterdam Noord district undergoing transformation into a sustainable, circular neighbourhood. The district includes two innovative building blocks - Republica and Poppies - whose designs align with the city's Environmental Vision 2050 and its ambitious zero-emission climate goals. Republica was completed in July 2023, while Poppies began development in October 2023. The project is part of the European ATELIER initiative and aims to demonstrate replicable PED solutions in a rapidly growing urban context.

The selection of Buiksloterham was driven by its redevelopment momentum and compatibility with sustainable ambitions, allowing for timely implementation of the PED concept. Key technological features include integration with district heating, heat pumps, energy storage, PV, ATES systems, and advanced energy flexibility. The district is seen as a blueprint for scaling PEDs across Amsterdam, with a focus on balancing growth, circularity, and emissions reductions.

Barriers list:

Type	Explanation
B	Political commitment to innovation: policy support present but implementation complexity remains.
B	Lack of space: spatial constraints limit renewable deployment.
B	Lack of flexibility in laws: procurement and self-consumption regulations hinder innovation.
B	Regulation hinders implementation: current net metering and incentives don't favor battery investment.
B	Complexity of actors: diversity of ownership models complicates coordination.
E	Effective community engagement: highlighted as an enabler.
E	Supportive policy frameworks: exceptional legal provisions apply.

Building typologies: Residential and mixed-use (Republica and Poppies).
Average building year: 2023 (Republica), 2023 onward (Poppies) NZEB.
Technologies list: HP, PV, ES, DHN, FLEX, ATES, DHN.

CASE STUDY NAME: EVORA

City: Évora
Country: Portugal
Density: 43 inhabitants/km²
GDP area/region: 33,308.5 Million USD, constant prices, constant PPP, base year 2015
Climate classification: Csa (Mediterranean climate, hot dry summer)

Description: Évora, a UNESCO World Heritage Site, is a historical city in the Alentejo region known for its architectural heritage and sustainable development efforts. As a Lighthouse city in the POCITYF project, Évora hosts three demonstration PEDs - City Centre, Valverde, and an industrial park - each testing solutions under distinct urban and infrastructural conditions. The city has prioritized sustainability since 2012 through its SEAP, aiming to cut energy use and CO_2 emissions by 20% relative to 1990.

The PEDs integrate a wide range of technologies, from BIPV, electric mobility, second-life battery storage, to advanced energy management platforms and citizen engagement apps. Despite its strong policy framework, Évora faces administrative and technical challenges, particularly due to heritage preservation regulations and infrastructure limitations. The city is committed to energy efficiency and future NZEB retrofits, supported by robust citizen-oriented digital tools.

Barriers list:

Type	Explanation
B	Regulation hinders implementation: BIPV and heritage protection require complex approvals.
B	Infrastructure inadequacies: limited grid injection capacity.
B	Complexity of actors: multiple levels of cultural administration complicate coordination.
B	Community opposition or skepticism: challenges in citizen engagement.
B	Technological limitations: high consumption buildings present in PEDs.
E	Effective community engagement: digital tools and apps promote involvement.

Building typologies: Historical city center, commercial and industrial areas, residential neighbourhoods.
Average building year: Varies (many historical buildings).
Technologies list:

Technology	Explanation	PED area
BIPV		Evora PED1
EM, FLEX	EV Chargers with flexibility algorithms	Evora PED1, 3
CE	Pay-as-you-throw (PAYT)	Evora PED1
PA	phone apps citizens	Evora PED1,2,3
PLA	hems, energy routers, smart inverters. P2P	Evora PED1,2,3
PV	Community Solar Farm (CSF) – 5 MW	Evora PED1
EL	Smart Lamp Posts	Evora PED1
CE	2ND LIFE batteries, PAYT	Evora PED2
ES	storage: 2nd Life batteries with flexibility algorithms	Evora PED2
PV		Evora PED3

B2- Energy flexibility, storage and smart grid integration: solutions and applications to PEDs

B2.1 - Smart solutions to promote energy flexibility and smart grid integration

By definition, a PED is a designated zone where an energy balance is calculated with the goal of achieving self-sufficiency and even producing more energy than it consumes. However, a key challenge in achieving this balance lies in the variability of both local energy generation and consumption. Renewable energy production fluctuates depending on weather conditions, time of day, and seasonal variations, while energy demand changes based on occupant behaviour, building usage patterns, and external climate conditions. Since these factors do not evolve at the same rate, there is often a mismatch between energy supply and demand within the PED boundaries.

For instance, in a study performed by Castillo-Calzadilla et al. it is seen that self-sufficiency is highly favored by irradiance patterns that affect the PV plates. Self-sufficiency increases as solar production rises. On the other hand, self-consumption appears to be primarily impacted by a combination of energy demands and limited energy harvesting from RES. The lower demand and better irradiance patterns increase the availability of energy generated from PV, thereby reducing self-consumption. The lower PV generation, the higher the self-consumption. This demonstrates that high self-consumption is directly linked to a poor irradiation profile (Castillo-Calzadilla et al, 2024).

To address the challenge of mismatches between energy supply and demand, typically three main strategies can be employed: controlling energy generation, managing consumption, and utilising energy storage systems. However, since the most common renewable energy sources in PEDs—such as photovoltaics and wind power—are inherently variable and non-controllable, direct regulation of generation is limited. This makes demand-side flexibility and energy storage essential components of an effective energy management strategy, even more for PEDs, as they need to manage a great amount of excess of energy and at the same time maintain the PED profitable and affordable.

Energy flexibility refers to the ability to adjust consumption patterns in response to renewable energy availability, local climatic conditions and network requirements (Jensen et al., 2017). This can be achieved by leveraging smart energy systems, demand response mechanisms, and flexible loads such as heat pumps, electric vehicles, storage effects of the building thermal inertia or industrial processes in case of residential-industrial symbiosis. By dynamically shifting energy usage to periods of higher renewable generation, PEDs can minimise curtailment of green energy and reduce reliance on external power sources. On this line, significant load-shifting and peak-shaving services are expected through the implementation of tailored-made energy flexibility strategies.

Energy storage solutions, on the other hand, play a critical role in bridging the gap between generation and consumption by capturing surplus energy when production exceeds demand and redistributing it when needed. This can be accomplished through various storage technologies, including battery storage systems (electricity storage solutions), thermal energy storage (power-to-heat solutions), and even hydrogen-based solutions. Integrating these storage solutions within PEDs ensures that excess renewable energy is not wasted and can be effectively utilised to maintain grid stability and self-sufficiency.

Therefore, the combination of energy flexibility and storage is fundamental to the success of PEDs. Without these solutions, the potential of local renewable energy generation cannot be fully harnessed, and self-sufficiency goals become more difficult to achieve. By implementing advanced energy management strategies, PEDs can optimise resource utilisation, enhance resilience, and contribute to a more sustainable and decarbonised urban environment.

Energy flexibility is a key characteristic of buildings and energy systems that enables the shifting of energy loads over time to better align consumption with renewable energy availability. Achieving this goal requires

specific boundary conditions to define the operational range within which adjustments can occur. These conditions determine the extent to which energy consumption can be modified without affecting system performance, , user comfort, or operational efficiency.
The extent of energy flexibility a system can provide is determined by two primary factors: the controllability range and the system's energy storage capacity within this range. The controllability range defines how much and how quickly energy demand can be increased or decreased in response to external signals, such as fluctuations in renewable energy generation or grid conditions. Meanwhile, the energy storage capacity dictates how much surplus energy can be stored and later used as system inertia to balance supply and demand.
By integrating advanced control strategies, demand-side management techniques, and energy storage solutions, a system can maximise its flexibility potential. This ability to dynamically shift energy consumption not only optimises resource utilisation but also enhances grid stability, improves energy efficiency, and supports the integration of renewable energy sources.
Flexibility in PEDs is crucial to optimising the integration of buildings, mobility, and Information and Communication Technology (ICT) systems. Aggregators, local distributed system operators (DSOs) and Mobility Service Providers (MaaS) can play a significant role in this process, as they can act as intermediaries in market development and interact closely with demand-side customers. They can leverage data exchange, integration, and interoperability platforms to enable market participation (e.g. in flexibility markets) and achieve their goals. For example, Piclo Flex or Crowd Balancing Plaform act as aggregators between customers and the flexibility platforms, managing energy assets, customer loads, or providing aggregated demand-side flexibility. NODES-IntraFlex has a few larger generators and some providers of flexibility from electric vehicles and is testing the use of continuously clearing market that operates from a few days ahead to close to real-time for the procurement of flexible generation and consumption (Charbonnier et al., 2021).
In addition, energy flexibility strategies can contribute to the achievement of the PED balance even in existing social housing contexts, counteracting energy poverty and the risk of green gentrification in the PED-oriented renovation.
More in general, residents and energy consumers, including the general public, civil society, and customers, are also pivotal. Recognised as experts of their daily environment, these end-users can identify opportunities for change by activating local knowledge and experience. To support their involvement, business models and social innovation tools are designed specifically for this group. Energy prosumers, who are both consumers and producers of energy, benefit from optimised integration within PEDs. By harmonising the functionalities of buildings, mobility services, and ICT systems, these prosumers contribute to creating more effective and sustainable energy districts.

Smart BMS design and auditing

The design of Building Management Systems (BMS) plays a crucial role in enabling the efficient operation of buildings within Positive Energy Districts (PEDs) by integrating advanced monitoring, control, and optimisation strategies. A well-designed BMS facilitates the seamless coordination of energy generation, consumption, and storage, ensuring that buildings operate efficiently while maximising renewable energy utilisation.
In PED applications, a smart and adaptive BMS is essential for balancing real-time energy demand and supply across multiple buildings. By leveraging IoT sensors, data analytics, and predictive control algorithms, BMS optimises HVAC systems, lighting, and other energy-consuming processes, enhancing overall energy efficiency. Furthermore, an advanced BMS supports demand response strategies, enabling buildings to interact dynamically with the power grid and adjust consumption based on energy availability and pricing signals.
The integration of renewable energy sources and energy storage systems within a BMS framework ensures that excess energy is efficiently stored and redistributed when needed, minimising waste and enhancing self-sufficiency. Additionally, interoperability with district-level energy management systems allows for coordinated energy exchange between buildings, further supporting PED objectives.
Ultimately, the design of BMS in PEDs must focus on scalability, interoperability, and data-driven decision-making to enable resilient, energy-positive urban environments. By ensuring optimal building performance and seamless integration with district energy networks, a well-structured BMS serves as the backbone of sustainable and intelligent PEDs.

Building Automation for Positive Energy Districts and EN15232

The revised EU legislation promotes the transition towards smarter buildings, with EN15232 providing the framework for assessing the energy impact of Building Automation and Control Systems (BACS). This standard categorises BACS into efficiency classes (A to D), where Class A represents the highest energy performance, and Class D indicates poor efficiency requiring significant upgrades. These classifications apply to both residential and non-residential buildings and are derived from simulations and calculations.
The European Building Automation and Controls Association recommends conducting an eu.bac system audit to assess compliance with minimum functionality requirements and identify necessary upgrades. This

certification scheme evaluates BACS performance using a point-based grading system, considering factors like usage period, building type, and area supplied. Case studies, such as Engvang et al.'s application of the eu.bac audit on a Danish university building, demonstrate promising energy efficiency gains. However, the complexity of existing tools like Siemens' Energy Performance Classification (EPC) and user-defined platforms, as applied by Ozadowicz et al., highlight the need for streamlined, accessible solutions.

BACS Design and Optimised Operation

Research studies highlight the role of BACS in enhancing energy performance within Positive Energy Districts (PEDs). Advanced automation systems have demonstrated energy savings of 20-45% through methodologies like fuzzy cognitive mapping. Smart lighting controls, such as those analysed by Aghemo et al., have achieved up to 32% energy savings. Further, self-commissioning strategies for shading and lighting automation, as proposed by Motamed et al., have enhanced both visual comfort and system efficiency.
Automated control strategies for blinds and shading, as explored in previous studies, indicate challenges with manual user interventions due to comfort preferences. However, adaptive strategies incorporating thermal comfort considerations have yielded positive outcomes. The impact of automation on heating and cooling was demonstrated by Sozer and Tuysuz, where dynamic setpoint controls significantly reduced energy consumption. Additionally, data-driven predictive control methodologies, such as those developed by Yoon et al., optimise energy use by integrating multiple power sources and real-time analytics.
Future BACS solutions must align with PED objectives by integrating energy flexibility, real-time responsiveness, and occupant empowerment. The Building Performance Institute Europe emphasises the importance of self-learning control systems that enhance comfort while providing users with transparent, data-driven insights.

IBACSA: A Smart Tool for PEDs

The IBACSA ('Interactive Application for Buildings Automation and Control Systems Auditing') was developed at the University of Southern Denmark to bridge regulatory frameworks and real-world BACS deployment. It serves as an advanced evaluation tool for new and existing automation systems, facilitating initial and retro-commissioning. Unlike conventional audits that primarily assess energy efficiency, IBACSA incorporates a comprehensive multi-criteria evaluation, making it highly relevant for PEDs.
The tool assesses eight key domains: heating, hot water, ventilation, cooling, lighting, dynamic envelope, electricity, and monitoring/control. Each domain includes multiple services aligned with EN15232, with a structured hierarchy of functionality levels. For instance, in the heating domain, the ‘Heat Supply Control’ service spans from no automation (Level 0) to advanced individual space control with presence detection (Level 4), with corresponding efficiency and comfort scores.

Multi-Criteria Framework for PED-Oriented BACS Evaluation

IBACSA evaluates BACS based on five key impact criteria:

- Energy Efficiency – Core metric in automation assessments.
- Maintenance & Fault Prediction – Enhances reliability and proactive servicing.
- Energy Flexibility – Crucial for PEDs in balancing supply and demand.
- Comfort – Ensures thermal and visual well-being.
- Occupant Information – Empowers users through digital communication.

While existing schemes like eu.bac focus solely on energy efficiency, IBACSA extends beyond this by incorporating energy flexibility and user-centric metrics. This holistic approach aligns with PED strategies by fostering grid-interactive buildings that maximise renewable energy utilisation and occupant engagement. Future developments should further refine multi-criteria methodologies to seamlessly integrate automation systems within PEDs, ensuring resilience, sustainability, and optimal performance.

Figure 11: Interactive tool for BACS Auditing – results

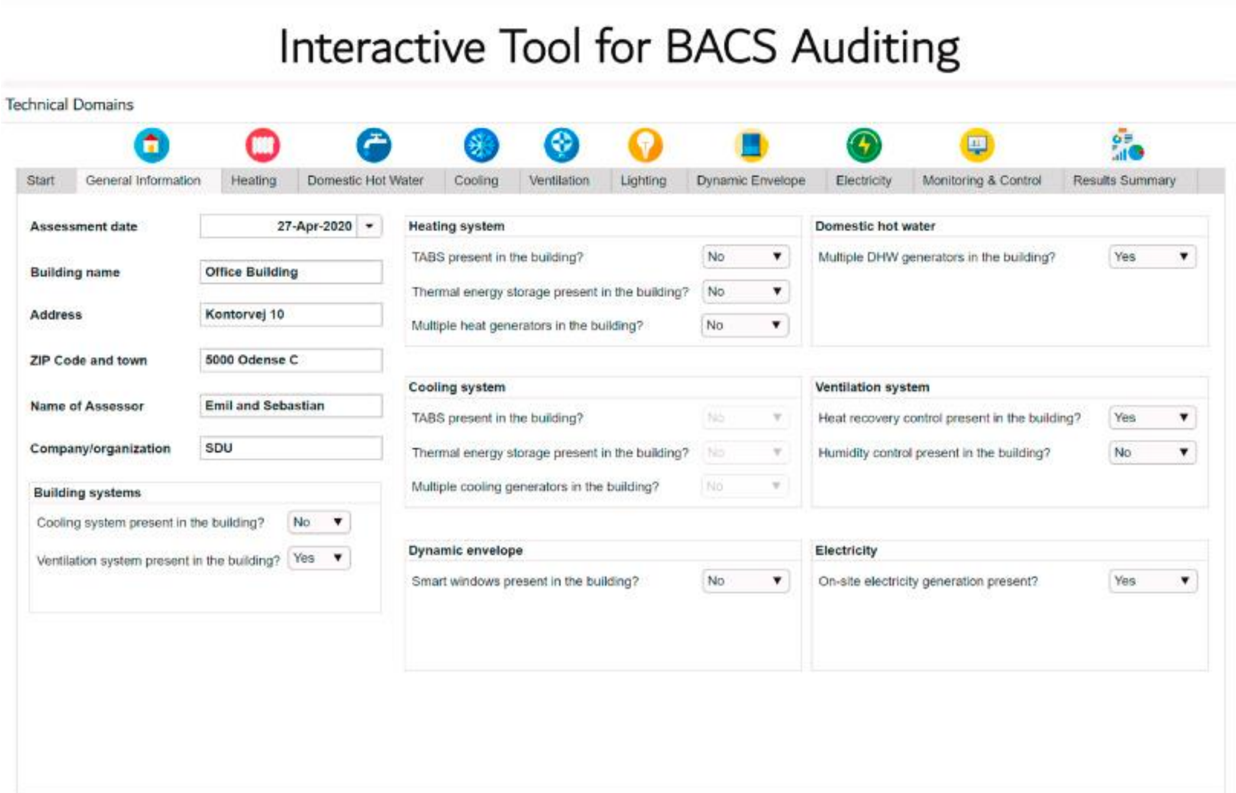


Figure 12: Interactive tool for BACS Auditing – parameter changes

Model Predictive Controller (MPC) application in buildings and PEDs

As urban sustainability initiatives gain momentum, Positive Energy Districts (PEDs) have emerged as a key strategy for fostering energy-efficient, self-sufficient, and carbon-neutral urban areas. A PED aims to generate more renewable energy than it consumes, requiring sophisticated control and optimisation techniques to efficiently balance energy generation, storage, and consumption. Model Predictive Control (MPC) has proven to be a crucial enabler in this context due to its ability to handle complex, dynamic energy systems while continuously optimising performance in real time over a predictive horizon.

MPC plays a central role in PEDs by optimising the interaction between energy supply, demand, and storage. One of its primary functions is energy demand-supply optimisation, where it anticipates future variations in energy generation and consumption using predictive models. By incorporating weather forecasts, occupancy patterns, and renewable energy availability, MPC enables proactive balancing of energy flows, ensuring that distributed energy resources such as photovoltaic panels, wind turbines, and battery storage operate at maximum efficiency.

Another key role of MPC is grid interaction and demand response management. By predicting fluctuations in energy prices and grid constraints, it can optimise real-time energy exchange and economic profitability on the one hand, and reduce peak loads, improving grid stability, on the other. This allows PEDs to function as active participants in energy markets, adjusting demand to benefit from lower electricity costs and alleviating stress on the power grid. Additionally, flexible loads such as HVAC systems, electric vehicle charging stations, and smart appliances can be coordinated in a way that minimises energy costs while maintaining user comfort and operational efficiency.

At the building and district levels, MPC enables precise energy management by regulating heating, ventilation, air conditioning, lighting, and other energy-intensive systems. When applied to smart buildings, it continuously adjusts operational parameters to optimise energy use while ensuring comfort and performance. At the district scale, MPC coordinates multi-energy systems, including electricity, heating, and cooling networks, optimising their interactions to achieve synergies that maximise overall efficiency.

The integration of renewable energy and storage systems is another area where MPC demonstrates significant advantages. Since renewable sources such as solar and wind energy are inherently intermittent, MPC mitigates their unpredictability by forecasting energy production and adjusting storage strategies accordingly. It ensures optimal charging and discharging of batteries and thermal storage, minimising energy waste and making renewable energy more reliable for PED operations.

In addition to optimising energy flows, MPC contributes to carbon emission reduction by prioritising low-carbon energy sources and minimising reliance on fossil-fuel-based generation. Its predictive capabilities allow PEDs to align energy consumption with periods of high renewable energy availability, significantly reducing their carbon footprint. By promoting energy efficiency and sustainability, MPC enhances the resilience of urban energy systems to climate variability and changing energy demands.

Several real-world applications demonstrate how MPC enhances the operation of PEDs. In smart district heating and cooling networks, MPC ensures that heating and cooling demand variations are predicted and met with the most efficient energy distribution strategies. This is particularly beneficial in PEDs where district energy systems integrate waste heat recovery and renewable-based thermal storage. By continuously adjusting supply according to anticipated demand, MPC minimises thermal energy losses and enhances the efficiency of heating and cooling infrastructures (see Figure 13).

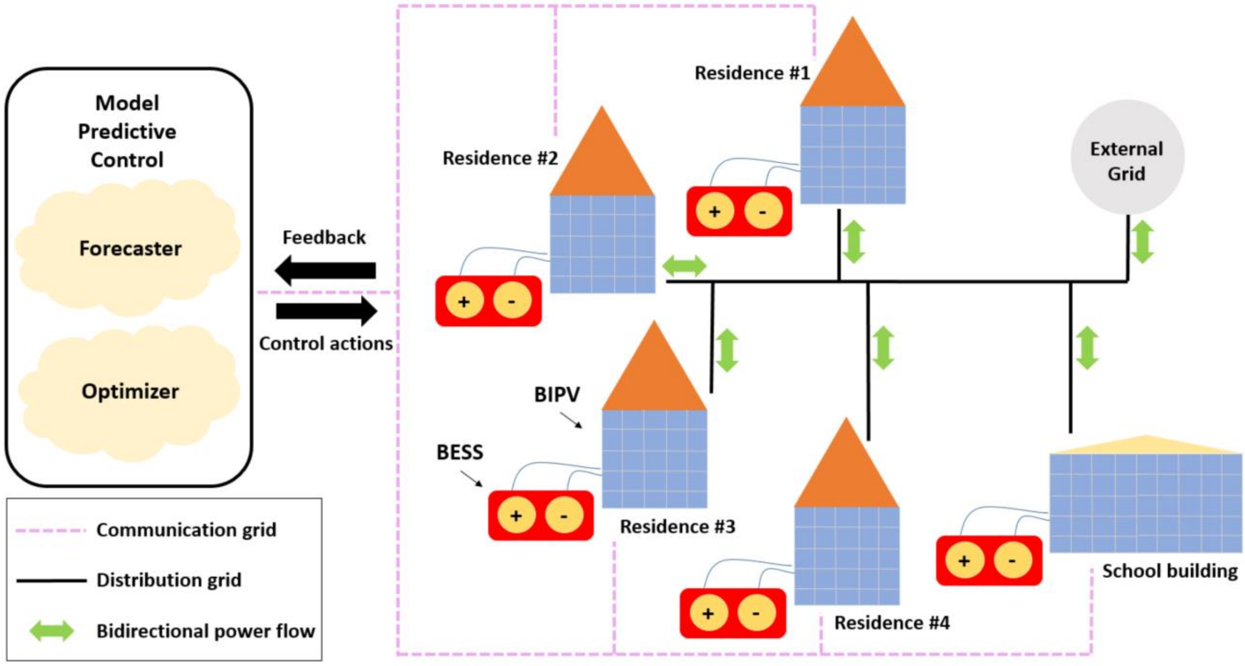


Figure 13: Model Predictive Control for the Energy Management in a District of Buildings Equipped with Building Integrated Photovoltaic Systems and Batteries (Fotopoulou et al., 2021)

Another important application is in electromobility and vehicle-to-grid (V2G) coordination. As PEDs incorporate increasing numbers of electric vehicles, MPC plays a vital role in managing charging and discharging schedules to avoid grid congestion while maximising renewable energy utilisation. By dynamically adjusting charging loads based on energy supply conditions, it enables electric vehicles to act as distributed energy storage units, contributing to the flexibility and stability of the local grid.
In building clusters within PEDs, MPC optimises energy management across multiple buildings, ensuring that energy is allocated efficiently and comfort levels are maintained. By integrating real-time data on occupancy, weather conditions, and energy prices, MPC enables buildings to operate in a coordinated manner, sharing energy resources and reducing overall consumption. This is particularly beneficial in mixed-use districts where energy demand patterns vary between residential, commercial, and industrial buildings.
Hybrid renewable energy systems also benefit from MPC, as it optimally manages multiple energy sources to ensure a stable and continuous energy supply. By forecasting generation patterns from solar, wind, and other renewables, MPC schedules energy storage and distribution in a way that minimises dependency on external power sources. This enhances the self-sufficiency of PEDs and strengthens their ability to operate independently from the main grid when needed.

In this context, Positive Energy Districts (PEDs) present a transformative opportunity by integrating smart, flexible, and energy-efficient building strategies. A promising development is the adoption of digital twins, which offer a comprehensive approach to modelling and optimising building energy performance. A digital twin consists of a physical system, a virtual representation, and a data-driven connection. It enables real-time monitoring, predictive control, and operational optimisation, contributing to continuous commissioning and strategic planning.
Building digital twins vary in complexity and scope. Some integrate diverse data streams throughout the building lifecycle, while others focus on specific aspects such as structural load calculations or energy system optimisation. Effective deployment requires automated setup, interoperability with Building Information Modelling (BIM), and flexible modelling capabilities adaptable across various building typologies. A hybrid approach combining physics-based and data-driven models ensures scalability and accuracy.
The increasing adoption of digital twins has accelerated advancements in building energy simulation. Many approaches leverage existing BIM frameworks, and energy simulation tools like EnergyPlus are commonly employed. Additionally, Model Predictive Control (MPC) has emerged as a preferred optimisation strategy for HVAC systems, outperforming rule-based controls in terms of energy efficiency, cost-effectiveness, and indoor environmental quality. Despite this progress, indoor air quality (IAQ) objectives remain underrepresented in MPC applications.
The research of Andersen and Jradi has introduced an advanced HVAC modelling framework integrated within a digital twin environment, applied to a university campus building. By implementing multi-objective MPC, the study optimises ventilation system performance with respect to energy cost, CO_2 emissions, and

indoor air quality. A novel air quality metric is introduced to enhance IAQ evaluation, addressing the lack of standardised assessment methods.
The framework enables a rapid, automated setup, leveraging available data to optimise ventilation system operation. Validation results indicate that model predictions align closely with observed system performance. Some discrepancies arise from unaccounted-for control strategies, suggesting the need for refined system-specific response modelling.
MPC consistently outperforms rule-based control in terms of energy efficiency and IAQ. The balanced MPC strategy achieves 18% energy savings while maintaining superior IAQ, aligning with existing studies that report 10–30% savings. A cost-focused MPC strategy further reduces energy consumption by 24% but compromises IAQ, whereas an air-quality-prioritised MPC strategy delivers optimal IAQ with an 11% energy reduction. A CO_2-focused MPC strategy demonstrates emission reduction potential, albeit closely tied to electricity price variations.
The integration of this framework within PEDs enhances energy efficiency and sustainability. By leveraging digital twins, real-time control, and predictive analytics, PEDs can optimise energy usage, reduce emissions, and improve occupant comfort. This study contributes to the advancement of smart urban planning, demonstrating how digital twin-enabled MPC frameworks serve as a cornerstone for energy-positive, climate-resilient built environments.

B2.2 - Overview of smart solutions in projects

The typical smart solutions to explore flexibility include:

- Virtual Power Plants (VPP)
- Sensors (IoT, smart meters, etc.)
- Modelling tools and Digital twins, including Building Information Modelling (BIM)
- Smart controls at building (BMS) or district level

SPARCS project

The SPARCS project in Espoo has implemented several control strategies to enhance the interoperability of holistic energy systems, contributing to the development of PEDs. Key strategies include: Renewable Energy Integration (e.g. geothermal energy, PV, and BESS) and smart control based on the following core features:

- Virtual Power Plant (VPP) for the aggregation of small to medium-sized installations (both energy producers and consumers) to trade energy collectively. Sello's multipurpose center in Espoo uses a VPP to integrate local energy production (e.g., solar PV) and participate in electricity reserve markets.
- Digital Twin technology for the digital representation of buildings, using real-time data from sensors to optimise efficiency and improve future designs: BIM was applied. The Sello flexibility prediction model forecasts energy flexibility based on historical data and external factors like temperature and holidays, aiming to optimise the building's energy performance and interaction with the grid.

Furthermore, in other areas Smart Building Energy Management to monitor and control energy usage in real-time is used. These systems facilitate demand response strategies, allowing buildings to adjust their energy consumption based on grid conditions and energy prices. Efforts have been made to integrate EV charging infrastructure with the local energy grid. This includes implementing smart charging solutions that align EV charging patterns with renewable energy availability, thereby reducing peak demand and supporting grid stability.

SPARCS project also studied the need for Electricity Storage Systems (ESS), finding that further grid enhancements are not required—even with grid connection constraints (e.g., capacity of 125 kW, 140 kVA, and 3 × 200 A fuses)—thanks to the inclusion of a certain battery storage capacity (i.e., 200 kW). The batteries help shorten the payback time and reduce overall costs compared to the reference case without ESSs. It should be noted that despite the reduction in payback times due to the use of PV technologies, grid upgrades become necessary for configurations with multiple electric vehicle (EV) charging points, particularly in the 49 charging point (49 CP) setup. In this configuration, on-site PV generation alone cannot ensure a continuous supply of energy throughout the year, primarily due to the seasonal variability of solar production and the fluctuating charging demand. Therefore, combining PV with ESS provides significant advantages in terms of both cost reduction and improved payback time.

On the other hand, "Fortum" - a pilot project that integrates a Siemens Building Management System (BMS) with the local district heating company - has demonstrated improved thermal flexibility. This integration contributed to reducing peak heating power demand by 32% from 2021 to 2022, and shifted higher demand to later hours, enabling more efficient use of renewable energy and reducing dependence on fossil fuels.

Moreover, EVs can serve as mobile energy storage units, providing flexibility to the grid through Vehicle-to-Grid (V2G) technology. This involves bidirectional charging, allowing EVs to store excess energy and supply it back during peak demand, thereby stabilising the grid.

Groningen case

In the MAKING-CITY project, smart grid technologies offer significant potential for energy savings, although initial investments can be substantial. These technologies, particularly Demand Response (DR) and Demand-Side Management (DSM), enable the optimisation of electricity use. By controlling devices like electric vehicles, heat pumps, and washing machines, they can help smooth out demand peaks and shift energy consumption to match renewable energy generation. This shift from "generation-follows-demand" to "demand-follows-generation" helps better integrate renewable energy sources (RES) into the grid, but it requires significant investment in smart devices, monitoring hardware, and control software to minimise grid impact and enhance efficiency.

One of the core technologies being explored is PowerMatcher, developed by TNO. PowerMatcher optimises grid load and fluctuations by enabling active demand and better integration of renewable resources. It offers a more efficient way to balance the supply and demand of energy, giving end-users more influence over grid operations. Another important innovation is ReFlex, a software solution designed to create Virtual Power Plants (VPPs) by aggregating the flexibility of small assets like electric vehicles, batteries, and solar panels. ReFlex helps prevent grid congestion and allows better energy market participation. It also provides insights into available flexibility and optimises energy usage through a combination of open standards, adaptability, and advanced algorithms.

HeatMatcher is another technology with strong potential, particularly in optimising heating systems. It uses a demand-supply matching algorithm to optimise heating energy usage, reducing reliance on non-renewable energy sources and lowering maintenance costs. HeatMatcher can be applied to installations with multiple heat sources and can significantly improve efficiency in buildings with flexible energy resources.

In Groningen, the project explored various possibilities for implementing these technologies. However, some challenges arose, such as the lack of flexible resources in certain buildings, which limited the effectiveness of technologies like ReFlex and HeatMatcher. Despite this, HeatMatcher's potential for optimising district heating grids remains promising, particularly in the North PED, where multiple heat sources and complex systems could benefit from more efficient management to save energy and reduce costs.

Oulu case

The BEMS in the Oulu PED area consists of the following five functional components (see Figure 14):

1. Resource Interface: Interface with the Building Management System (BMS) and site-specific metering infrastructure. It also handles secure data transfers via SSL connections.
2. Resource Manager: Manages resource access, ensuring control commands respect constraints like room temperature.
3. Energy Management Agent (EMA): The core of the system, responsible for energy management at the building level. It provides forecasts for load and flexibility to assist district-level energy management. The process includes:
    1. Energy Planning: The energy planner creates a load plan for both electricity and district heating at fixed intervals.
    2. Flexibility Management: The system provides flexibility potential to district-level energy management systems.
    3. Optimisation: The EMA uses an MPC to define energy management decisions. It involves creating load plans based on the current state of the system, which can be adjusted as needed to optimise energy use. The controller manages flexible resources in accordance with these plans.
4. Site-data Service: Stores energy and sensor data for analysis and monitoring.
5. User Interface: Allows end-users to view and monitor the building's energy data.

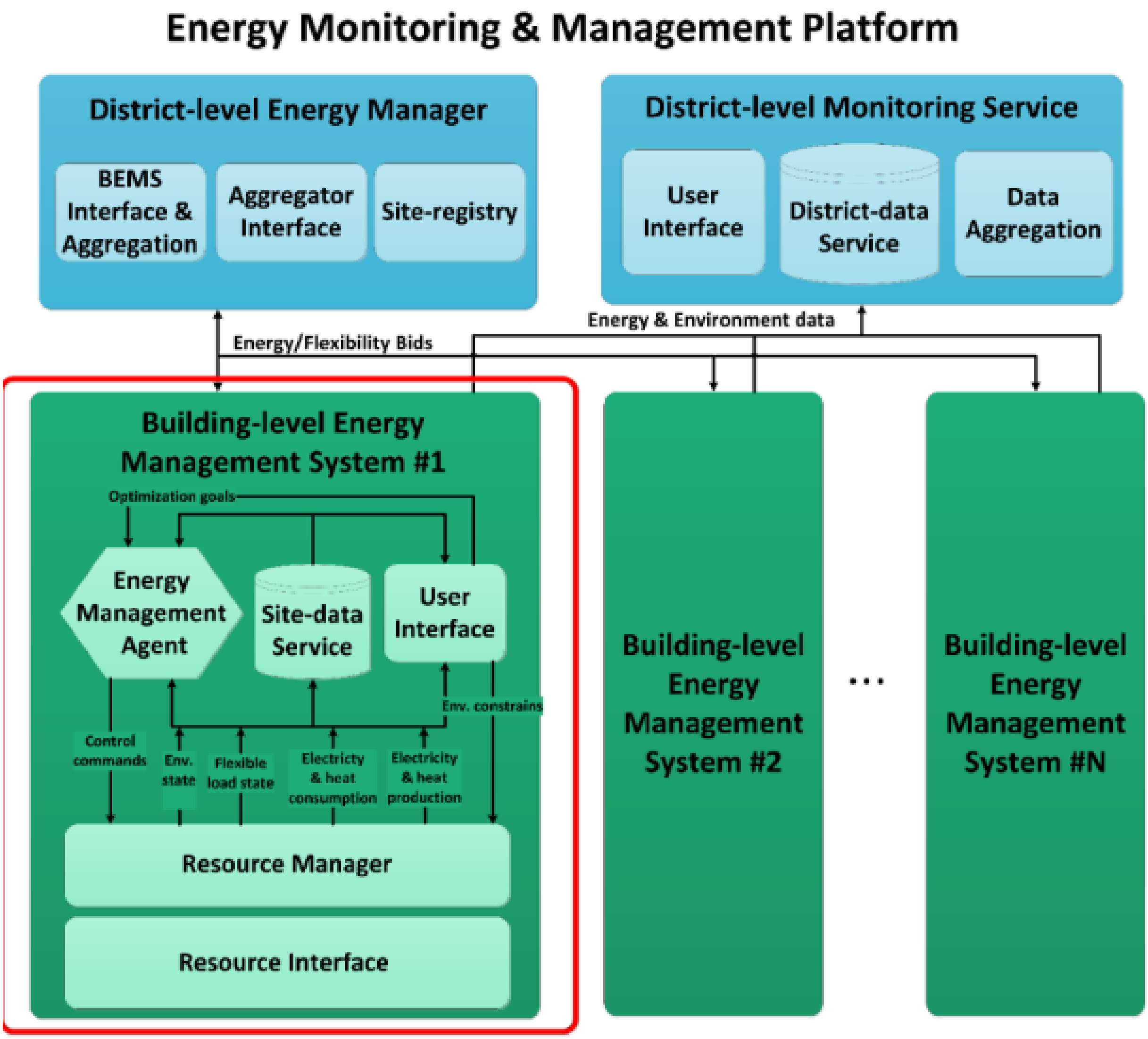


Figure 14: Oulu management system

Bilbao case energy management system

For this use case, the Energy Management System (EMS) depicted in Figure 15, named “RESTORATIVE”, was developed. The framework leverages a fuzzy logic scheme to optimise the renewable energy system and operation and economic profitability, guaranteeing battery health of an EMS within the PED frame. It is oriented towards managing the energy surplus for further use in the PED during periods with lower RES production and /or high energy prices.

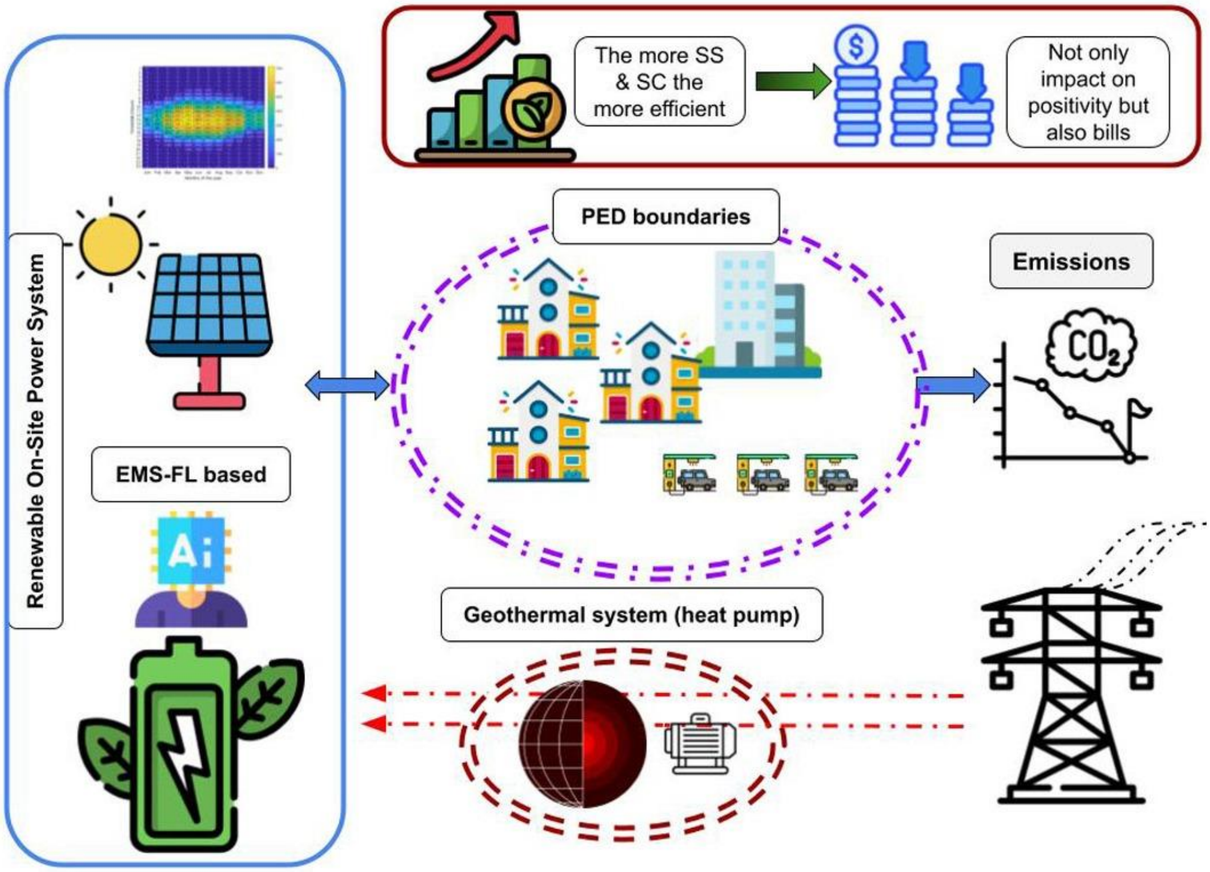


Figure 15: Zorrotzaure RESTORATIVE system (Castillo-Calzadilla, et al, 2024)

To meet this objective, they must incorporate distributed generation based on renewable systems within their boundaries. In this context, RESTORATIVE considers the fluctuations in electricity prices and local renewable availability on a PED archetype with a centralised energy storage system. This simulated use case focused on electricity self-sufficiency and self-consumption. RESTORATIVE is a fuzzy logic-based energy management system that optimises the state of charge (SoC) of the energy storage solution, considering local electricity production and loads along with the contracted electric tariff. The methodology was tested in a PED comprising 360 households in Bilbao (a city in the north of Spain). Several scenarios were investigated, including changes in the size of the electricity storage system, long-term climate change effects due to global warming, and extreme changes in the price of energy carriers. The study revealed that the PED-case could reach up to 75.6% self-sufficiency and 76.8% self-consumption. Furthermore, the effects of climate change are expected to positively influence performance, leading to an improvement in these values. On economic aspects, the return on investment of the proposal ranges from 6 up to 12 years depending on the configuration choice. In addition, the case that boosts the economic viability is tight to non-business as usual (BaU), whichever event spiked up the prices or climate change conditions shortens the economic variables. The average bill is around 12.89 EUR/month per house for scenario BaU; meanwhile, a catastrophic event increases the bill by as much as 76.7%. On the other hand, climate crisis events impact energy generation, strengthening this and, as a consequence, slightly reducing the bill by up to 11.47 EUR/month.

In conclusion, only scenarios under certain climate alterations reach the positivity condition to be considered a PED. There are also scenarios with major reductions in electricity bills. Scenarios 1, 2, 3, and 4 might reach positivity if the building's energy label is enhanced from "C" to "B" or even "A". Besides, climate change would favour the deployment of PV facilities due to the rise in irradiation patterns in Cantabrian areas, as in Bilbao. Tenants can recover their investment in around 7 years, which is very promising considering the system lifetime of 25 years, saving about 20 million for the whole PED (360 tenants). Additionally, the study revealed significant disparities in emissions across thermal, mobility, and electric demands within the PED.

synikia project

The synikia project focused on the deployment of advanced methodologies that enable demand-side flexibility, enhance renewable energy integration and support intelligent control across interconnected energy systems. On this line, the syn.ikia project has pioneered a package of innovations that collectively address these challenges, offering a multi-scalar framework for real-time optimisation and systemic resilience in the built environment. Central to the syn.ikia approach is the development of Grey Box Models (GBMs), which synthesise physical building characteristics, energy system configurations, meteorological forecasts, and occupant behaviour data. These hybrid models support Model Predictive Control (MPC) strategies that optimise energy performance across diverse neighbourhood typologies. A novel methodological procedure has been formulated to derive GBMs from white-box models (such as TRNSYS models), leveraging statistical classification techniques to identify optimal structures from heterogeneous data sources. As demonstrated in multiple pilot sites, this procedure enables scalable and automated model generation, forming the analytical foundation for district-wide control architectures. Beyond individual building systems, GBMs are designed to incorporate broader energy assets, such as electric vehicle (EV) charging cycles and stationary batteries, facilitating comprehensive optimisation at the PED scale.

Derived from the GBM architecture, Flexibility Functions (FFNs) constitute a dynamic modelling layer that anticipates the flexibility potential of PEDs under varying climatic and tariff conditions. These functions inform control strategies by computing the Flexibility Index (FIN) and producing penalty signals that steer MPC algorithms toward optimal energy flow configurations. Each demonstration site has deployed tailored FFNs, which assure the flexibility of technical installations and control logic both pre- and post-construction. The hierarchical structure of these control mechanisms significantly improves energy system responsiveness and load balancing. The Flexibility Index evaluates the extent to which control algorithms and storage assets can shift energy demand. Variations in this Index across demo-sites underscore the importance of appropriately sized storage systems and incentivised control strategies. Furthermore, it offers valuable input for policymakers in shaping future taxation, tariff structures, and incentive mechanisms aimed at promoting district-scale flexibility.

In addition, the Dutch demo - a total of 39 social housing dwellings located in Uden - is a demonstrator of the DigiTwinN digital platform. This platform provides a predictive, data-driven interface for monitoring and optimising district energy performance throughout its lifecycle—from design through operation. Calibrated using real-time sensor data, weather information, and PV production metrics, DigiTwinN generates ensemble simulations to guide domestic hot water and heating control strategies. Its principal objective is to maximise local renewable energy use while mitigating grid congestion. This adaptive modelling tool accounts for occupant behavioural variability, ensuring that the prediction engine reflects evolving usage patterns and contributes to more resilient control decisions.

The Digital Cloud Hub serves as the central conduit for data exchange and computation across all *syn.ikia* innovations. It comprises:

- Structured repositories for BMS data and meteorological forecasts
- Computational modules for algorithm execution
- Visualisation tools for performance evaluation
- Interfaces for stakeholder interaction and decision-making

By harmonising the GBMs, FFNs, and FIN within a unified software ecosystem, the Cloud Hub enables real-time insights and coordinated control actions. It supports a diverse range of end-users, including ICT providers, facility managers, and energy aggregators.

Finally, complementing the technical framework, *syn.ikia* has outlined strategic business model formulations targeting long-term viability and monetisation of surplus energy. These include: local energy markets and peer-to-peer trading, and Power Purchase Agreements.

Building upon the syn.ikia project's overarching framework - which integrates Grey Box Models (GBMs), Flexibility Functions (FFNs), and predictive control architectures to enable demand-side flexibility and systemic optimisation - the Spanish demonstrator in Santa Coloma de Gramenet exemplifies the practical implementation of these innovations at both building and neighbourhood scales.

This case study, situated in the Mediterranean, is embedded within an urban regeneration initiative aimed at improving habitability and energy performance. The demonstrator consists of a newly constructed multi-family building comprising 38 dwellings, 2 commercial units, and 38 parking spaces, with a gross floor area of

2,495 m², of which 2,154 m² are heated. The building integrates both passive and active energy-saving strategies: optimised façade insulation, thermal inertia, solar shading, and material absorbency control are complemented by a centralised heat pump system for space heating and domestic hot water (DHW), powered by 119 rooftop photovoltaic panels. Excess PV generation is shared with the surrounding neighbourhood, reinforcing the building's role within a local energy community.

To manage energy consumption dynamically, the demonstrator deploys an Economic Model Predictive Controller (EMPC), designed to minimise electricity costs while satisfying thermal comfort and power constraints. Two control scenarios were simulated—one with a constant penalty signal and another with a time-varying signal—demonstrating that the EMPC effectively shifts thermal loads away from high-cost periods, resulting in a 5.6% reduction in total energy cost compared to a non-price-sensitive reference controller. The EMPC is supported by the SirinE hybrid digital twin model, which reflects the GBM architecture by combining physics-based building simulation with AI-driven occupant behaviour modelling. This enables scalable and adaptive control, particularly under varying climatic and occupancy conditions.

A series of flexibility scenarios were developed to assess the interaction between climate conditions, user behavior, and control strategies. Climate inputs included both current conditions and future projections based on IPCC A2 and B1 emission pathways. Four user profiles were modelled, combining active versus passive behaviour with standard versus increased occupancy. Active users engage in adaptive ventilation and solar shading based on temperature and radiation, while passive users exhibit minimal interaction with building systems. Flexibility is further explored by modifying thermal setpoints during periods of excess PV generation—raising space heating by 1°C and DHW by 5°C—to enable thermal storage and reduce grid export.

B3- Energy Modelling of PEDs: a review of tools, modelling techniques and critical approaches to simulation

B3.1. What is needed to model a district?

PEDs are characterised by a holistic integration of various systems and infrastructures to achieve sustainability goals. Key district elements include energy-efficient and energy-flexible urban areas or groups of connected buildings that aim to produce net zero greenhouse gas emissions.
These areas actively manage an annual local or regional surplus production of renewable energy, thereby supporting the overarching goal of climate neutrality (JPI Urban Europe / SET Plan Action 3.2, 2020; Lindholm et al., 2021a).

Effective PEDs necessitate the interaction and integration between buildings, users, and the regional energy supply, mobility, and ICT systems. This integration involves optimising the technology, spatial, regulatory, financial, legal, social, and economic perspectives to create an interconnected and cohesive urban environment (JPI Urban Europe / SET Plan Action 3.2, 2020). By aligning these diverse elements, PEDs can ensure the reliable supply of energy while maintaining a high quality of life, thus embodying the principles of social, economic, and environmental sustainability (Lindholm et al., 2021a).
Given the innovation brought by this concept, the implementation of PEDs comes with a series of challenges. These range from the high use of renewable energy sources, through the need for a positive balance at the end of the year. To have a more optimised deployment, it is important to understand what are the must-haves that are necessary to consider when modelling PEDs. This section aims at investigating and presenting these must-haves for modelling PEDs and analysing them in relation to some of the most common definitions of PEDs to understand how this affects the modelling of a PED. The identified must-haves, i.e. the loads and the technologies, the spatial and temporal dimensions and the objective function, specify how PEDs are modelled when the strictest definition is considered. However, in the case of a virtual PED, which is the less strict definition, the differences of modelling a PED compared to a normal district are almost none (Bottecchia et al., 2022).

Elements in PED modelling include:

1. Elements/Assets:
    a. Loads and energy demand: Includes thermal (heating, cooling, domestic hot water) and electricity loads (lighting, appliances, mobility, district infrastructure).
    b. Energy management: Includes load shifting, demand response, and RES prediction to optimise energy use.
    c. Technologies include solar PV, wind, geothermal, and biofuels. Energy Storage Systems (ESS) like batteries, thermal storage, and power-to-hydrogen help manage renewable variability. Virtual Storage (VS) using the grid is common but may impact grid stability.
    d. Data
2. Spatial Dimension: Understanding system boundaries, urban energy flows, and available space for generation units is key.
3. Temporal Resolution: Data needs depend on the model's purpose. Hourly, monthly, or yearly resolutions are used depending on whether the goal is planning, design, or long-term assessment.
4. Objective Function and Optimisation. PED Balance must be positive, meaning more renewable energy is exported than imported. Different evaluation approaches:
    - Mono-criteria (focus on energy positivity).
    - Multi-criteria (including economic, environmental, and social factors).

PED modelling is complex and depends on the final objective (technical implementation vs. policy planning). Data availability and resolution impact accuracy and computational efficiency. While PED positivity is often the goal, other priorities like self-sufficiency or air quality improvement may take precedence depending on the project's scope. The effective and widespread use of such urban energy tools is associated with a variety of challenges and shortcomings that hinder their adoption. Yazdanie et al. classifies these challenges into three categories: technical, methodological, and institutional. The first two challenges encompass the technical constraints that these urban models have to overcome, while the third involves organisational, educational, and structural gaps. The analysis of the main obstacles to implementing these methodologies identifies institutional challenges as having the greatest impact (Yazdanie & Orehounig, 2021).

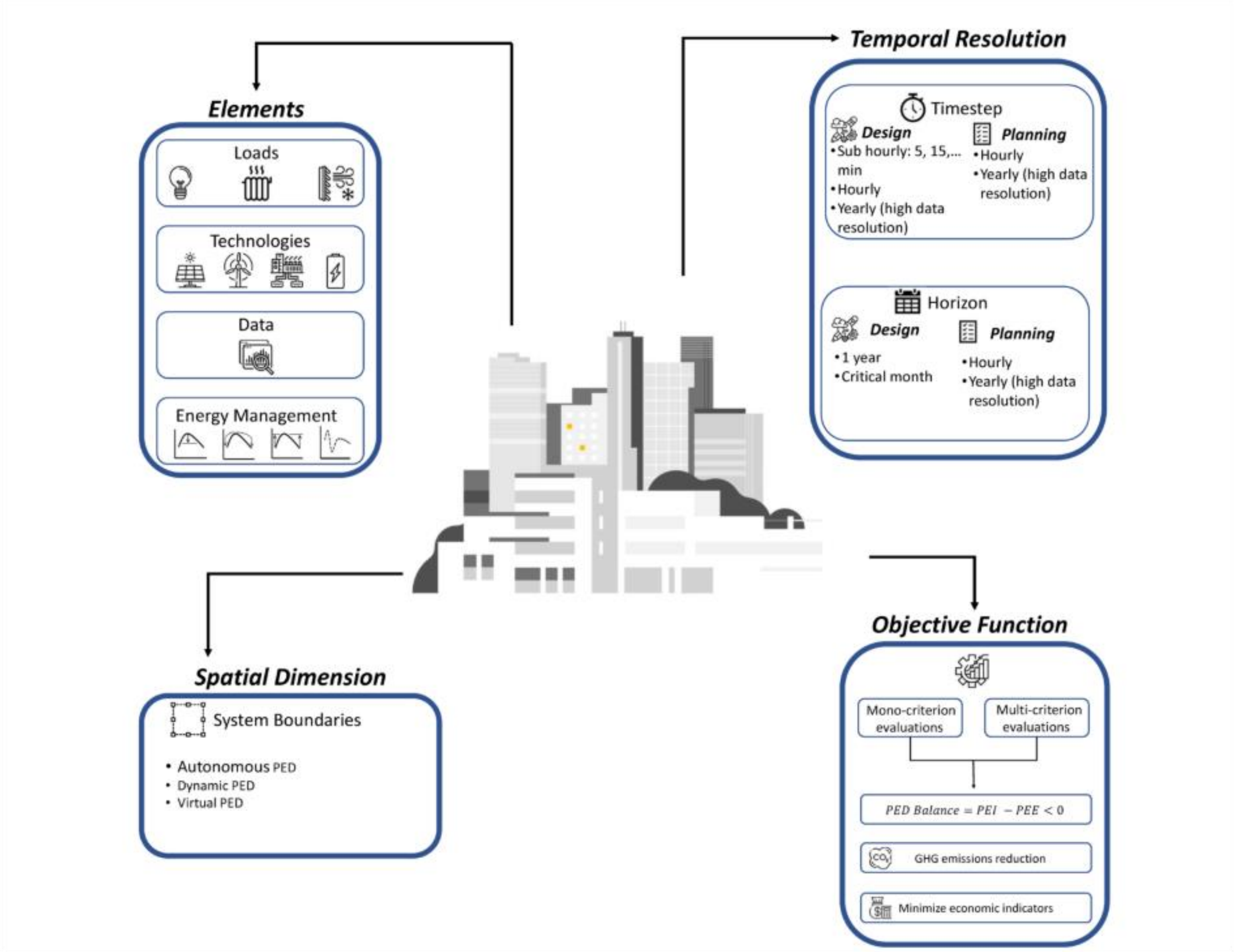


Figure 16: Fundamental elements while modelling PEDs (Bottecchia et al., 2022b)

B3.2. Energy Modelling of PEDs: a review of tools, modelling techniques and critical approaches to simulation

Urban modelling workflows in different use cases

The development and real-world implementation of PEDs can be enhanced through urban energy modelling. However, assessing PEDs can be challenging, and information on this topic is scarce and fragmented. The main contribution of this section is collecting and analysing challenges and limitations of energy modelling software for assessing PEDs through five case studies in Italy, Spain, The Netherlands, Denmark and Canada. Case studies are assessed first from a modelling approach, then the main identified challenges and limitations of modelling tools for PEDs are discussed, and finally, research needs in this field are suggested. Main challenges and limitations found are:

- Input Data – Data collection and integration are complex due to the need for multiple tools and external sources. Harmonisation between databases is complex due to accuracy, aggregation, formats or resolution. Accurate data is time-consuming to obtain, while using standard data increases model uncertainty. Issues related to data ownership, sharing, and protection also arise.
- Meteorological Data – Weather data is often not integrated or is limited, requiring external files. This restricts the ability to consider micro-climate effects or future forecasts, and limits compatibility with different weather file types.
- Geometry – Modelling complex building geometries is difficult, often leading to oversimplifications that reduce accuracy (LOD1). Some tools struggle with reading building floors, orientations, and distinguishing between buildings and other objects.

- Energy system parameters – Defining HVAC, renewable, and multi-supply systems is often limited. Many tools use default parameters (capacity, efficiency) or do not allow coupling between systems, but accurate modelling requires detailed technical specifications (e.g. in TRNSYS).
- Building energy modelling – Some tools make concessions or simplifications when modelling physical phenomena, such as the assumption of considering all spaces conditioned, which generates uncertainties in the modelling process that lead to inaccuracies. Manual modifications are often needed to refine the models.
- User Interface and Complexity – Many tools lack user-friendly interfaces, requiring expertise in energy systems. The complexity of simulations must be balanced with cost-effectiveness.
- Modelling process and accuracy – High-resolution modelling is computationally expensive. Simplifications in variables, time resolution, and technological parameters are often necessary, impacting accuracy.
- Data Integration – Limited integration between geospatial data and energy modelling tools requires custom coding to bridge the gap.

State-of-the-art building energy simulation tools (e.g. EnergyPlus, TRNSYS) have strong capabilities, including dynamic and physically detailed modelling approaches. However, their data-intensive input requirements and computational demands pose significant challenges when applied to city- or district-scale modelling. To address these limitations, advancements in uncertainty analysis, parametric design tools, and co-simulation approaches are being explored to enhance model efficiency, scalability and accuracy for large-scale models.

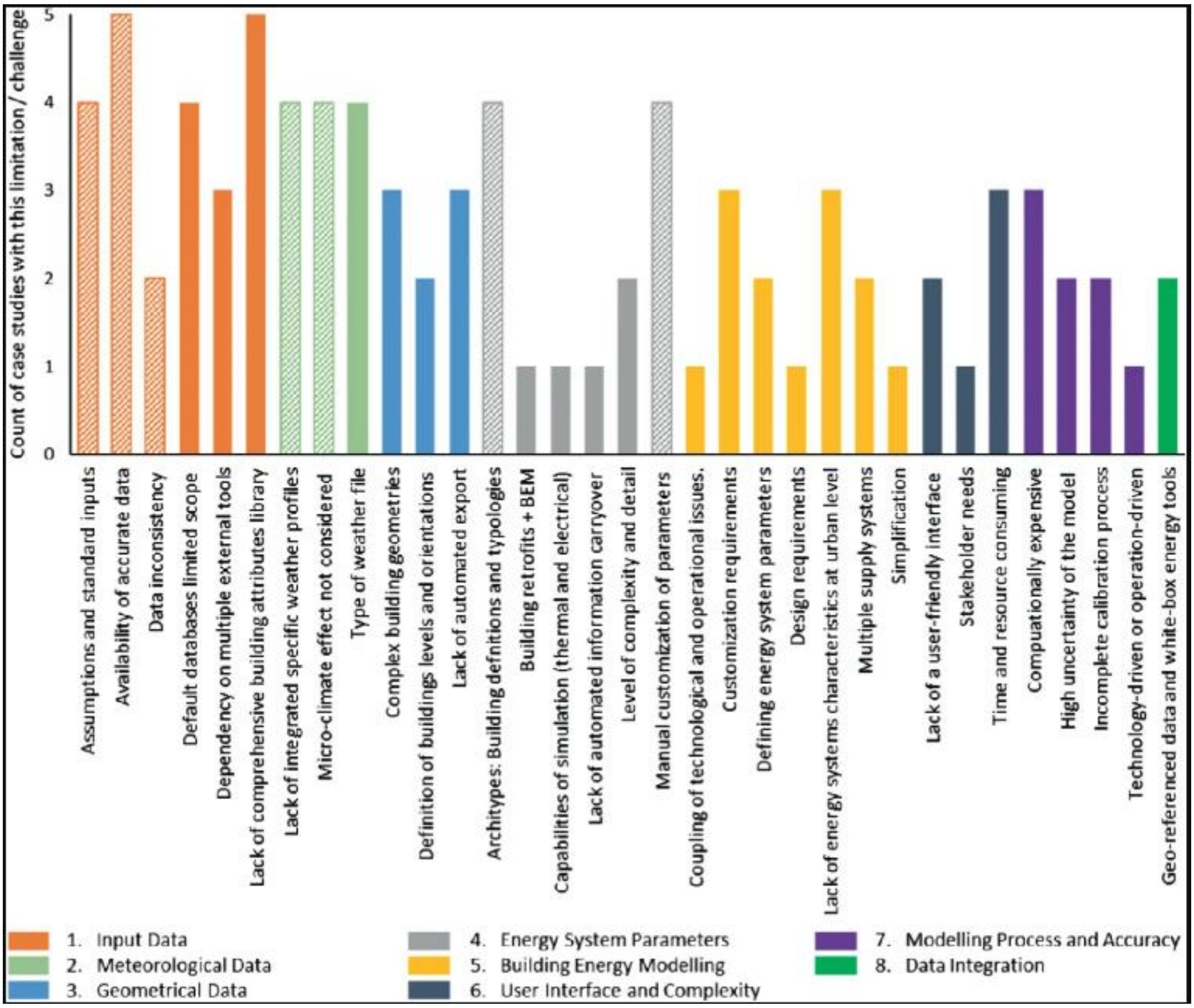


Figure 17: Models limitations. Belda, A. et al. (2022). Reviewing Challenges and Limitations of Energy Modelling Software in the Assessment of PEDs Using Case Studies.

Following, different workflows for different modelling tools are explained, as well as the parameters usually used per technology.

City Energy Analyst (CEA) - workflow

CEA[4] is an urban-scale energy planning tool used for district energy system analysis, renewable integration, and building energy simulations.

Typical Steps in CEA Workflow include:

Step 1: Data Collection & Preprocessing.

- Import building footprints and GIS data (custom shapefiles or use the user interface to obtain the zone shape file from OpenStreetMaps). Use data helpers for processing some of the data (e.g. generate surroundings shape file setting a buffer, generate streets shape file, etc.). These data helpers use OpenStreetMaps but also generate needed input files (e.g. typology.dbf, etc.) for running CEA
- Define building archetype and building year in typology.dbf.
- Assign properties (floor area, height, use type, HVAC systems, etc.) based on archetype-based data with Archetypes mappers.
- Collect climate data (using weather epw files).

Step 2: Energy Demand Simulation.

- Get radiation on different surfaces (Daysim assisted).
- Assign schedules and other data based on function (residential, commercial, industrial) and archetypes.
- Use occupancy and internal gains schedules – based on use types and schedule_maker.py.
- Get demand from 5R1C model (one single zone) for each of the buildings considering the schedules (and internal gains), and radiance (and its solar thermal gains).
- Simulate space heating, cooling, hot water, lighting, and plug loads.

Step 3: Supply System Analysis.

- Get potentials (solar thermal, solar PV, ground coupling, water/lake potential, waste heat recovery from DHW).
- Model district heating and cooling networks.
- Evaluate different energy generation systems (PV, wind, CHP, heat pumps).

Step 4: Energy System Optimisation.

- Optimise system sizing (e.g., PV panel area, battery capacity) coupling with potentials and district heating options.
- Decide which option is more feasible: district heating or individualised options.
- Perform cost-benefit analysis for different energy strategies.
- Analyse CO_2 emissions and sustainability impact.

Step 5: Results Visualisation & Decision Support.

- Map energy demand and supply potentials at the district scale.
- Identify peak loads and seasonal variations.
- Compare scenarios for energy-efficient urban planning.

TRNSYS Workflow

TRNSYS is a transient system simulation tool used for building energy modelling and district energy system analysis. Unlike CEA, TRNSYS is more focused on detailed thermodynamic modelling. It is a highly flexible and modular software designed to simulate the transient behaviour of energy systems, particularly those involving thermal, electrical, and renewable energy components. TRNSYS employs a component-based simulation approach, where systems are built by linking mathematical models, or "Types" that dynamically interact based on user-defined inputs, allowing for detailed and customisable simulations of complex energy systems. Within TRNSYS, Types are grouped into Libraries that represent diverse energy technologies. These include renewable systems (solar thermal, photovoltaics), conventional equipment (boilers, chillers, heat pumps), building and HVAC models, thermal storage, electrical systems, and control strategies, enabling flexible simulation of complete energy systems.

The typical steps in TRNSYS Workflow include:

Step 1: Model Setup & Inputs Definition.

- Define the simulation period and timestep.
- Load climate/weather data (e.g., TMY files, epw files, etc.): Weather information for TRNSYS simulations can either be provided in one of many standard weather data formats or can be in user-supplied files of measured data. Type 15 processes the standard format files and includes modes for TRNSYS TMY, TMY2, TMY3, EPW, IWEC, Meteonorm and German TRY. User-supplied weather data can be read using Type 99 or a combination of Type 9 and Type 16.

[4] CEA v3

Step 2: Building Energy Modelling.

- Model buildings using Type 56 (multizone building model): with trnViewBUI it is possible to explore the 3D geometry of the multizone building description files, which is an AddOn for Type 56 / TRNSYS 18. trnViewBUI has been developed by Transsolar Energietechnik GmbH allowing Trnsys 18 users to view and explore 3D geometry included in the building description file (*.b18) of TRNBuild graphically.
- Define thermal properties (walls, windows, insulation, etc.).
- Define gains schedules (inside type 56).
- Add HVAC components (heat pumps, boilers, chillers) as additional types (step 3) and connect with building loads.

Step 3: Renewable Energy & Storage Integration.

- Add PV (Type 190/103) or wind turbines (Type 90).
- Integrate HVAC types as Variable Speed Compressor Water (Source) to Water Heat Pump (Type1323), or Simple Boiler with Efficiency Inputs (Type 700), or Air-Cooled Chiller (Type655).
- Integrate energy storage (lead-acid storage batteries (Type 47a), Vertical Cylindrical Storage Tank storage (Type 534) or even geothermal field for thermal seasonal storage as Vertical Ground Heat Exchanger (Type 557a).

Step 4: Simulation & Calibration.

Run transient simulations (sub-hourly/hourly/daily/seasonal analysis). Both input data and simulation results can be integrated into different time steps with Quantity Integrator (Type 24), or apply time dependent forcing function which has a behaviour characterised by a repeated pattern with types as (Type 14h) to represent different profiles.

- Adjust parameters for calibration with real data. With external data files that can be read at regular time intervals with (Type 9c) as hourly demand profiles, or weather files (Type 15-3), which also calculates several useful terms including the mains water temperature, the effective sky temperature, and the heating and cooling season forcing functions. In addition, it is also possible to make a call to external programs such as EXCEL (Type 62), EES (Type 66), Matlab (Type 155) or Python (Type 163/169), as well as the call to other simulation tools such as CONTAM (Type 97) or ESP-r (Type 130).
- Optimise energy systems for efficiency and cost using TRnsOPT
- Calibration with real data using Type 783: RMSE Calculator / Calibration Analyzer.

Step 5: Post-Processing & Analysis.

- Analyse outputs: heating/cooling loads, energy savings, emissions.
- Visualise results in charts and graphs. The selected variables can be displayed in a separate plot window on the screen with Online Plotter (Type 65), or can be exported or printed at specified (even) intervals of time, into different file extensions such as (.csv, .xlsx, or .txt) with (Type 25).
- Compare different scenarios for urban energy optimisation.

OEMOF Workflow

OEMOF (Open Energy Modelling Framework) is an open-source tool for optimising energy systems. It is primarily used for energy system analysis and optimisation at different scales (building, district, national).

Typical Steps in OEMOF Workflow include:

Step 1: Data Collection & Input Definition.

- Define the different buses (heat, electricity, etc.) typically corresponding to each energy carrier
- Define a grid component (which should be infinite in principle or limited to its capacity of the transformer). The same can be done for the gas grid and district heating grid
- Define energy demand as sinks (typically using time series)
- Define generation components (As sources and converters)
- Define storage components (defining different parameters)
- Add everything to the energy system model

Step 2: Modelling Energy System Components.

- Define conversion efficiencies and capacities
- Import climate/weather data, if other tools such as pvlib, oemof.thermal and other python libraries want to be coupled.

Step 3: Define constraints.

- Set system constraints and optimisation objectives.

Step 4: Optimisation & Simulation.

- Run linear optimisation to find cost-optimal solutions.
- Assess energy flow, losses, and grid interaction.

Step 5: Post-Processing & Analysis.

- Visualise results (costs, emissions, performance metrics).
- Compare different energy system configurations.

CERC Hub Workflow

CERC Hub consist of a set of classes (Central data model), importers and exporters to help researchers to create better and more sustainable cities. Based on CERC Hub TOOLS4Cities is created (see Chat 16). This newly developed model is, thus, based on creating a central data model with a clear definition of all the processes in cities that could be used for decarbonisation. This central data model is where different sources of information would be stored and structured, and the structure could produce the necessary input files for different typologies of software, depending on the use case. It would also be a framework that could allow different processes to store information and chain different software, using the output of one process as an input for the following processes.

The workflow is part of the TOOLS4Cities urban simulation platform, developed at the Next Generation Cities Institute of Concordia University, aiming to simulate urban areas holistically. The main part of this simulation platform is a set of pipelines, data models, datasets, and catalogs called the TOOLS4Cities Hub. The building retrofit tool comprises building modelling, energy system modelling, scenario selection, techno-economic assessment of scenarios, and visualisation modules using different parts of the TOOLS4Cities Hub (Gavaldà-Torrellas et al., 2025).

Typically, the workflow includes:

1. Data Collection & Input Definition.
   - Building Geometry: Imported via GeoJSON/CityGML; buildings enriched with construction year, function, and height.
   - Archetypes Assignment: Construction and usage archetypes based on function, age, and climate zone.
   - Weather Data: EPW files used to provide climatic conditions.
   - Energy System Data: Retrieved from XML-based catalogues describing generation, distribution, and storage components.
2. Modelling Energy System Components.
   - Energy systems assigned based on building archetypes.
   - Modeled using a modular UML structure (EnergySystemCatalogue) with detailed attributes (e.g. HVAC type, efficiency).
   - Integration of PV modeled via radiation calculations using Simplified Radiosity Algorithm (SRA).
3. Define Constraints.
   - Scenarios: Four retrofit scenarios (Business-as-usual, Skin retrofit, HVAC+PV, Deep retrofit).
   - Techno-Economic Parameters: Includes cost, emissions, component lifetimes, and shading thresholds.
   - Software Compatibility Constraints: Exportable to EnergyPlus, INSEL, TRNSYS; allows for one-zone building simplification to reduce simulation time.
4. Optimisation & Simulation.
   - Energy demand and system simulations conducted via EnergyPlus (main engine for costing), SRA (for irradiance), and optional INSEL/TRNSYS.
   - Supports simulating up to 3000 buildings in <2 hours using optimised export libraries.
   - Simulation results loop back into the model for further analysis.
5. Post-Processing & Analysis.
   - Results are re-integrated into the central ‘City’ data structure.
   - Life Cycle Costing (LCC) performed using ISO 15686-5 methodology.
   - Visualisation via GIS-based maps; analysis includes investment cost, operational cost, and emissions per scenario.
   -

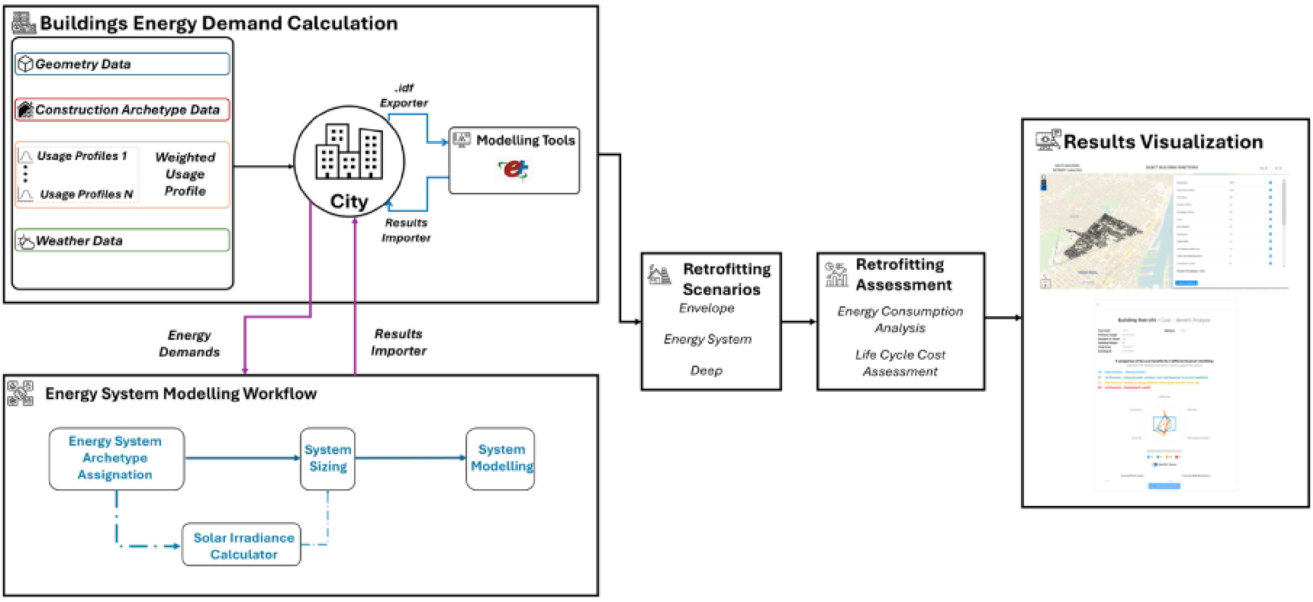


Figure 18: Retrofitting workflow in TOOLS4Cities

Comparison and discussion

Table 2 shows a concise comparative summary of the four tools — CEA, TRNSYS, OEMOF, and Hub — focusing on their main features (input data, simulation type, outputs, technologies considered), strengths (best for), and use cases (main use case, scale). While CEA and Hub are best suited for urban energy planning, especially for retrofitting and policy impact assessment; TRNSYS excels in detailed simulation of building systems and component-level dynamics, ideal for HVAC/control design. oemof offers powerful tools for optimisation and operation modelling, applicable to multi-energy systems. Open-source options (CEA, oemof, Hub) favor integration with Python-based workflows. TRNSYS requires licensing and uses a proprietary simulation interface.

Table 2: Comparison of tools

	CEA	TRNSYS	OEMOF	Hub
Scale	Urban/District	Building/Component Level	Urban/District	Urban/District
Main use case	Energy demand analysis, district energy planning	Transient simulation of energy systems	Energy system optimisation and operation modelling	Energy demand analysis, district energy planning
Input data	GIS, building metadata, climate data, country specific indicators	Building data or timeseries. Weather files, system specifications	Climate data Timeseries energy demand Cost data (timeseries, fixed values)	GIS, building metadata, climate data, country specific indicators
Simulation type	Annual energy demand estimation. Partial/Some specific dynamic system simulations Energy balances of energy systems	Dynamic system simulations	Optimisation-based energy flow modelling	Annual energy demand estimation. Energy balances of energy systems
Renewable integration	PV, CHP, DHN, heat pumps, storage, geothermal, lake-integration, etc.	Detailed component-level renewable modelling (Very high diversity and availability of systems)	PV, wind, CHP, heat pumps, storage, etc.	PV, CHP, DHN, heat pumps, storage, geothermal, lake-integration, etc.
Outputs	Energy demand, emissions, network performance	System performance, detailed heat transfer	Optimised energy flows, costs, CO_2 emissions	Energy demand, emissions, network performance
Best for	Urban planning, economic, LCA and technical decisions for retrofitting and decarbonisation scenarios	Detailed HVAC and renewable system design	Optimisation of multi-energy systems at different scales	Urban planning, economic, LCA and technical decisions for retrofitting and decarbonisation scenarios

Modelling approach	Bottom-up physics-based demand estimation. Physic-based and empirical energy systems models for simulation of their behaviour (energy balances)	Component-based transient simulations (physic-based models)	Mathematical optimisation (linear/nonlinear programming). Estimated efficiencies and simplified modelling approach	Bottom-up physics-based demand estimation. Physic-based and empirical energy systems models for simulation of their behaviour (energy balances)
Flexibility	High for urban planning. Multiobjective optimisation	High for transient system simulations, control systems, detailed behaviour of the energy system	High for optimisation and dispatch analysis. Multiobjetive optimisation	High for urban planning. Multiobjective optimisation
Open source	Yes	No (licensed)	Yes	Yes
Programming interface	Python (with GIS tools)	Graphical interface (Simulation Studio), Fortran for development of types	Python	Python (with GIS tools)

Energy system component catalogues and standardisation of data models

Energy System Component Catalogues are predefined libraries or templates that describe various configurations of energy system components (e.g. PV arrays, CHP, heat pumps, storage) along with:

- Mathematical or data-driven (or mixed) representation of the behaviour of the energy system. Allows to simulate its behaviour (based on inputs and parameters).
- Control strategies (control rules that allow to operate the energy system differently).
- Interaction with energy carriers (heat, electricity, gas) and external data (weather, location, etc.)

These catalogues, often coded in Python (e.g. in oemof or Hub), allow users to assemble modular and flexible system architectures to simulate energy flows, costs, emissions, and system behaviour under different scenarios.
A review is made of the most common technologies (photovoltaics, wind, solar thermal, ground coupling, electric storage,

Photovoltaics:

TOOL	Component	inputs	parameters	Outputs
PVGIS	Photovoltaic	• Location (latitude, longitude) • System size • Tilt angle, azimuth • PV technology type • Mounting position • Loss factors	• Technology type (crystalline silicon, etc.) • Mounting position • Loss factors	• Monthly/yearly/hourly energy production • Performance ratio • Irradiance and losses
TRNSYS 18	Type 103/190 (Basic & Advanced PV Model)	• Solar radiation • Temperature • Wind speed (Advanced) • Solar zenith (Advanced) • Load	• Module efficiency • Temperature coefficient • Tilt, orientation, shading effects	• Power output • Voltage, current, efficiency • Cell temperature
CEA	PV Module	• Solar radiation • Surface area • Tilt angle, orientation	• Efficiency parameters (air mass, degradation) • Shading, albedo	• Power output

Wind:

TOOL	Component	inputs	parameters	Outputs
TRNSYS	Type 90 (Wind Turbine Model)	• Wind speed • Air density • Turbine power curve	• Hub height • Cut-in/cut-out speed • Efficiency	• Power output • Rotor speed • Power coefficient (Cp)
WindLib	Wind Turbine Model	• Wind speed • Air density • Turbine specifications • Power curve data	• Hub height • Turbulence intensity • Losses	• Power output • Capacity factor • Energy yield

Solar thermal:

TOOL	Component	inputs	parameters	Outputs
OE-MOF.Thermal	Solar Thermal Collector	• Global/direct/diffuse irradiation • Ambient temperature • Connected to heat bus	• Optical efficiency (η_0) • Thermal losses (a_1, a_2) • Collector geometry • Temperature differences	• Useful heat (Qcoll) • Efficiency • Collector irradiance
CEA	Solar Thermal Collector	• Global/direct/diffuse irradiation • Ambient temperature	• Efficiency (N_0, c_1, c_2) • Module size, aperture area • Flow rates • Pressure drops • Cp fluid	• Useful heat (Qcoll) • Radiation (kWh) • Supply/return temperatures • Losses

Thermal storage:

TOOL	Component	inputs	parameters	Outputs
CEA	Thermal Storage	• Heat demand • Surplus thermal energy • Storage medium	• Storage volume • Heat loss coefficient • Charging/discharging efficiency	• Stored energy • Discharge profile • Losses
TRNSYS	Type 340	• Inlet temperature • Mass flow rate • Store volume, height	• Heat loss coefficients • Heat exchanger specs • Auxiliary heater settings	• Node temperatures • Power transfer • Heat losses • Energy balance

Heat pumps

TOOL	Component	inputs	parameters	Outputs
OEMOF.Thermal	Absorption Chiller	• Cooling demand • Air temperature	• Characteristic coefficients (a, e, r, s) • Temperature differences (ddt, ddts) • Hot/cool/chill temps	• Cooling capacity ($\dot{Q}E$) • COP
OEMOF.Thermal	Compression Heat Pump / Chiller	• Heat demand • Ground or air temperature • Time step	• Temperature limits • Quality grade (COP/Carnot) • Nominal conditions	• COP / EER • Heating/cooling power • Power consumption

TRNSYS	Type 927 / 941 (Air/Ground Source HP)	• Ambient or ground temperature • Heat source/sink temperature • Load demand	• Flow rates • COP performance maps • Capacity settings	• Power output • COP • Temperatures

Other

TOOL	Component	inputs	parameters	Outputs
OE-MOF.Thermal	Cogeneration Emissions Model	• Electric and thermal efficiencies (ηel, ηth)	• Reference efficiencies (ηel_ref, ηth_ref)	• Electrical and thermal emissions
TRNSYS	Type 907 / 908 (Micro CHP / Gas Engine CHP)	• Fuel input • Ambient temperature • Thermal/electrical load	• Electrical/thermal efficiency • Fuel type • Heat recovery ratio	• Electrical and thermal power output • Overall efficiency • Fuel consumption

To improve interoperability between CEA, TRNSYS, oemof, and other software models we should define a shared set of parameters and default values. This could include:

- Physical Parameters: Efficiency, performance curves, thermal properties.
- Economic Parameters: Investment cost, maintenance cost, lifetime.
- Operational Constraints: Minimum load, ramp rates, part-load efficiency.
- Environmental Factors: CO_2 emissions factors, embodied energy.

This catalog would help users compare models, validate results, and standardise assumptions across tools which could be illustrated as in Figure 19.

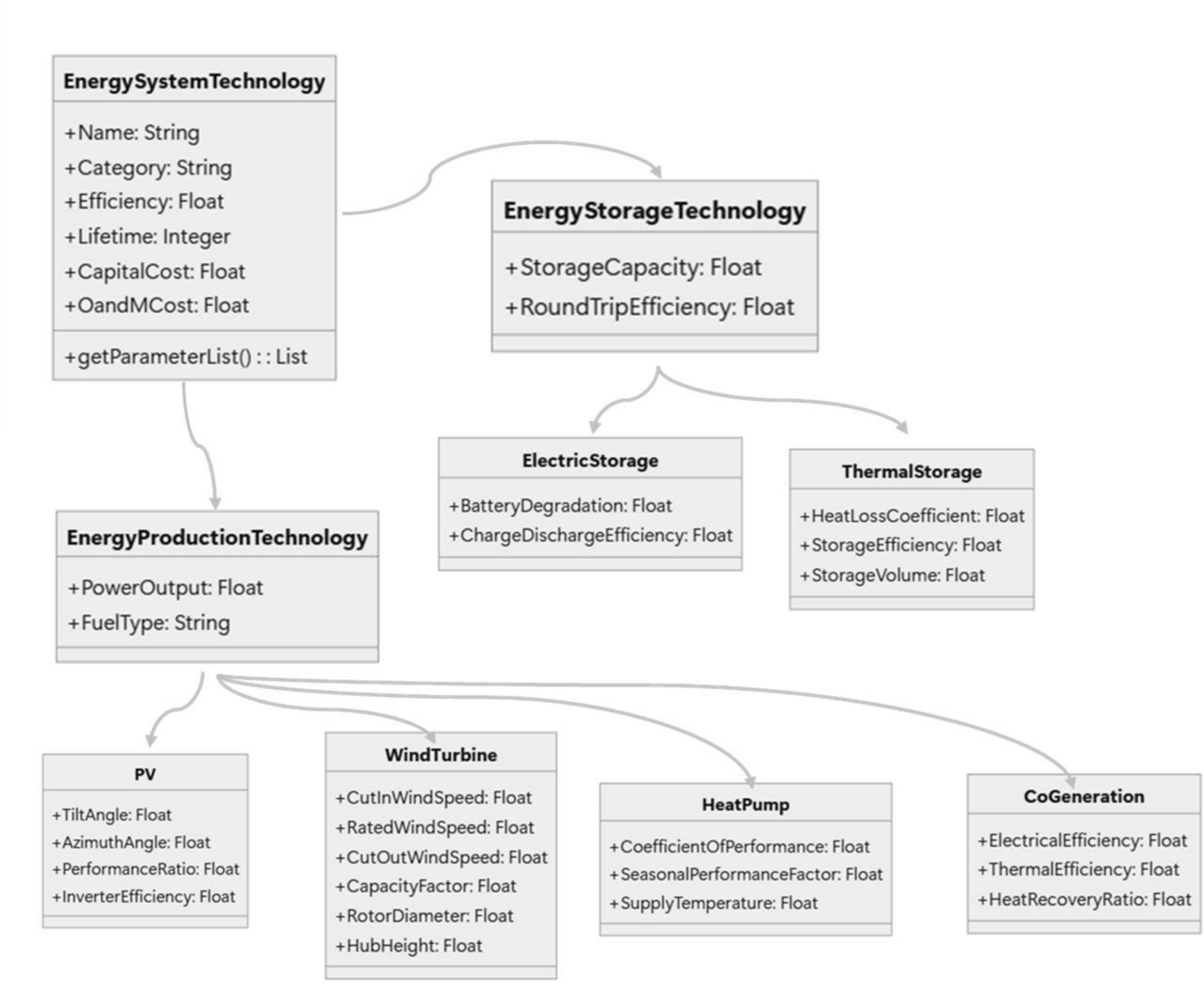


Figure 19: proposed UML (Unified Modelling Language) schema to map different levels of details of energy systems models

B3.3- Modelling district scale case studies

To discuss and illustrate how different case studies approach modelling, two cases (one from Canada and one from Italy) are explained hereafter.

Lachine: DH&CN

Located in the Lachine district along the Lachine Canal (see Figure 20), the Lachine-East sector is undergoing an urban planning process driven by an initial public consultation that led to the creation of a draft Special Urban Planning Program (PPU) for the Lachine-East Eco-District. The project aims to transform Lachine-East into an eco-district by utilising renewable energy sources (RES) and incorporating buildings designed to the highest urban and environmental standards. The eco-district is planned to feature 7,800 homes (see Figure 20), including social housing, schools, sports centers, and 30% green spaces, along with 223,000 m^3 of economic activity (L'écoquartier Lachine-Est PROGRAMME PARTICULIER D'URBANISME, 2023).

Figure 20: Lachine-East Eco-District (L'écoquartier Lachine-Est PROGRAMME PARTICULIER D'URBANISME, 2023)

The selected area includes 38 mixed-use buildings, covering residential, commercial buildings, a school and a sport center. The main objective is to reduce dependency on the grid through energy efficiency and self-sufficiency, promoting use in responsible energy consumption and production.

For the case study, different assumptions had to be made. For instance, as Lachine is a new district and not built yet, construction code standards had to be reviewed. The minimum requirements for U-values (overall thermal transmittance) for new buildings in terms of walls, windows, and other building elements are specified for both residential and commercial buildings. Table 3 summarises these minimum Canadian U-value requirements.

Table 3: Minimum U-Value Requirements

Building Element	Residential Buildings	Commercial Buildings
Exterior Walls	0.27 W/m²K	0.27 W/m²K
Windows	1.4 W/m²K	1.4 W/m²K
Roof/Ceiling	0.15 W/m²K	0.15 W/m²K
Floors (above unheated space)	0.18 W/m²K	0.18 W/m²K
Doors	1.8 W/m²K	1.8 W/m²K

The process of modelling 38 buildings begins with the input of GeoJSON data (illustrated in Figure 21), which contains the geographic locations of each building (and its surface), and information of the building year and function of the building. This data is fed into Hub workflow. Within Hub based on the building year archetype data is utilised, detailing various architectural aspects such as U-values, renovation rates, schedules, internal loads, and emitters. The construction factory, weather factory and usage are used to enrich the buildings with this information.

Using Simplified Radiosity Algorithm photovoltaic (PV) production are calculated. For each building, energy systems are assigned which allows to calculate the electric energy consumption of the buildings. The results are then analysed to determine the self-consumed PV, grid consumption, and any excess PV energy produced.

For processing the data further, demands are aggregated per type (space heating-SH, space cooling-SC, domestic hot water – DHW, lighting and appliances) at district level. Each scenario assumption is explained in detail below.

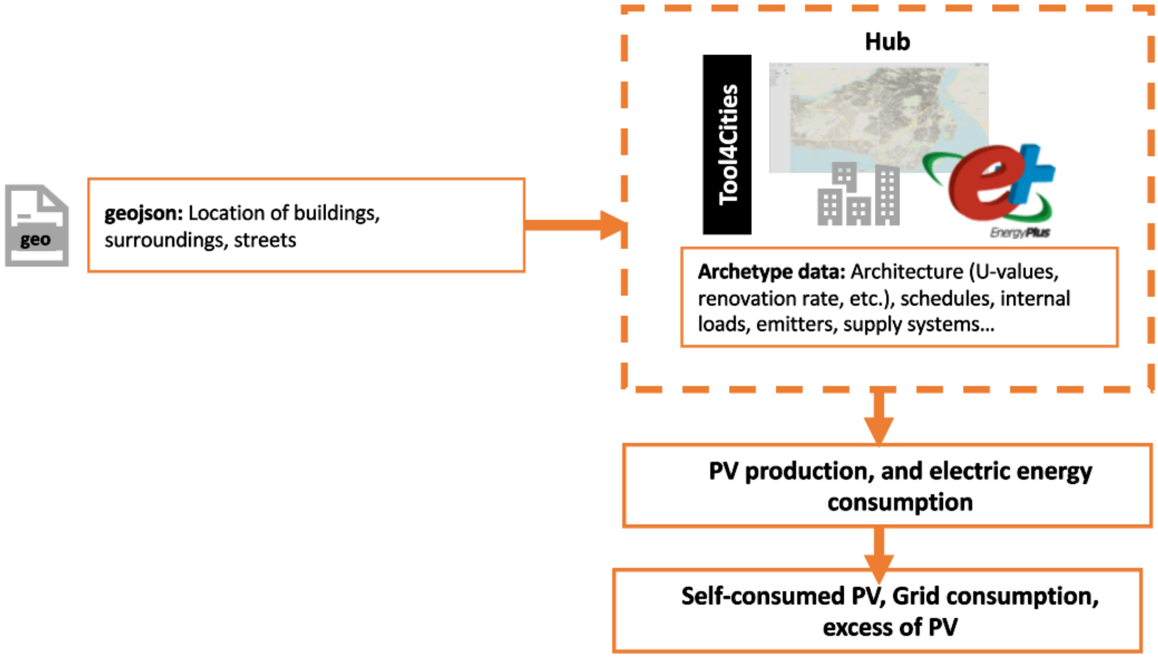


Figure 21: Methodological process followed in Hub

Regarding the energy supply of the district energy needs, the 'baseline' scenario assumes the entire district is electrified with the most common energy system used in Montreal, and consuming power from the grid. Thus, air-air units for cooling, electric boiler for DHW, and electric baseboards for SH are enriched in the Baseline scenario (system archetype called "system 1 electricity" (see Figure 22). The eco-district scenarios integrate additional elements: PV on roofs (SC2a), PV on roofs and facades (SC2b), air-water heat pumps with storage and PV on roofs and facades (SC3), and canal-water heat pumps to a district heating network with PV on roofs and facades (SC4), assuming a 15°C supply temperature.

```
<system_cluster name="system 1 electricity">
    <systems>
        <system_id>16</system_id>
        <system_id>10</system_id>
    </systems>
</system_cluster>
<system_cluster name="system 1 electricity pv">
    <systems>
        <system_id>16</system_id>
        <system_id>10</system_id>
        <system_id>15</system_id>
```

Figure 22: System archetypes for SC1 and SC2a and SC2b

The PV potential is assessed in hub using the GeoJSON file from the district and the Simplified Radiosity Algorithm (SRA). The methodology of SRA focuses on predicting how sunlight, daylight, and longwave radiation interact with urban environments. In each surface the view factors are calculated, and via matrixes and for each hour, the model calculates the amount of sunlight and daylight for each surface, reflection of lights and longwave radiation exchange between surfaces. Obstacles are considered in the calculation (Robinson, D and Stone, A, 2005). Furthermore, not all the surface of the roofs and façades are considered suitable for installing panels. Factors to reduce the usable area are assumed, such as a maintenance factor (a reduction of 10%), losses from shading/orientation of the panels (10%) and mechanical factors (20% for residential buildings, 30% for commercial buildings). A distance between the panels is also assumed in the algorithm, and this way the number of panels is calculated for each building. For façades, only south-facing walls are considered, which are identified by checking the azimuth_degree of each wall (see Figure 23).

```
# %%-------------------------------------------------
# """South facing facades"""
# %% # ------------------------------------------------
# Function to convert radians to degrees
import math
1 usage  Andrea Gabaldon Moreno
def radians_to_degrees(radians):
    return radians * (180 / math.pi)
# Step 1: Create the walls_id dictionary
walls_id={}

for building in city.buildings:
    ids = {}
    for walls in building.walls:
        id=walls.id
        azimuth_degree=radians_to_degrees(float(walls.azimuth))
        if azimuth_degree>90.0 or azimuth_degree <float(-90.0):
            ids[id]= {
                'azimuth': azimuth_degree,
                'global_irradiance': walls.global_irradiance[cte.HOUR],
                'area': walls.perimeter_area
            }
    walls_id[building.name] = ids

# Step 2: Calculate pv_on_facade for each wall
for building_id, ids in walls_id.items():
    for wall_id, wall_data in ids.items():
        if 'global_irradiance' in wall_data:
            ghi = [x / cte.WATTS_HOUR_TO_JULES/1000 for x in wall_data['global_irradia
            wall_data['pv_on_facade'] = [x * 0.6 * wall_data['area']*0.22 for x in ghi
```

Figure 23: South facing façades identification and calculation of PV potential

Regarding SC3 and SC4, archetype 13 energy system simulation model from Ranjbar, S. is used (Illustrated on Figure 24). The archetype consists of an air water heat pump, backup system (gas boiler), and thermal storage tank.

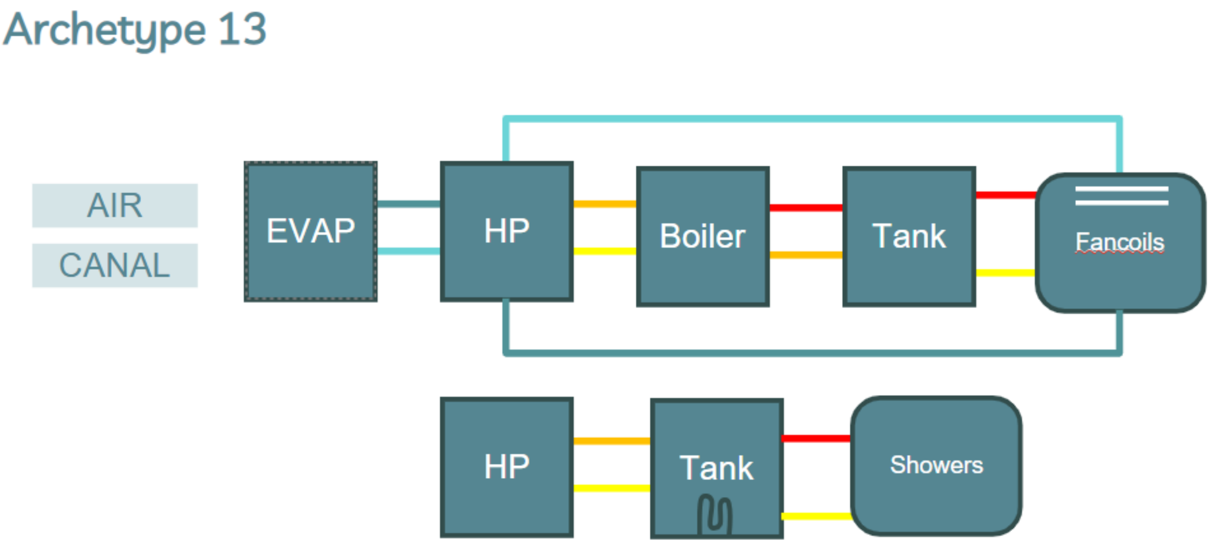


Figure 24: Archetype 13 elements

The archetype assumes the following size and generator (source) for each element:

- 50% of the heating peak load for the heat pump.
- 50% of the heating peak load for the backup system.
- 100% of the cooling peak load for the heat pump in cooling mode.
- Thermal storage to meet ΔT of 25°C and the peak heating flow.
- 70% of the dhw peak load for the heat pump, and a heating coil of 5kW for peaks, with thermal storage to meet ΔT of 10°C and the DHW heating flow.

For SC3, the generator (source) is changed on the backup system to be an electric boiler (change id from 16 to 17). For SC4, the backup system is also an electric boiler for both DHW and SH needs. The heat pump type is changed to 'water water heat pump' (change id from 23 to 25) and canal temperature is assumed to be 15°C and the source input (or sink temperature in summer) for the water water heat pump. These ids are changed in the XML Montreal future systems (see Figure 25).

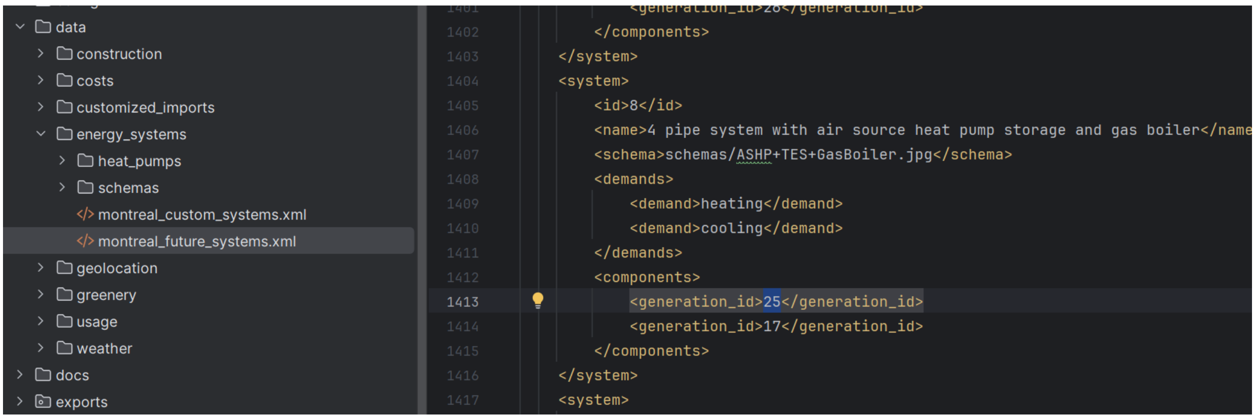


Figure 25: changes made in montreal_future_systems.xml

A constant efficiency is determined using the following formula:

$$COP = \frac{T_{high}}{T_{high} - T_{low}} \cdot \eta = COP_{carnot} \cdot \eta$$

Where η [5] is the quality grades of the heat pump which typically are 0.4 for air-source heat pumps, 0.55 for ground-source ("brine-to-water") heat pumps using a ground heat exchanger, and 0.5 for heat pumps using groundwater as source. Assuming Thigh as 55°C for SH and 60 °C for DHW, and source 15°C with a quality grade of 0.4-0.5, the COP in heating mode is assumed 4.07, cooling mode 4 and DHW 3. This is applied to archetype13.

For SC4 clusters (see Figure 26) are obtained using QGIS plugin selecting the peak demands (of SH, DHW, SC) as the clustering variables. The route is obtained using the modelling workflow from Rezaei A.

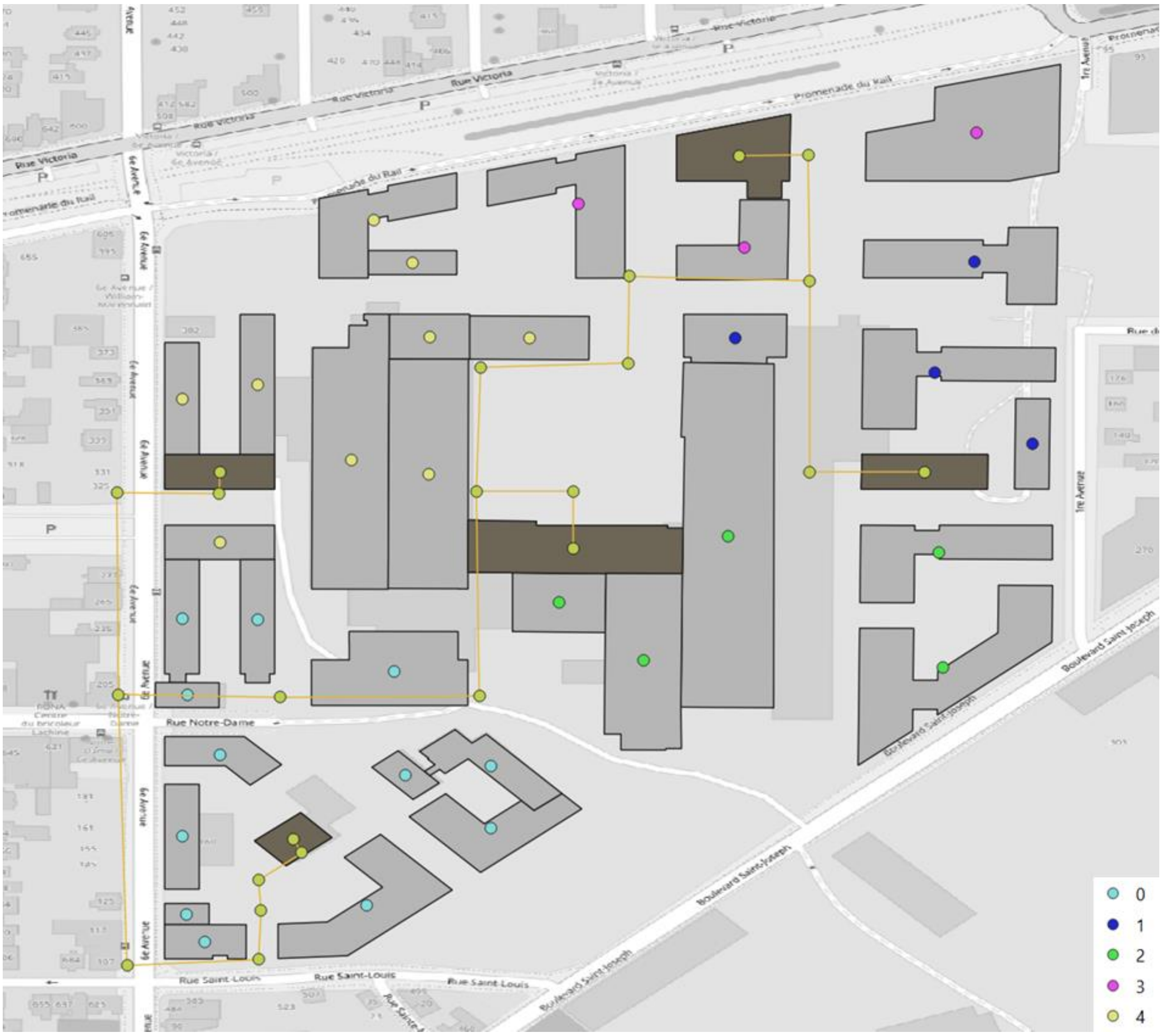


Figure 26: clusters (in dark colour the technical room supplying each cluster)

To obtain the energy demand, the area selected is partially constructed, but most of the buildings will be new and those existing are assumed to be retrofitted in the 'efficient scenario'. The cbc map is used to get the buildings construction year of those existing buildings. Most buildings were constructed from 1960-2015, therefore the conservative value of 1990 is assigned to the existing buildings. The U-values from Hub of 1990 and climate zone 6 are assigned (Table 4).

[5] https://oemof-thermal.readthedocs.io/en/latest/compression_heat_pumps_and_chillers.html

Table 4: U-values for existing buildings for 'baseline scenario'

Building Element	U-value	Data from 1981-1990, climate zone 6
Exterior Walls	W/m²K	0.426
Windows	W/m²K	2.95
Roof/Ceiling	W/m²K	0.267
Floors (above unheated space)	W/m²K	3.822

For those new buildings, the U-values correspond with the NRCAN archetype from the period of construction of 2017-2019 and climate zone 6 (see Table 5).

Table 5: U-values for 'baseline scenario' for new buildings

Building Element	U-value	Data from 2017-2019, climate zone 6
Exterior Walls	W/m²K	0.247
Windows	W/m²K	1.9
Roof/Ceiling	W/m²K	0.156
Floors (above unheated space)	W/m²K	0.183

As the window U-value does not meet the requirements of Quebec, this value is changed manually in the database from 1.9 to 1.4 W/m²K (see Figure 27).

```
{
  "Window_2017_2019_6": {
    "period_of_construction": "2017_2019",
    "climate_zone": "6",
    "shgc": 0.39,
    "type": "Window",
    "frame_ratio": 0,
    "u_value": 1.4
  }
```

Figure 27: Manual change in window of 2019

This means the archetype that calls the exterior walls, roofs/ceiling and floors of the period of 2017-2019, and a window with 1.4 W/m²K.
Scenario 1, called "energy efficiency", the period of construction of 2020-3000 (Table 6) and climate zone 6 is used with a 20% improvement from the 2019 U-values.

Table 6: U-values for 'energy efficiency scenario' for existing and new buildings

Building Element	U-value	Data from 2020-3000, climate zone 6
Exterior Walls	W/m²K	0.192 (manually changed for a 20% improvement)
Windows	W/m²K	1.12 (manually changed for a 20% improvement)
Roof/Ceiling	W/m²K	0.1248 (manually changed for a 20% improvement)
Floors (above unheated space)	W/m²K	0.1464 (manually changed for a 20% improvement)

Therefore, these U-values are assigned for the baseline scenario for the new buildings of Lachine in Hub. For each scenario results regarding energy consumption and the supply sources are obtained. The self-consumed PV electricity, grid consumption and excess of PV are differentiated in each case.
The baseline scenario consumes 99.5 GWh/year of electricity from the grid, from which 40.45% is used to supply SH needs, 32.68% DHW needs, 3.69% SC needs, 11.77% lighting and 11.40% appliances. The monthly variation is shown in Figure 28 are constant, whereas the highest demand is found in winter months (December and January).

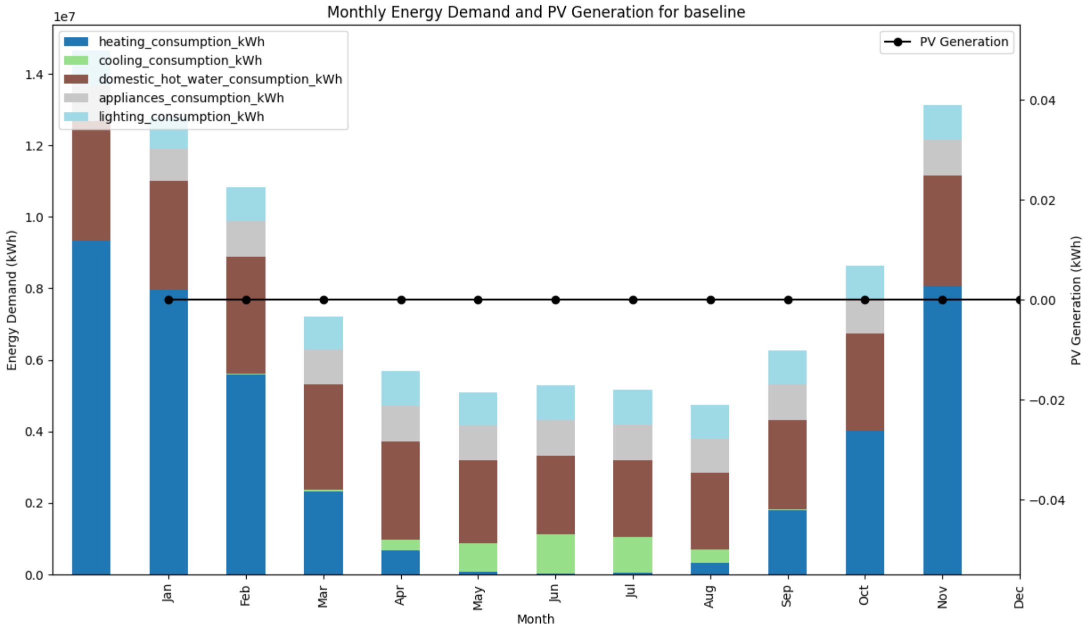


Figure 28: Monthly energy demand for the baseline (note that PV generation is zero)

From the baseline scenario, the U-values are improved by 20%. This results in a reduction of 5.04% in the yearly total electricity consumption, consuming 94.5 GWh/y of electricity.

The results are summarised in Table 7.

Table 7: Scenario 1 in Hub compared to Baseline scenario

	Hub results (kWh/m²)	
Energy Needs	**Baseline**	**Efficient scenario**
Space heating	100.6	87.2
Space cooling	9.2	10.0
DHW	81.3	81.3
Lighting	29.3	29.3
Appliances	28.3	28.3

The difference (comparing first scenario with the second done) in terms of energy efficiency is the following one:

- There is no greater improvement in terms of energy efficiency for heating in most buildings (see Appendix for more details per building).
- The cooling demand gets worse results as the U-value is improved (see Appendix for more details per building).
- The DHW, appliances and lighting does not change, which means it is independent on the year of construction

From the efficient scenario, PV on roofs (Scen. 2a) and PV on roofs and facades (Scen. 2b) are included. Implementing energy efficiency measures alone (Efficient scenario) reduces grid consumption modestly. Adding PV panels (Scenario 2a) significantly reduces grid consumption and increases self-sufficiency. Installing PV panels on both roofs and façades maximises PV generation, further reducing grid consumption and increasing self-sufficiency, though it results in more excess energy and a lower percentage of self-consumption (results are summarised in Table 8).

Table 8: Scenario 1 in Hub compared to Baseline scenario

	Base-line	Efficient scenario (SC1)	Scen. 2a PV on roofs	Scen. 2a PV on roofs, fa-cades	Units
Grid consumption	99.5	94.5	71.8	67.0	GWh/y
PV self-consumption	-	-	22.6	27.4	GWh/y
Excess of PV	-	-	5.7	15.2	GWh/y
Percentage of self-consumption[6]	-	-	79.75%	64.27%	GWh/y
Percentage of self-sufficiency[7]	-	-	23.94%	29.02%	GWh/y

Scenario 2a: PV on roofs are added. Solar tilted radiation 45 tilted and south facing obtained is mostly constant throughout the buildings (Figure 29). PV production is obtained and represented in Figure 30.

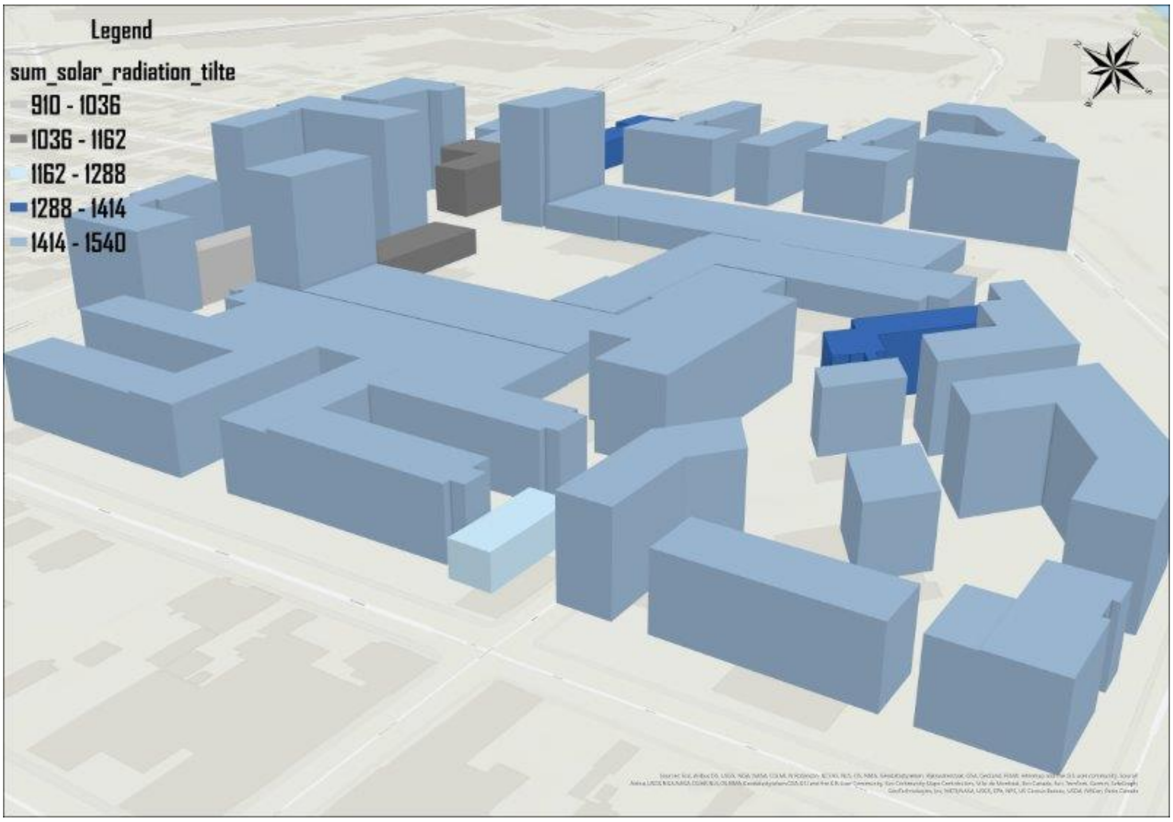


Figure 29: Solar tilted radiation (45 south facing) per building

[6] Ratio between the overall electrical energy that is self-consumed within the assessment boundaries and the total production within the assessment boundaries
[7] Amount of locally consumed renewable energy relative to all consumed energy

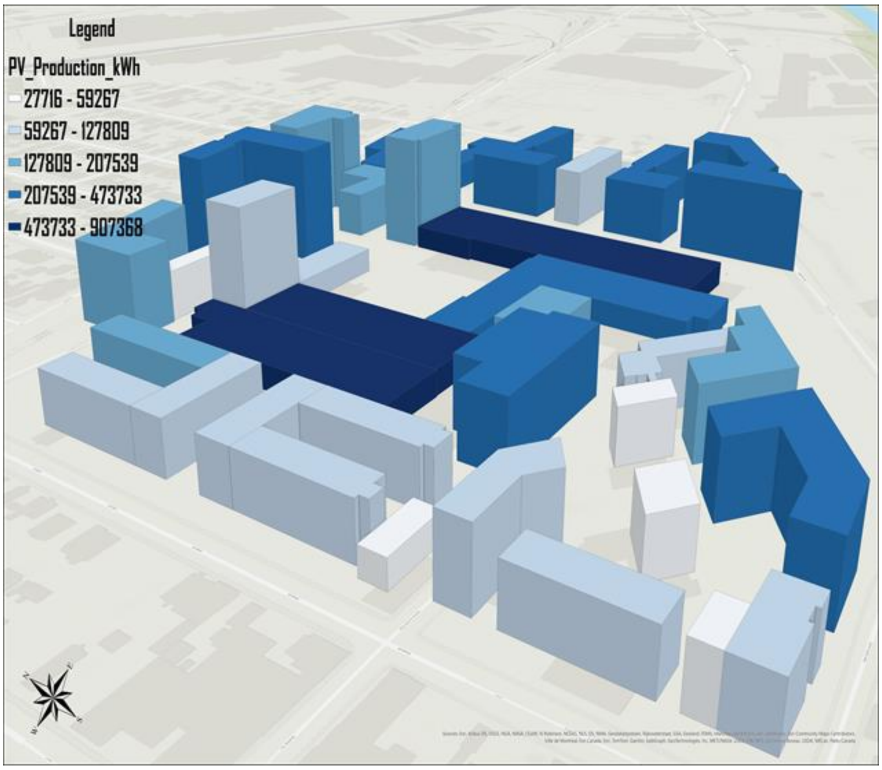


Figure 30: PV production per building (45 south facing)

What is the most technical and cost-optimal solution from the scenarios selected?

In terms of energy efficiency, and grid consumption, the best results are achieved for scenario 4 (see Figure 31). This scenario achieves the highest electricity consumption reduction, and the lowest net[8] grid yearly balance (24.2 GWh/y).

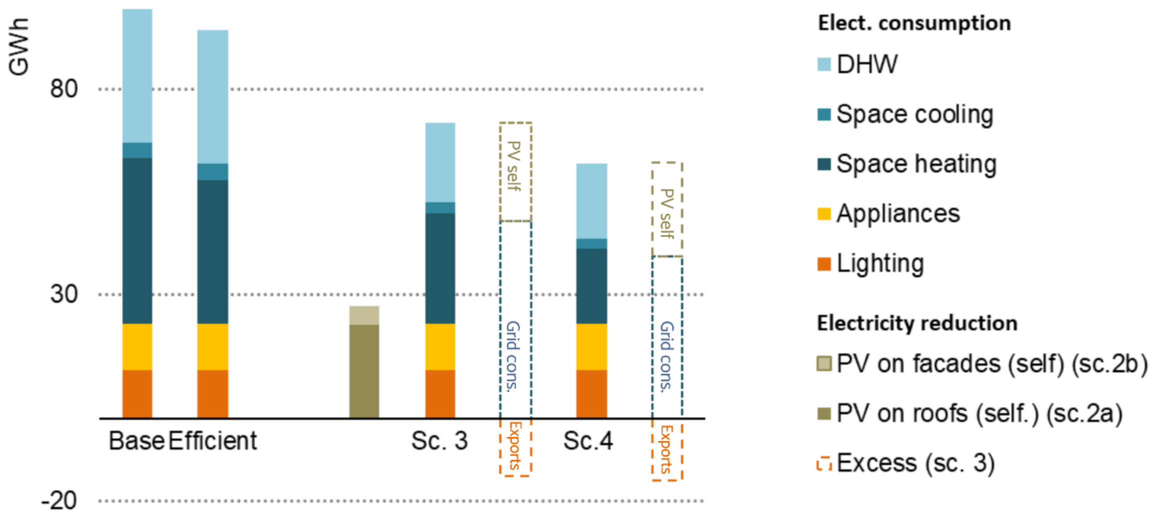
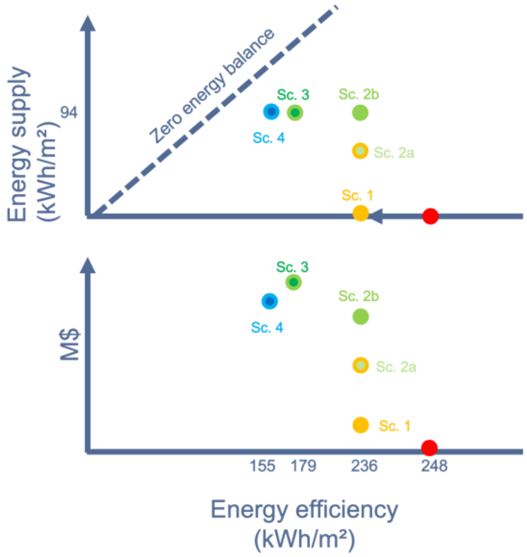


Figure 31: Summary of results

The same information is summarised per kWh/m² in the following figure. Scenarios 3 and 4 are closer to the "Zero Energy Balance" line, indicating that these scenarios achieve a better balance between energy supply and consumption, aiming for near-zero energy status. However, significant CAPEX investment is needed, and although the highest costs and energy savings are achieved, financing instruments and funds will be needed. Net energy consumption is reduced dramatically to 94 GWh/y from the efficient scenario (sc.1) to 24.2 GWh/y in scenario 4. In terms of energy efficiency and cost savings scenario, 2[9] followed by scenario 4 are the most optimal solution.

[8] Imports minus exports.
[9] See financial results for clarifying this comparison further

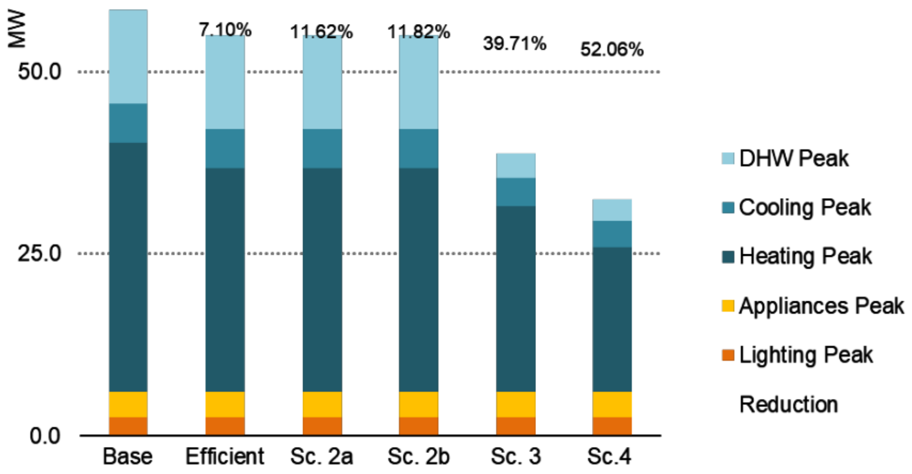


	Net GWh/y	CAPEX M$	Sav. M$/y
Baseline	**99**	**-**	**-**
Sc.1	94	12	0.3
Sc. 2a	66	47	2.1
Sc. 2b	51.8	91	2.5
Sc. 3 (+2b)	33.9	134	4.0
Sc. 4 (+2b)	24.2	112.1	4.6

Figure 32: Summary of economic results

Do these solutions reduce dependency on the grid?

Figure 33 illustrates the impact on the maximum grid peak demand (in MW) and the associated reduction percentages and self-sufficiency percentages. The graph also shows peak demands for each service DHW (Light blue), SC (teal blue), SH (dark blue), appliances (yellow) and lighting (orange). These peaks do not happen at the same time in the year. In the baseline scenario the total grid peak is 49.3 MW. This can be reduced by 7.1% only with efficiency measures (improvement of U-value by 20%). With PV the grid peak reduces further to 43.6 MW, with an 11.62% reduction compared to the baseline. The self-sufficiency rate is 23.94%. Adding PV on façades has no major effect on peak reduction, whereas the yearly self-sufficiency improves slightly to 29.02%. Adding heat pumps significantly drops to 30 MW the grid peak, a 39.71% reduction from the baseline, with a self-sufficiency rate of 33.24%. Lastly, the DHN scenario achieves the lowest grid peak of 23.65 MW, a 52.06% reduction compared to the baseline, with the highest self-sufficiency rate of 36.69%. The self-sufficiency percentage increases with scenario 3 and 4, indicating that the further the improvement of SH, SC and DHW system efficiency the larger proportion of energy needs are met by on-site generation rather than relying on the grid. While energy efficiency measures alone (Efficient scenario) provide some reduction of electricity consumption from the grid and peak reduction, the addition of PV and heat pumps (and district heating) yields much more substantial benefits in reducing grid dependency and improving energy self-sufficiency. The latter one can be further improved if e-storage is added.



	Base	Efficient	Sc. 2a	Sc. 2b	Sc. 3	Sc.4
Grid peak (MW)	49.3	45.83	43.6	43.5	30	23.65
Reduction (%)	-	7.1	11.6	11.8	39.7	52.06
Self-sufficiency (%)	-	-	23.94	29.02	33.24	36.69

Figure 33: Peak reduction (Grid peak is not the summed but the maximum value obtained over the year, as cooling peak and heating peak do not happen at the same time).

What is the finance gap between normal district (baseline scenario) and achieving an eco-district?

Energy Service Companies (ESCOs) play a crucial role in advancing energy efficiency projects by providing both the expertise and financial mechanisms needed to achieve significant energy savings. This report evaluates and contrasts two financing methods across five distinct scenarios, each aimed at reducing net electricity consumption from a base case of 99 GWh annually. The analysis incorporates the cost savings generated from energy savings in each scenario. Additionally, several financial assumptions pertinent to the scenarios are outlined and analysed in Table 9.

Table 9: Economic assumptions

Assumption	Value	Source
Cost per m²	$3 k per m²	(Riedel et al., 2022)
Cost increase for 50% energy efficiency	5%	(*Construction Cost of Buildings in Montreal*, n.d.)
PV CAPEX	$3 k/kWp	(*Report*, n.d.)
Loan interest rate	3%	(*Annual Maintenance Cost for Solar PV*, n.d.)
Cost of equity	6%	(*Annual Maintenance Cost for Solar PV*, n.d.)
OPEX (PV)	2% of the total cost	(*Annual Maintenance Cost for Solar PV*, n.d.)
Available Government Grant	5%	(*Heat Pumps*, n.d.; *HydroQuebec*, n.d.)
AWHP CAPEX	$1.087/kW	(Fedrizzi et al., 2015)
OPEX (AWHP)	1.5% of the total cost	(Fedrizzi et al., 2015)
Electric boiler CAPEX	$271.8/kW	(Fedrizzi et al., 2015)
OPEX (Electric boiler)	1.5% of the total cost	(Fedrizzi et al., 2015)
Tank Volume cost	$1.812/m³	(Energy Storage Technology Descriptions-EASE-European AssocIaton for Storage of Energy Thermal HoT WaTer STorage Thermal Energy STorage 1. Technical Description, n.d.)
DHN (District Heating Network) cost	$550/m, $53/(m³/h) *	(Saini et al., 2023)

*Note: district heating operators usually sell the heat (heating as a service) and own the heat pumps, we are assuming that the developers invest in the network and heat pumps, but the price of electricity is paid by the owners of the households, so no selling of heat is considered (to be fair with the decentralised case) but it will provide additional revenues for developers. For instance, the price could be a bit higher than the electricity price and the developers should assume the cost of electricity of the heat pumps.

Method 1: Traditional ESCO Model

The traditional ESCO model involves the ESCO taking on both debt and equity investments. In this approach, the ESCO secures debt financing for a significant portion of the capital expenditure (CAPEX), while also investing its equity into the project. A small percentage of the funding is typically provided by government grants aimed at promoting low-carbon projects. This method leverages the energy savings generated by the project to repay the debt and provide returns on equity.

Method 2: Hybrid Financing Model

The hybrid financing model involves a partnership between the developer and the building owner. The developer funds a portion of the project through the sale of building units, while the remaining funding comes from owner contributions. This approach allows for a diversified funding base and often results in shorter payback periods for the developer. However, the incremental cost savings from the implemented energy systems influence the owner's payback period. The payback period is analysed in two scenarios: one considering a regular contract between Hydro-Québec and the customer, and the other using a contract with winter credit.

Results and Analysis

Table 10 shows the results of the analysis across different scenarios.

Table 10: Results

Sce-nario	Cost Savings (annu-ally, M$)	CAPEX (M$)	Debt Share	Equity Share	Finance Type 1	Finance Type 2			
					Payback for ESCO (years)	Increased cost of household (k$/household)	Payback for Developer (years)[10]	Payback for Owner (years)[11]	Payback for Owner + Winter Credit (years)
1	$0.3	$12.0	48%	47%	35	-	10.2	30	30
2.a	$2.1	$35.5	90%	5%	21	16	6.7	36	22
2.b	$2.5	$79.9	47%	48%	36	23	9.6	44	26
3	$4.0	$134.0	45%	50%	38	31.7	9.1	38	27
4	$4.6	$112.1	62%	33%	28	36.7	7.2	37	27

The comparative analysis of the two financing methods across the scenarios reveals significant differences in payback periods for both the ESCO and hybrid models.

Under the traditional ESCO model, projects involving extensive upgrades or solar energy installations tend to have shorter payback periods due to the significant cost savings they generate. For instance, the scenario involving adding solar rooftops and improving the building envelope in the district (Scenario 2.a) shows the shortest payback period of 21 years. Other scenarios, however, exhibit payback periods of at least 28 years. The hybrid financing model generally results in shorter payback periods for developers, making it an attractive option for those seeking quicker returns. The scenario with the shortest developer payback period also involves adding solar rooftops, reflecting the high efficiency and rapid cost recovery associated with renewable energy installations. However, payback periods for owners are longer, particularly in scenarios with significant upfront investments and extensive energy upgrades. Additionally, we analysed the impact of winter credit on reducing the payback period. The results show that, except for Scenario 1, the impact is substantial, reducing the owner's payback period by 10 years (Scenario 4) to 18 years (Scenario 2.b).

Industrial & residential users case: wind turbine, PV panels and electrolyser

The case study investigated by Marrasso et al. (Marrasso et al., 2024b) focuses on identifying the optimal configuration of RES to supply an existing district aiming to achieve the PED status. The district under analysis is in the industrial area of Benevento, a city in southern Italy, and includes both residential and non-residential users. Unlike conventional studies that primarily target the decarbonisation of electricity consumption, this case study also incorporates renewable thermal energy systems. Specifically, evacuated tube solar collectors are integrated alongside PV panels and wind turbines. In addition, the study explores a power-to-gas strategy to further reduce emissions from thermal energy consumption, typically reliant on fossil fuels. Surplus renewable electricity is used to power an electrolyser to produce green hydrogen, which is then blended with natural gas (Schiro et al., 2020a). This mixture is supplied to domestic boilers, adhering to safety thresholds for hydrogen use in residential appliances (Schiro et al., 2020b). Any excess green hydrogen not consumed within the district is assumed to be injected into the existing natural gas grid, respecting the 10% maximum allowable hydrogen blend (Erdener et al., 2023; Lewandowska-Bernat & Desideri, 2018).This export capability not only addresses the intermittent nature of renewable sources but also enables the decarbonisation of thermal energy demand beyond the district itself, contributing to carbon neutrality on a broader scale.

The district under analysis comprises nine users situated within 1 km, specifically:

- User 1 (Us#1): a mixed-use building hosting offices and companies operating in the service sector.
- User 2 (Us#2): the industrial wastewater treatment plant.
- Users 3–8 (Us#3 to Us#8): six residential buildings.
- User 9 (Us#9): an office building.

[10] The total CAPEX is divided by the earnings of the developer. The earnings are calculated by multiplying the increased cost per household by the number of households sold per year (assumed to be 10% of the total household stock).
[11] This calculation is done by dividing the increased household cost (for example, in the DHN scenario, a $36.4k increase compared to the market price) by the household savings (which include savings on electricity costs and credits earned from excess energy).

Installed energy systems have been categorised into three groups: those serving residential users (including electric heat pumps, evacuated tube collectors, and boilers), those for non-residential users (such as split air conditioners for Us#1 and an electric heat pump for Us#9), and district plants, which include all centralised renewable energy systems and the electrolyser used for green hydrogen production. The available surface area within the district can accommodate up to 1,679 PV panels, equivalent to an installed capacity of 549 kW. As alternatives or complements to PV systems, two wind turbine models have also been considered for installation: Model A, featuring a two-blade rotor with a rated power of 250 kW[12], and Model B, featuring a three-blade rotor rated at 660 kW[13].

A range of dynamic simulation tools and models has been employed. All simulations cover a one-year period but are conducted with different time steps depending on the specific application.

The thermal load, cooling load, and electrical demand for appliances of residential users are calculated using building simulations in TRNSYS 18 (Solar Energy Laboratory, 2018b). In the TRNSYS environment, all system components, including ducts, circulating pumps, and control devices, are modeled using subroutines known as *types*. These types are sourced either from the standard TRNSYS library or from the TESS (Thermal Energy Systems Specialists) library (Solar Energy Laboratory, 2018a). The main types used for the purposes of this research are type 941 (electric heat pump, TESS), type 534 and 533 (thermal energy storages, TESS), type 71 (evacuated tube solar collectors, TESS) and type 122 (boiler, TESS). The models require input weather data and technical parameters for all plants. In the case of EHPs, performance maps are built according to the data provided in the manufacturer datasheet.

Renewable plants for electricity generation were modeled using HOMER Pro® (UL Solutions, n.d.) and dynamically simulated over a one-year period with a 15-minute timestep.

To model hydrogen mass flows on an hourly basis, a dedicated MATLAB® (Mathworks Inc., 2016) script was developed.

Electricity sharing from renewable sources has been implemented in accordance with Italian regulation governing Renewable Energy Communities, using a virtual self-consumption model (GSE, 2020). Under this framework, the national power grid (PG) facilitates energy sharing. Renewable electricity generated but not consumed on-site is injected into the PG. Conversely, users whose energy demand exceeds their own generation capacity can draw electricity from the PG. Virtual self-consumption occurs when electricity is simultaneously injected into and withdrawn from the PG by district users. Any electricity injected into the PG that is not consumed within the district is exported to external users via the PG as surplus energy. However, the installation of the electrolyser enhances local self-consumption, thereby minimising energy exports. Regarding hydrogen production, two electrolyser configurations have been analysed. In the first scenario, the electrolyser (180 kW) is sized to maximise annual operating hours, utilising all surplus renewable electricity that would otherwise be exported from the district via the PG. In the second scenario, only a portion of the surplus electricity is used to operate the electrolyser (80 kW), aiming instead to maintain a positive electricity balance. In this case, the amount of renewable electricity exported exceeds the electricity drawn from the PG by district users. In both scenarios, any surplus green hydrogen exceeding the demand of district users is injected into the natural gas pipeline and supplied to users outside the district. For the purposes of this study, the resulting hydrogen-natural gas blend delivered via the pipeline is assumed to be used in domestic boilers originally designed to operate on natural gas. Consequently, the export of green hydrogen also corresponds to the export of thermal energy.

The electric load profiles for the non-residential users, namely Us#1, Us#2, and Us#9, were obtained from the Italian electricity distributor[14], with a time resolution of fifteen minutes. In contrast, the electric, heating, and cooling energy load profiles of residential users have been dynamically simulated. For each season, daily occupancy schedules for residential flats and offices were determined using a high-resolution model based on survey data collected in the United Kingdom. This model employs first-order Markov-chain techniques (McKenna & Thomson, 2016) to generate stochastic occupancy sequences. Using these sequences, electric load profiles for appliances and lighting were calculated based on the resulting occupancy patterns. The DHW demand was determined using dynamic simulation software that accounts for the number of occupants in each household, with a maximum daily DHW demand set at 50 L/person (Jordan & Vajen, 2001). These simulations were carried out with a 1.5-minute timestep. Similarly, building simulations were conducted in TRNSYS 18 using a 1.5-minute timestep to determine the thermal and cooling energy demand of residential users, as well as the electric load from the activation of appliances, including plugs and lighting.

[12] https://windenergysolutions.nl/wes/windturbine-wes-250/
[13] https://www.thewindpower.net/turbine_en_176_vestas_v47-660.php
[14] https://www.e-distribuzione.it/servizi.html

The evaluation of space heating and cooling energy needs was carried out in accordance with Italian regulations[15]. The city of Benevento, with 1,316 heating degree days, falls within a specific climatic zone that defines the heating season from 15th November to 31st March, with a maximum of 10 operating hours per day. Conversely, the cooling season is assumed to extend from 1st June to 30th September. During the intermediate months, only DHW demand is considered. Indoor comfort conditions used to calculate thermal and cooling energy requirements were also defined based on national regulatory standards. Specifically, the set-point indoor temperature was assumed to be 20 ± 2 °C during the heating season and 26 ± 2 °C during the cooling season[16]Still, models need to be calibrated.

Role of Ontologies:

Positive Energy Districts (PEDs) aim to produce more energy than they consume, promoting sustainable urban development. Assessing and managing PEDs requires the integration of diverse data sources and systems—including building models, energy systems, climatic data, and urban infrastructure. However, the heterogeneity of data models and analytical tools presents a significant barrier to effective integration and interoperability. In this context, ontologies play a crucial role in standardising knowledge representation and enabling seamless data integration and exchange.

Various tools and platforms exist for analysing cities, buildings, and energy systems. These tools are typically developed independently, each with its own data schema, terminology, and modelling assumptions. Consequently, attempting to reuse data or analytical outputs from one tool in another can be complex and error-prone. For instance:

- Different tools may use distinct terms to refer to the same concept (e.g., "zone temperature" vs. "indoor climate").
- Data properties may be structured differently or lack clear semantic definitions.
- Models might capture information at varying levels of granularity or temporal resolution.

These inconsistencies block the ability to perform integrated assessments of PEDs, where diverse systems need to interact dynamically.

An ontology in the IT context is a formal, structured representation of knowledge within a particular domain. It defines a set of concepts (or classes), their properties (relationships), and the rules or constraints governing them. Ontologies enable both humans and machines to share a common understanding of information, facilitating data interoperability and semantic reasoning.

The key characteristics of ontologies are:

- Formal Structure: Ontologies are defined using formal, logic-based languages such as OWL (Web Ontology Language), making them interpretable by software agents for reasoning and inference tasks.
- Concepts (Classes): Represent core entities or phenomena within the domain (e.g., Building, Energy System, Sensor).
- Relationships (Properties): Specify how concepts relate to each other (e.g., has Location, measures, consumes Energy).
- Instances (Individuals): Denote specific, real-world examples of a concept (e.g., "Building_123", "Sensor_A").
- Hierarchy (Taxonomy): Ontologies often include subclass relationships that create a conceptual hierarchy (e.g., Photovoltaic Panel is a subclass of Energy Generation Device).
- Constraints & Rules: Include axioms and business logic (e.g., “Every building must have at least one energy system”) to guide validation and reasoning.

Ontologies serve as a foundational element for creating a unified data model for PEDs. By aligning the various tools and datasets with a common ontological framework, data from heterogeneous sources can be harmonised and integrated. This approach addresses many challenges outlined earlier and provides several benefits:

- Improved interoperability between systems and analytical tools.
- Reusability of existing data and models across different PED implementations.
- Scalability, allowing new systems or data types to be integrated by extending the ontology.

[15] https://www.gazzettaufficiale.it/eli/id/1993/10/14/093G0451/sg
[16] https://www.gazzettaufficiale.it/eli/id/2013/06/27/13G00114/sg

- Support for semantic reasoning, enabling advanced querying, validation, and analytics.

Several standardised ontologies have been developed for domains relevant to PEDs. Notable examples include among others:

- SAREF4CITY: Focuses on city-level concepts.
- SAREF4SYST: Models system behaviours and interconnections.
- GeoSPARQL: Used for representing geospatial information.
- OWL-Time: Captures temporal information and events.

A prominent example of ontology integration is the BIGG Ontology (https://github.com/BeeGroup-cimne/big-gontology). It harmonises several domain-specific ontologies to enable unified semantic representation for smart cities and energy systems. This integrated model supports:

- Semantic mapping of data from building information models (BIM).
- Linking temporal and spatial data for energy simulation.
- Unified querying of heterogeneous datasets.

Such frameworks are particularly well-suited to the multi-domain, multi-scale nature of PEDs.

By adopting an ontology-based approach, a coherent and extensible data model for PEDs can be developed. The process typically follows these steps:

1. Ontology Selection and Integration: Select relevant ontologies and integrate them into a coherent framework tailored for PEDs.
2. Data Mapping: Align existing datasets and tool outputs with the ontology concepts and properties.
3. Model Generation: Generate a semantically rich data model that adheres to the ontology structure.
4. Data Integration: Import data into the model, ensuring consistency and enabling cross-tool analytics.

This method ensures that all incoming and outgoing data conforms to a shared vocabulary and structure, facilitating interoperability and system-wide understanding.

However, not all tools natively support or align with existing ontologies. In such cases, two harmonisation strategies are necessary:

- Tool-to-Ontology Mapping: Define a transformation layer that maps the tool's internal data schema to the ontology. This allows data to be extracted and used within the common semantic model.
- Ontology-to-Tool Mapping: In cases where the goal is to inject already-modeled data into a legacy tool, a reverse transformation is required. This maps the ontological model to the tool’s expected data format.

These harmonisation processes ensure bi-directional interoperability, enabling both data extraction and injection across systems.

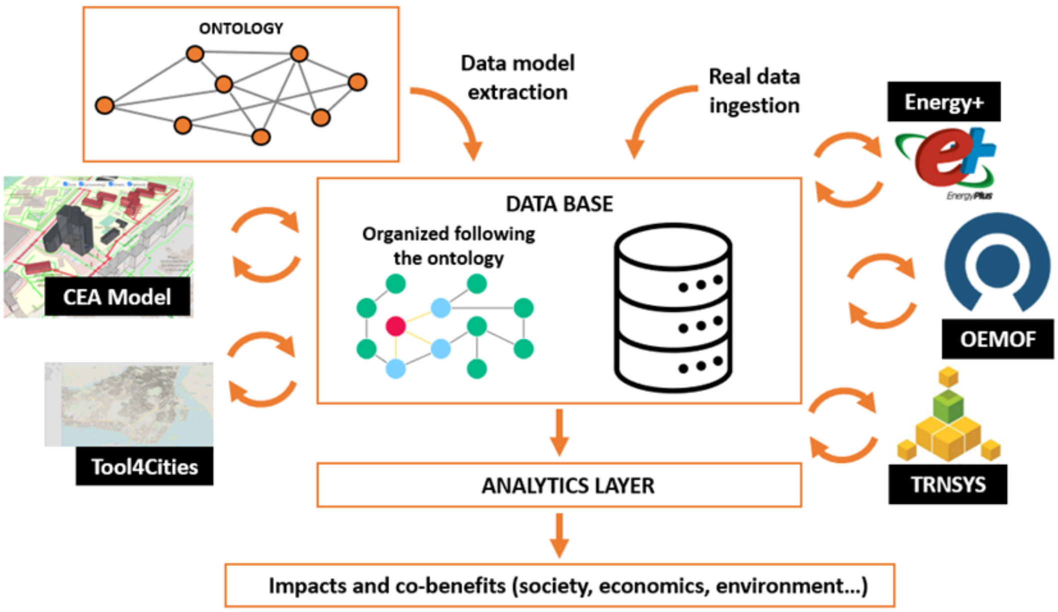


Figure 34: Schema of ontology use in the PED context integrating data from different systems to assess PED KPIs.

Ontology-driven integration offers two key advantages in the evaluation of Positive Energy Districts (PEDs). First, it supports multiscale simulation by enabling different aspects of a PED—such as building energy consumption, urban mobility, and climate impacts—to be analysed using specialised tools that can interoperate without requiring extensive redesign. Second, it promotes the reuse of existing data by facilitating the extraction and integration of information already collected and structured within various tools. This not only minimises redundancy but also streamlines and accelerates the overall PED assessment process.

In conclusion, ontologies provide a robust, flexible, and scalable framework for overcoming the challenges of data integration and interoperability in Positive Energy Districts (PEDs). By establishing a shared semantic foundation across diverse systems and datasets, ontologies enable comprehensive analysis, seamless simulation, and effective optimisation of PEDs. Adopting ontology-based models in future initiatives will be essential for achieving sustainable, interoperable, and data-driven urban energy planning.

Conclusions

This study starts with subtask B1, with an integrated analysis based on systematic and grey literature reviews, as well as a diverse set of case study interviews. The findings reveal that it is premature to identify conclusive patterns linking specific technologies to climatic zones or barriers. However, some indicative trends emerge. Central and Northern European climates tend to exhibit a greater diversity of applied technologies—ranging from microgrids and district heating networks (DHNs) to energy flexibility measures and green mobility solutions. Conversely, Mediterranean regions appear to adopt a narrower range of technologies, focusing primarily on electrification, solar PV, and battery storage. Case-specific observations further underscore climate- and context-dependent decisions. In Singapore, the emphasis is on passive strategies and energy minimisation, while energy circularity focuses on systems like rainwater harvesting. In temperate oceanic climates (Cfb), as seen in Amsterdam, the integration of thermal storage, battery systems, and flexibility measures is more pronounced, especially due to grid congestion. The Dfb climate regions show extensive use of heating and storage technologies, including seasonal thermal storage and geothermal systems. Barriers identified across case studies are multifaceted. Regulatory hurdles are frequent, such as heritage restrictions in Évora or net metering limitations. Ownership structures, particularly in collectively owned RES, add layers of complexity in governance and decision-making. Infrastructure limitations, whether related to grid capacity, spatial constraints, or outdated systems, were consistent across cases like Åland, Amsterdam, and Trondheim. Funding emerges as both an enabler (e.g., Singapore, Okotoks) and a barrier, especially when public incentives are lacking or fragmented. The lack of public awareness and technical capacity, particularly among citizens and skilled labor—further complicates PED implementation. In some cases, such as Amsterdam, this has direct consequences on energy peak management and user engagement. Despite these advancements, limitations remain. The sample size across climate zones and density types is uneven, potentially skewing interpretation. Further, the technical capacities of deployed technologies were not always disclosed. Thus, future work should expand the scope and depth of case studies using structured, harmonised data frameworks. Particular attention should be paid to transport, waste, and outdoor public space integration, which are currently underrepresented.

Achieving climate neutrality through Positive Energy Districts (PEDs) necessitates a holistic, systemic approach. Stakeholder alignment and cross-sectoral collaboration are critical. Multi-stakeholder forums, such as those implemented in Amsterdam, can help bridge the gap between research, policy, markets, and communities. Citizen engagement must go beyond awareness campaigns, integrating participatory and co-creation strategies to foster behavioural change and long-term involvement. The Évora case demonstrates the effectiveness of such participatory approaches for building trust and social acceptance.

The absence of adaptive regulatory frameworks continues to impede the deployment of novel technologies like peer-to-peer trading or high-capacity energy storage. Urban sandboxes could serve as transitional mechanisms, allowing cities to test regulatory innovations in controlled environments. Financially, PEDs require high upfront capital. The experiences of most cases confirm the necessity of diversified funding streams, including EU support and national incentives. For instance, incentives for collective self-consumption - such as Italy's feed-in tariffs or Spain's tax rebates - have proven effective in initiating household-scale PV deployment.

Technical training is another key enabler. Okotoks highlighted the limited acceptance of radiant heating in North America due to unfamiliarity, leading to design compromises. In Amsterdam, information technologies and grid constraints are critical bottlenecks for implementing advanced energy management and storage solutions. Despite technical feasibility, economic viability is compromised when systems fail to qualify for frequency regulation, as observed in Amsterdam's exclusion of innovative energy storage systems from frequency containment reserve schemes.

In task B2, it has been seen that integration of flexible assets supports grid stability, reduces external energy dependency, and enhances profitability when managed effectively, particularly under variable energy pricing and incentive structures. Smart Building Management Systems (BMS) and advanced control strategies like Model Predictive Control (MPC) are fundamental for managing energy in PEDs. These systems use real-time data, forecasts, and algorithms to optimise energy flows across buildings, storage units, and generation assets. Standards like EN15232 and tools like IBACSA provide frameworks for evaluating and improving building automation systems, with a focus on energy efficiency, flexibility, and occupant comfort. When combined, BMS, MPC, and energy-aware automation enable dynamic, responsive, and optimised energy operations within PEDs, promoting decarbonisation and urban sustainability. Real-world applications in projects like SPARCS (Espoo), MAKING-CITY (Groningen, Oulu), and Amsterdam demonstrate MPC's value in optimising district heating and cooling, V2G operations, and shared mobility services, often leveraging digital twins and virtual power plants to unlock flexibility and support scalable, smart urban energy systems.

In task B3, different modelling methods and tools have been checked. The assessment of existing modelling tools for Positive Energy Districts (PEDs) reveals several persistent limitations and challenges across different domains. Data acquisition and integration remain central obstacles. Accurate datasets are difficult to collect and often require time-intensive processes. While using standard datasets may speed up model preparation, it significantly increases uncertainty. Moreover, issues related to data ownership, sharing protocols, and data protection further complicate the modelling process.

Many tools do not natively integrate meteorological data or rely on external weather files, limiting the representation of micro-climate conditions and reducing compatibility with diverse climate datasets. Current tools often oversimplify building geometries (typically using LOD1), which undermines simulation accuracy. Furthermore, reading building-specific attributes—such as floor differentiation, orientation, and distinguishing between buildings and non-building structures—remains problematic. The modelling of HVAC systems, renewable energy technologies, and multi-supply configurations is frequently constrained. Most tools rely on default parameters (e.g. capacity, efficiency), though high-fidelity modelling necessitates detailed, technology-specific input (as seen in tools like TRNSYS). Several tools default to assuming that all interior spaces are fully conditioned, leading to overestimations of energy demand unless manual corrections are applied. Many tools lack user-friendly interfaces and require significant expertise in energy systems. Balancing model complexity and cost-effectiveness is essential, particularly for practical applications. High-resolution simulations (temporal or spatial) are computationally demanding. Consequently, simplifications are often applied, reducing model accuracy. This includes assumptions in time granularity and the technical behaviour of systems.

Current tools offer limited integration between geospatial data and energy simulation engines, frequently requiring custom scripts or manual processes to ensure interoperability. Despite these limitations, advanced simulation environments such as Hub, CityEnergyAnalyst, EnergyPlus and TRNSYS provide strong capabilities but are built upon legacy architectures. Recent advances in parametric modelling, co-simulation frameworks, and uncertainty analysis aim to improve flexibility, efficiency, and accuracy in PED modelling. To model PEDs effectively, several core components must (hourly, monthly, or yearly dictated by the modelling objective e.g. planning, design, or policy analysis) and the objective function and balance. PEDs must demonstrate a net-positive renewable energy balance. Evaluation approaches may be mono-criteria (energy-only) or multi-criteria, incorporating economic, environmental, and social metrics.

Regarding the use of these elements, it has been seen that the implementation, modelling and evaluation of PEDs require vast amounts of heterogeneous data. To manage this complexity, data harmonisation through ontologies is helpful and it could lead to standardising different ways of assessing PEDs and reutilising data pipelines. The ontology-driven process adopted in subtask B allows for structured data integration, enabling inference, automatic classification, and scalable analysis. Data from various sources is mapped to a shared semantic framework and stored in graph and non-structurated databases. This facilitates the assessment of results with tools such as Hub or CEA and standardises outcome evaluation through harmonised pipelines.

As lessons learnt, the authors conclude that:

- PED boundaries need to extend beyond physical space to include virtual or contractual exchanges.
- Although most tools are designed to be replicable, their effectiveness is hindered by the availability and quality of local data.
- Building archetypes and system configurations are highly context-dependent, as are economic assumptions and control strategies.
- PV is ubiquitous in PEDs but insufficient alone to ensure energy positivity.
- Heating and cooling decarbonisation remains a bottleneck. While heat pumps are gaining ground, alternatives (e.g., co-generation with biofuels) are underrepresented.
- There is a lack of real-world demonstrators that move beyond PV-dominant solutions, particularly in showcasing centralised vs. decentralised systems.
- The integration of smart control strategies in complex energy systems is limited. Ontology-based approaches show promise for standardising and accelerating the deployment of intelligent controls.

Several critical areas require additional research and development:

- *What cost structures and financing schemes best support PED implementation at scale?*

    - A clearer understanding of investment schemes, subsidies, and incentives is needed to accelerate PED deployment.
- *Can harmonised hourly datasets enable cross-comparisons between PEDs under similar climatic and urban conditions?*
    - The collection and use of harmonised, hourly-resolution datasets would enable better comparability across case studies and improve modelling robustness. Developing shared metrics and rating systems for PEDs—akin to energy performance certificates but at the district scale—would improve transparency and replicability.
- *Are existing incentive structures for energy communities sufficient to foster full PED development?*
    - The effectiveness of energy sharing schemes (e.g. in Italy, Spain) must be systematically assessed to understand their impact on PED viability.
- *How can seasonal mismatches in renewable generation be addressed under high-renewable scenarios?*
    - Electrification and high renewable scenarios can often cause peaks and fluctuations in the power grid. The role of short, long-term storage, demand management, etc. needs to be studied further
- *What grid-side solutions (e.g., flexibility, storage, demand response) can mitigate the impact of electrification on network infrastructure?*
    - Strategies to address seasonal generation mismatches and mitigate grid congestion under high-renewable scenarios need further exploration.
- *How can mobility be accurately modeled within PED energy balances?*
    - More robust methodologies are needed to integrate electric mobility into PED calculations, including data on usage profiles, charging patterns, and system impacts.
- *Which control standards and automation protocols can streamline smart building integration and system interoperability?*
    - Research into standards and frameworks for reducing complexity in building automation and smart control systems is essential to scale up intelligent energy management.

These questions will be central to the next stages of the research on PEDs. More pilot projects with open data are urgently needed, especially those that move beyond PV-centric approaches, to demonstrate the value of centralised and integrated district-level solutions. Moreover, the role of ontologies in structuring smart control and facilitating scalability of digital solutions must be further explored to avoid fragmented, ad hoc implementations.

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Definitions

Definitions of energy performance according to EN 15603:2008 (Official Journal of the EU, 19.4. 2012, p. C 115/9):

Energy source: source from which useful energy can be extracted or recovered either directly or by means of a conversion or transformation process.

Energy carrier: substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes.

Energy system: A complex and interconnected arrangement of technologies, infrastructures, and processes that generate, convert, store, distribute, and consume energy to meet human needs.

District Heating Network: A centralised infrastructure for supplying thermal energy (heat) to multiple buildings from one or more heat generation sources.

Energy Community: A local collective of energy users and/or producers who manage their energy generation, storage, and consumption collaboratively.

Modelling: a mathematical or data-driven abstraction that computationally allows to simulate the behaviour of an energy asset a building or an energy system.

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