ANNEX **83**

EBC

Energy in Building and
Communities Programme

International Energy Agency

# Deliverable 1 - Framework of Definitions and Key Concepts on Positive Energy Districts

## Positive Energy Districts (Annex 83)

**Energy in Buildings and Communities Technology Collaboration Programme**

June 2026

Technology Collaboration Programme
by iea

ANNEX 83

EBC
Energy in Building and Communities Programme

International Energy Agency

# Deliverable 1 - Framework of Definitions and Key Concepts on Positive Energy Districts

## Positive Energy Districts (Annex 83)

## Energy in Buildings and Communities Technology Collaboration Programme

June 2026

## Authors

Vicky Albert-Seifried, Fraunhofer Institute for Solar Energy Systems, Germany
(vicky.bo.ki.albert-seifried@ise.fraunhofer.de)
Caroline Yeng-Ting Cheng, SINTEF Community Architecture, Materials and Structures, Norway
(caroline.cheng@sintef.no)
Xingxing Zhang, Dalarna University, Sweden
(xza@du.se)

## Contributing Authors

Mengjie Han, Dalarna University, Sweden (mea@du.se)
Juveria Shah, Dalarna University, Sweden (juh@du.se)
Helin Ulgen Elmacioglu, Fraunhofer Institute for Solar Energy Systems, Germany (helinulgen@gmail.com)

All other participants in subtask A are fully acknowledged for their contribution directly and indirectly to this report.

Participating countries in the EBC TCP: Australia, Austria, Belgium, Brazil, Canada, P.R. China, Czech Republic, Denmark, Finland, France, Germany, Ireland, Italy, Japan, Republic of Korea, the Netherlands, New Zealand, Norway, Portugal, Singapore, Spain, Sweden, Switzerland, Turkey, United Kingdom and the United States of America.

Additional copies of this report may be obtained from: EBC Executive Committee Support Services Unit (ESSU), c/o INIVE vzw – International Network for Information on Ventilation and Energy Performance, Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium).

www.iea-ebc.org
essu@iea-ebc.org

# 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 - Building Energy Codes

# Summary

This report presents a comprehensive framework for defining and assessing Positive Energy Districts (PEDs) as a transformative approach to urban energy systems aimed at achieving climate neutrality. PEDs are urban areas that generate more renewable energy than they consume annually, contributing positively to both their local environments and the broader energy grid. The concept, which was endorsed by the European Commission through SET-Plan Action 3.2, has been promoted through numerous European initiatives and projects, such as the Smart Cities and Communities projects funded by Horizon 2020. The lack of a common PED definition across these initiatives has led to varied interpretations, each emphasising different aspects like geographical boundaries, energy balance, and socio-economic integration. By reviewing existing definitions and analysing their similarities and differences, the report proposes a more inclusive and flexible framework, emphasising the positive impact of PEDs beyond just energy surplus, incorporating aspects like governance, community involvement, and environmental benefits.

Furthermore, the report delves into the methodologies used to assess PEDs, focusing on energy balance calculations and key performance indicators (KPIs). Various projects utilise different methods, with some emphasising annual energy exports over imports, while others consider hourly data and broader sustainability indicators. Case studies from selected projects highlight the practical challenges and benefits of these assessment approaches. The report underscores that a rigid focus on positive energy balance may exclude districts with limited renewable resources, advocating instead for flexible and context-sensitive assessments. By synthesising data from a large number of PED-related projects across Europe, the report identifies common characteristics, challenges, and best practices, particularly concerning energy technologies. Ultimately, it presents a set of PED archetypes that balances technical rigor with adaptability to diverse urban contexts and climatic conditions.

The discourse on PED has shifted the last years. The meaning of “positive” has been reinterpreted from a narrow definition of a positive energy balance to a broader sense of driving positive urban changes concerned with a positive development in the quality of life for the people living in a PED. The evolution of the PED concept also necessitates an update of our thinking about the process flow of PED development, how we address the shifting constellation of PED stakeholders to drive PED development as well as PED-related regulations and legal barriers.

Given its complexity and its intersection among sectors such as construction, energy, real estate, and the built environment in general, the phases of PED development and the levels of granularity are not universal. Phases of PED development would be dependent on whether the PED project is a new build or a refurbishment/ retrofit, the building scale vs. district scale infrastructures, and further juxtaposed against the local social, economic, regulatory aspects. The process flow of PED development calls for a balanced approach that integrates elements of both rational and incremental planning to navigate the complexities of a PED project.

It is useful to reimagine PED stakeholders **as interactive actors** since stakeholder roles shift during the PED process (design, build, own, operate and use). It is therefore helpful to map them not only according to the process, but also on the building, district and the city scale. This would facilitate keeping in view the diverse ambitions, agendas, interests and constraints of industry and contextual actors in order to work towards long-lasting commitment for collaboration and coordination in any PED development.

# Table of Contents

# 1. Introduction

## 1.1 General Context

Positive Energy Districts (PEDs) represent a transformative and systemic shift in urban energy systems, aimed at enabling climate-neutral cities through decentralised, renewable, and community-integrated energy solutions. Defined as urban areas that generate more renewable energy than they consume on an annual basis, PEDs offer a scalable and flexible pathway to decarbonisation. This report is deliverable of subtask A, which is part of the IEA-EBC Annex 83 initiative and serves as a deep exploration of the PED concept's evolution, current implementation challenges, and pathways forward.

PEDs function as integrated ecosystems—leveraging technologies such as solar photovoltaics, heat pumps, geothermal systems, district heating and cooling, and smart grids—to achieve high energy efficiency, storage capacity, and resilience. These systems are not only technical constructs but socio-technical configurations that require coordinated planning across stakeholders, sectors, and governance levels. Beyond achieving a net positive energy balance, modern PEDs aim to contribute more broadly to sustainable urban development, considering aspects such as quality of life, equity, mobility, and governance.

This report positions PEDs within this broadened context by drawing on data and experiences from over 60 PED-related initiatives across Europe, as well as analytical insights into their design, performance, and operationalisation. It acknowledges the limitations of a one-size-fits-all approach and emphasises the need for adaptable definitions, inclusive stakeholder processes, and assessment frameworks that are sensitive to local economic, climatic, social, and regulatory conditions.

## 1.2 Structure of the Report

To guide the reader through the multidimensional nature of PEDs, the report is organised as follows:

- **Chapter 2** traces the historical development of the PED concept, presenting a critical comparison of various definitions used by EU bodies and national programs. It identifies a lack of consensus and highlights the need for a harmonised yet adaptable definition framework.
- **Chapter 3** explores existing PED assessment methods by evaluating their applicability across different types and boundary definitions. The analysis reveals inconsistencies in current methodologies, especially regarding energy balance calculations and the integration of mobility and socio-economic indicators. Recommendations are offered for more inclusive and dynamic assessment practices.
- **Chapter 4** provides a detailed characterisation of PEDs based on case studies. It classifies projects according to climatic zones, technology mixes, financing models, and implementation barriers, ultimately proposing a set of PED archetypes, such as the Solar-Dominant, Hybrid, and Arctic Thermal Resilience models, which reflect Europe's climatic diversity and policy landscape.
- **Chapter 5** reframes the PED development process as a participatory and iterative journey. It emphasises the evolving roles of stakeholders and presents regulatory, technical, financial, and social challenges at different implementation stages. The discussion advocates for stakeholder mapping at multiple spatial scales and a shift from rigid planning models to adaptive, process-based approaches.
- **Chapter 6** concludes by reinforcing the notion that PEDs are not merely energy surplus zones but dynamic drivers of positive urban transformation. It underscores the need for flexible frameworks, cross-sector collaboration, and iterative learning to achieve equitable and resilient energy futures.

This introduction sets the stage for an in-depth investigation into how PEDs can be not only technically feasible but socially inclusive, economically viable, and environmentally just. The report aims to inform both policymakers and practitioners seeking to implement PEDs in diverse urban contexts, offering both conceptual clarity and practical tools for future action.

# 2. PED Concept and Definitions

## 2.1 Evolvement of the concept of PEDs

Positive Energy Districts (PEDs) are recognised as one of the central pillars for driving the urban energy transition in Europe. The concept of PEDs can be traced back to the concept of net-zero energy districts (NZEDs) that corresponds to the transformation at the neighbourhood level triggered by the implementation of the EU 2020 energy and climate targets. The concept marked a shift from individual buildings to the neighbourhood level as a way to scale up the efforts, derive synergy and cost efficiencies and speed up the pace of the global energy transformation [1]. Building on NZED, the Energy Efficient Building Committee of the European Construction, Built Environment and Energy Efficient Building Technology Platform (ECTP) designed the concept of Positive Energy Blocks (PEB) to stimulate the citywide energy transition in Europe [1]. The concept was strongly promoted by the European Innovation Partnership on Smart Cities and Communities (EIP-SCC), which established an initiative on PEBs in 2016. The main goal of the initiative was to facilitate the deployment of 100 PEBs throughout EU and neighbouring countries by 2020 [2].

A step up from PEBs came the concept of Positive Energy Districts (PEDs). The European Commission (EC) endorsed the SET Plan Action 3.2 "Smart Cities and Communities" in June 2018. The main objective of Action 3.2 is to develop integrated and innovative solutions for the planning, deployment, and replication of PEDs. According to the Action, 100 PEDs are expected to be in concrete planning, construction or operation, synergistically connected to the energy system in Europe by 2025 [3].

The concept of PEBs/PEDs is recognised by the EC under is research and innovation framework. Through pilot projects financed by the Horizon 2020, Horizon Europe and the Driving Urban Transitions Partnership (DUT) funding programmes, the EC supports a wide deployment of PEBs/PEDs. Since the implementation of the SET Plan Action 3.2, there has been a growing number of PED-oriented initiatives and projects at both the EU and national levels. However, there is not a common European definition of PEDs and as a result, different notions of PEDs are in use. Section 2 presents a review of PED definitions developed and used by a number of key initiatives and projects.

The Joint Programming Initiative Urban Europe (JPI UE) published a framework definition of PEDs in 2019. The framework seeks to create a joint vision on PEDs across Europe [3]. DUT has since updated the PED definition framework to make it more operable on the ground and the latest revision is known as "PED Definition Framework 3.0" (more information in Section 2). Despite being widely acknowledged by key stakeholders, there are still important questions concerning PED definitions that need to be further discussed in order to make the concept more workable and appealing to urban practitioners.

Within the IEA Annex 83, a common PED definition for the Annex was established in the 8th Working Meeting on 27 February 2024 in Pamplona, Spain. More information about the Annex 83 PED definition is presented in Section 2.

## 2.2 Existing PED-related initiatives/projects and their PED definitions

### 2.2.1 PED Definitions Used by EU Organisations and Programmes

At the European level, there are several major organisations, initiatives or programmes, which have a stake in driving the deployment of PEDs. They are (i) the SET-Plan Action 3.2, (ii) the Horizon Framework Programmes, (iii) EC Joint Research Centre, (iv) JPI Urban Europe, (v) Driving Urban Transitions Partnership, (vi) European Energy Research Alliance (EERA), (vii) COST Action Positive Energy Districts European Network and (viii) International Energy Agency Annex 83 Positive Energy Districts. The PED definitions developed by them are widely adopted and are presented as follows.

**SET-Plan Action 3.2**. The SET-Plan defined PED as "a district with annual net zero energy import, and net zero $CO_2$ emissions working towards an annual local surplus production of renewable energy". They are expected to be implemented in newly built, retrofitted or mixed districts. According to the SET-Plan, PEDs should be driven by renewable energy and be an integral part of the urban and regional energy system. They should be based on high energy efficiency and make optimal use of technologies to reduce energy use and greenhouse gas (GHG) emissions. Besides the energy aspect, PEDs should offer affordable living for the inhabitants [3].

**Horizon Framework Programmes**. The concept of PEDs was first included in the Horizon 2020 proposal call for the Smart Cities and Communities lighthouse projects and in there, “Positive Energy Blocks/Districts consist of several buildings (new, retro- fitted or a combination of both) that actively manage their energy consumption and the energy flow between them and the wider energy system. Positive Energy Blocks/Districts have an annual positive energy balance. They make optimal use of elements such as advanced materials (e.g. bio-based materials), local RES, local storage, smart energy grids, demand-response, cutting edge energy management (electricity, heating and cooling), user interaction/involvement and information and communications technology (ICT). Positive Energy Blocks/Districts are designed to be integral part of the district/city energy system and have a positive impact on it (also from the circular economy point of view). Their design is intrinsically scalable, and they are well embedded in the spatial, economic, technical, environmental and social context of the project site” [4].The PED development was continuously supported by the subsequent Horizon Europe programme, in which the term “Positive Clean Energy Districts” was introduced and used alongside PEDs. The two terms are used interchangeably in the calls within the framework programme.

**EC Joint Research Centre (JRC)**. PED is considered as an area with defined borders that has an overall positive energy balance over a year. It has buildings with a near zero or very low energy demand owing to their very high energy performance complying with applicable minimum energy performance requirements and local building codes. The building demand is covered to a very significant extent, or more, by renewable energy sources produced on-site or nearby. The primary purpose of a PED is to provide environmental, economic or social community benefits based on open and voluntary participation. A PED is autonomous and is effectively controlled by its citizens [5].

**JPI Urban Europe (JPI UE)**. The reference framework definition for PEDs developed by JPI UE states that “Positive Energy Districts are energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero GHG emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility and ICT systems, while securing the energy supply and a good life for all in line with social, economic and environ- mental sustainability”. Each PED is expected to find its own optimal balance between energy efficiency, energy flexibility and local/regional energy production on its way towards climate neutrality and energy surplus. While the resilience and security of energy supply are important guiding principles, the development of PEDs should also respect sustainability and inclusiveness and, in more general terms, enhance the quality of life [6].

**EERA Joint Programme Smart Cities (EERA JPSC)**. According to EERA JPSC, PEDs are “mixed-use energy-efficient districts that have net zero $CO_2$ emissions and actively manage an annual local surplus production of renewable energy. They require interaction and integration between buildings, the users and the regional energy, mobility and ICT system, while ensuring social, economic and environmental sustainability for current and future generations” [7].
Beyond the definition, different types and boundary definitions for PEDs were proposed. At the PED Definition Workshop organised by the EERA Joint Program Smart Cities and involved participants from +CityxChange partners as well as members from other projects and representatives from institutions, three different boundary approaches have been introduced [8].

- **Geographical boundary:** The spatial and physical limits of the PED, encompassing the district's buildings, sites, and infrastructure. These boundaries may be contiguous or composed of detached areas.
- **Functional boundary:** The energy grids that serve the PED, such as:
  - An electricity grid behind a substation functioning as an independent entity for the PED.
  - A district heating system that serves the PED, even if its service area extends beyond the district.
  - A gas network with similar functionality.
- **Virtual boundary:** Contractual limits of the PED, including energy production infrastructure owned by the district's occupants but located outside the geographical boundaries, such as an offshore wind turbine owned through shares by the PED community.

Addition to these boundaries, EERA introduced different PED types [7]. The purpose is to allow for system flexibility and better optimisation of PEDs. The four PED types proposed are as follows:

- **PED-autonomous**: Net positive yearly energy balance within the geographical boundaries of the PED and internal energy balance at any moment in time (no imports from the hinterland) or even helping to balance the wider grid outside.
- **PED-dynamic**: Net positive yearly energy balance within the geographical boundaries of the PED but dynamic exchanges with the hinterland to compensate for momentary surpluses and shortages.
- **PED-virtual**: net positive yearly energy balance within the virtual boundaries of the PED but dynamic exchanges with the hinterland to compensate for momentary surpluses and shortages.
- **Pre-PED:** no net positive yearly energy balance within the geographical boundaries of the PED but energy difference acquired on the market by importing certified green energy (i.e. realising a zero-carbon district).

Within the boundaries of each PED type, a wide range of energy-related components are taken into accounted including energy efficiency measures, renewables (solar, PV, wind, biomass, geothermal, small hydropower), waste heat recovery, electric and thermal storage, mobility energy needs (and EVs as batteries), sector coupling between electric and thermal. These boundaries and types allow PEDs to be adapted to different urban contexts and energy infrastructures, offering a flexible approach to energy management at the district level while also distinguishing them.

**Driving Urban Transitions Partnership (DUT)**. Building on the reference framework developed by JPI UE, the subsequent PED Reference Framework 2.0 published in 2019 as well as considering the challenges in operationalise the PED concept on the ground based on feedback from urban practitioners, DUT simplified the PED definition to make it more operable in practice. The DUT PED Definition Framework 3.0 states that "Positive Energy Districts (PEDs) are energy efficient and energy flexible urban neighbourhoods or areas of connected buildings and facilities, that produce local renewable energy, achieve net zero greenhouse gas emissions, and actively contribute to overall climate neutrality. Core aspects are renewable energy production, affordability, and financial sustainability, enabling PEDs to unlock their full potential as drivers of systemic transformation. By integrating diverse systems and infrastructures such as energy, mobility, and ICT and fostering interactions between buildings, users, and regional networks, PEDs align with a clear mission toward sustainability. Through engagement at all levels of governance, the empowerment of local energy communities, and alignment of initiatives, PEDs secure energy supply and a good life for all in line with social, economic, and environmental sustainability" [9].

**COST Action Positive Energy Districts European Network (PED-EU-NET)**. PED-EU-NET largely adopted the reference definition framework developed by JPI UE but with some modifications to make the concept more inclusive. The PED-EU-NET definition considers the requirement of an annual positive energy balance as optional provided that most of the other requirements in the JPI UE reference framework are respected. This definition is applied in the data collection of the PED Database (https://pedeu.net/map/) – an inventory jointly developed by PED-EU-NET, DUT and IEA Annex 83 that attempts to capture all existing PED cases across Europe [10].

**International Energy Agency (IEA) Annex 83.** IEA Annex 83 adapted the PED definitions from SET-Plan Action 3.2 and EERA JPSC but with stronger emphasis on energy efficiency and the use of local renewable resources. It states that "Positive Energy Districts are energy-efficient districts with net zero greenhouse gas emissions and an annual positive energy balance. They prioritise the use of local renewable energy and resources. They seek to optimise the interaction and integration between buildings, the users, mobility, energy and ICT systems. Positive Energy Districts strive to bring positive impacts to the wider energy system as well as social, economic and environmental benefits to the communities. The assessment of the annual energy balance is open to any methods that are well defined and grounded on sound principles." [11].The IEA Annex 83 definition highlights especially the expectation of PEDs in bringing positive impacts to the wider energy system in addition to other social, economic, and environmental benefits, which is a crucial aspect that has arisen during the course of the PED transition in the last few years.

While the PED concept has emerged from Europe, the initiation of IEA Annex 83 demonstrated a spread of the discussion to the global stage. This international collaboration signals a growing interest beyond Europe in adapting energy-positive neighbourhood models to different contexts and climates. Nevertheless, it is important to note that similar concepts already exist globally, although often framed under different terminologies. In countries such as the United States, Canada, Australia, Japan, terms like Net Zero Energy Communities, Zero Carbon Districts and Buildings, Carbon Positive Neighbourhoods, and Sustainable Smart Cities are commonly used. These concepts share the main objective of PEDs, such as producing a surplus of renewable energy at the district level, improving energy efficiency and reducing greenhouse gas emissions. Despite the similarities, there are notable differences. The European PED approach is generally more formalised and holistic, combining energy efficiency, renewable energy production, storage, flexibility, citizen engagement, and alignment with long-term climate neutrality targets. In contrast, international approaches often focus more on technological solutions and achieving net-zero targets at the building or precinct level, with less emphasis on integrated governance models or community co-creation processes. Furthermore, while PED development in Europe is strongly supported by public funding and policy-driven frameworks, similar projects outside Europe are more commonly driven by private initiatives, local governments, or specific climate strategies, without a common theme alike PED concept used in Europe. This highlights that, while the objectives are largely shared globally, the methods, frameworks, and levels of integration differ significantly. Understanding these differences is essential for knowledge exchange and the future scaling of energy-positive neighbourhood models worldwide.

### 2.2.2 PED Definitions used in Relevant Projects of National Programmes

There has been a booming of PED projects in recent years, and each project interprets the concept of PEDs in its own way. As a result, there exists multitude of PED definitions. This section reviews the PED definitions used in fourteen prominent projects in the landscape of PEDs.

**Project 'ATELIER'**. ATELIER aims to create and replicate community-driven PEDs in two lighthouse cities (Amsterdam and Bilbao) and six fellow cities to save $CO_2$ emissions and to demonstrate that integrated smart urban solutions support the deployment of PEDs. According to the project, PED is defined as a district that produces more renewable energy than it consumes on an annual basis. In addition to renewable energy production, the PED concept also considers energy efficiency and flexibility, energy autonomy and zero direct emissions of non-biogenic $CO_2$. The PED demonstrations are composed of areas connected geographically as well as virtually through smart grids. The project developed a framework for the monitoring and evaluation of PEDs based on a set of Key Performance Indicators (KPIs) covering energy, environment, economy, electro-mobility, citizen engagement and governance. Besides, environmental impacts are evaluated from the life cycle perspective including the consumption of products and services within the PEDs [12].

**Project '+CityxChange'**.+CityxChange (Positive City Exchange) defines PEDs as urban areas composed of new and existing buildings, along with their surrounding neighbourhoods, that generate local renewable energy while actively managing consumption and energy flows to the wider grid [13]. A PED maintains a positive annual energy balance, allowing the surplus to be shared with the surrounding city. This is achieved through increased energy efficiency, reduced demand, and the integration of local renewable city sources. The project aims to develop, deploy and scale up PEBs and PEDs in two lighthouse cities (Limerick and Trondheim) and five fellow cities to support the European Clean Energy Transition. The project not only focuses on the technical solutions around PEBs/PEDs but also the interaction between buildings, users, cities, the wider energy system, as well as the implications on city planning, digitalisation, citizen involvement, regulations, socio-economic issues and so on. According to the project, PEB is defined as a compact area comprising at least three mixed use buildings (>15,000 m2), which produces more energy than it consumes over a year by including local renewable energy production and measures to reduce energy demand [13].

**Project 'MAKING-CITY'**. MAKING-CITY aims to develop new integrated strategies to address the low-carbon urban energy transformation through large-scale demonstrations in two lighthouse cities (Groningen and Oulu) and six fellow cities. The project seeks to establish evidence on using the PED concept as a foundation to progress towards sustainable urban transformation. The project defines PED as an urban area with clear boundaries comprising buildings of different typologies that actively manage the energy flow among them, as well as the larger energy system to reach an annual positive energy balance [14]. The PED concept used in the project includes positive energy buildings, on-site renewable energy systems, energy sharing, flexibility and optimisation and smart control. The project developed guidelines for PED design, guidelines to calculate the annual primary energy balance and a GIS-based methodology for identification of PED concept boundaries in cities.

**Project 'POCITYF'**. POCITYF aims to implement and demonstrate innovative solutions at the building and district level that enable the increase of energy self-consumption, energy savings and locally produced renewable energy. The project adopted the PED definition from the Horizon 2020 Framework Programme. The PED concept is achieved through measures such as building integrated photovoltaics, P2P energy markets, storage solutions, integrated electro-mobility, integrated ICT solutions, active citizen engagement. The project facilitates the development of PEDs in mixed use urban districts with a focus on cultural heritage areas. Two lighthouse cities (Alkmar and Évora) serve as large-scale demonstrations of the proposed solutions and six fellow cities support the replication.

**Project 'SPARCS'**. SPARCS aims to create a network of sustainable energy positive and zero carbon communities in two lighthouse cities (Espoo and Leipzig) and five fellow cities. SPARCS largely adopted the PED definition framework developed by EERA JPSC with three types of PEDs, namely, PED-autonomous, PED-dynamic and PED-virtual. Both PED-autonomous and PED-dynamic have clearly defined geographical boundaries. PED-autonomous is completely self-sufficient with energy demand covered by onsite renewable sources. PED dynamic allows the import of external energy insofar as the annual energy balance is positive. PED-virtual operates within virtual boundaries, which allows the use of renewable energy sources or energy storage outside the geographical boundaries. However, renewable energy generation or energy storage that locate outside must be an asset of the district.

**Project 'syn.ikia'**. syn.ikia puts forth the concept of Sustainable Plus Energy Neighbourhood (SPEN) that strongly aligned with the broad concept of PEDs. SPEN is defined as a group of interconnected buildings with associated infrastructure, located within both a confined geographical area and a virtual boundary [15]. It aims to achieve more than 100% energy savings, 90% renewable energy generation triggered, 100% GHG emission reduction, and 10% life cycle costs reduction, compared to the level of 2020 nearly zero-energy buildings (nZEBs). Additionally, a SPEN covers five main objectives including (i) net-zero GHG emissions, (ii) active management of energy surplus, (iii) cost efficiency and economic sustainability, (iv) improved indoor environment, and (v) social inclusiveness and affordable living. The project developed a methodological framework for the evaluation of SPEN including the assessment of the positive energy balance. syn.ikia aims to increase the share of SPENs with surplus renewable energy in different contexts, climates and markets in Europe.

**Project 'Zukunftsquartier—Vienna'**. The Project 'Zukunftsquartier' (translated as 'Future Neighbourhood') explores the feasibility of applying the plus energy neighbourhood concept in four project sites in Vienna. The project aims to develop a scientifically sound and practical definition that can be used to assess and certify PEDs as a cornerstone to support the national climate neutral target [16]. The PED concept focuses on 100% renewable energy supply. In addition to energy, economic feasibility and other sustainability requirements are considered. Based on the setup of system boundaries, the project proposes three types of PEDs:
•**PED Alpha**: a district that reaches a positive annual primary energy balance based on all energy services (operational energy and user electricity) and monthly conversion factors. A credit or discount based on structural density is applied.
•**A PED Beta:** meets the above criteria with the inclusion of private everyday mobility and a per capita RES credit for surpluses of the energy system by large RES power plants.
•**A PED Omega**: covers all the above energy services as well as the embodied energy for structure, building and mobility. On the basis of hourly conversion factors, the PED achieves a global warming potential below 500 kg/cap/annum. The definition can be extended to include emissions from individual consumption as a way to connect to individual carbon budgets.

**Project 'PHVision—Heidelberg'**. The City of Heidelberg in Germany envisions to transform the Patrick-Henry-Village into a PED with mixed living and working space for around 15,000 people [17]. The project defines PED as a district that produces more renewable energy than it consumes on an annual basis. The proposed PED is composed of a clearly defined geographical area and virtual system boundary that allows dynamic energy exchanges with the wider region. The project developed a method for calculating the energy balance including space heating, cooling, domestic hot water and electricity use in buildings as well as energy use in transportation. Concerning transportation, local public transport, private and business mobility are assumed to be entirely electric in the project and included in the energy balance calculation. In addition, the embodied energy related to the construction and renovation of buildings is considered. The project also devised a method for estimating the district's share in the total renewable energy potential of the region, which serves as a cap for potential green energy import.

**ZEN Centre**. The Research Centre on Zero Emission Neighbourhoods (ZEN) in Smart Cities is a Norwegian research centre. ZEN combines the concept of PEDs with climate neutrality. It aims to reduce its direct and indirect GHG emissions towards zero over its lifetime. The ZEN Centre developed a definition of ZENs and KPIs to assess them. A neighbourhood is defined as a group of interconnected buildings with associated infrastructure located within a confined geographical area. However, the system boundary for analysis of energy facilities serving the neighbourhood can include infrastructure for exchange, generation and storage of electricity and heat outside of the geographical boundary. The total GHG emissions are accounted based on a life-cycle assessment in all phases of the neighbourhood development including planning, implementation, operation and demolition. ZENs compensate the emissions through onsite renewable energy production during the operation phase and achieve a positive energy balance on a yearly basis. In addition to GHG emissions, other KPIs include energy, load, mobility, economy, spatial qualities and innovation. The definition and KPIs are tested in nine neighbourhood-scale demonstration sites in Norway [18, 19].

**Project 'NEUTRALPATH'.** NEUTRALPATH defines Positive and Clean Energy Districts (PCEDs) as urban areas made up of interconnected buildings that are both energy-efficient and flexible in their energy use.

These districts are considered “clean” because they rely entirely on renewable energy sources and “positive” because they not only achieve net-zero greenhouse gas emissions but also generate a surplus of renewable energy. The project adapts both geographical and virtual boundaries in PCEDs. To realise PCEDs, the project implements a range of actions at both the building and district scales, including energy-efficient façade design, energy system optimisation, renewable energy integration, grid management, e-mobility, and community engagement. The proven solutions at the district level are expected to be scaled up at the city level. Istanbul, Ghent, and Vantaa as fellow cities are working alongside Lighthouse Cities Zaragoza and Dresden. The collaboration aims to integrate the PCED concept into local decarbonisation strategies with a shared goal of achieving climate neutrality by 2050 [20].

**Project ‘ASCEND’**. ASCEND considers Positive Clean Energy Districts (PCEDs) as comprising of five key pillars: active citizenship, zero-carbon frugal buildings, smart energy grids, decarbonised public spaces and mobility, and digital tools. At the core of this approach is an urban orchestrator, a public entity that coordinates all components and services to ensure long-term transformation at the district level. To facilitate collaboration and implementation, ASCEND connects each pillar to the urban orchestrator through a digital platform and a human network that engages local stakeholders in the transition to clean energy [21].

**Project ‘HARMONISE’**. The HARMONISE project aims to transform traditional districts into PEDs. The project defines PEDs as urban areas with interconnected, energy-efficient buildings that achieve net-zero emissions and manage surplus renewable energy. It provides an interoperable, scalable solution for optimal PED design, management, and integration, using fog-enabled devices, blockchain-based transactive energy systems, and open-standard interfaces. By unifying energy transactions across electricity, heating, mobility, and storage networks, HARMONISE supports multi-sectoral PED expansion. The project will demonstrate its approach through four physical pilots and one digital pilot, integrating all components into a Supernova Grid to advance the European Super Grid transition [22].

**Project ‘PEDvolution’.** PEDvolution envisions them as dynamic, evolving urban ecosystems that not only produce at least as much energy as they consume annually but also continuously adapt to changing external conditions. Rather than static endpoints, PEDs dynamically interact with urban development, legislation, renewable energy integration, electric mobility, and fluctuating energy markets. This perspective aligns with an evolutionary approach, where PEDs develop and optimise their structures in response to their surroundings. The project aims to facilitate the cross-sectoral integration and continuous evolution of PEDs through the development and implementation of seven interoperable solutions, focusing on social, technological, interoperability, and market aspects [23].

**Project ‘InterPED’**. The InterPED project defines PEDs as interconnected urban areas that achieve net zero greenhouse gas emissions while actively managing renewable energy, storage, and waste heat to enhance efficiency and grid stability. InterPED’s approach focuses on sector coupling, cross-vector integration, and demand flexibility, ensuring PEDs make optimal use of local renewable energy sources, storage, and excess/waste heat. A key component of the project is its scalable, cloud-based platform, which provides analytical, modelling, and optimisation services for managing power, heating, cooling, and mobility systems within PEDs. Additionally, consumer engagement is central to InterPED’s strategy, with participatory co-design processes enabling service providers and residents to collaborate on energy solutions. By fostering community-driven demand response strategies and ensuring system interoperability, InterPED aims to create replicable and commercially viable PED solutions, which will be tested in four large-scale pilot sites [24].

**Project ‘ARV’.** ARV is a Horizon 2020 project that aims to accelerate the implementation of Climate Positive Circular Communities (CPCCs) across Europe by demonstrating attractive, resilient, and affordable solutions for deep energy renovation and sustainable urban transformation. A CPCC is defined as an urban area that aims to achieve net zero greenhouse gas emissions, enables energy flexibility, and fosters a circular economy alongside social sustainability. The CPCC concept emphasises the interaction and integration between new and regenerated buildings, users, and energy systems, supported by innovative ICT tools to deliver holistic and scalable solutions. ARV introduces a novel framework built on three conceptual pillars: integration, circularity, and simplicity. This framework couples stakeholders with energy systems, promoting resource efficiency through life cycle assessments and material banks, and ensuring solutions are accessible to all. The project includes six large-scale demonstration sites across different European climate zones, focusing primarily on the renovation of social housing and public buildings. Additionally, ARV is structured around nine thematic focus areas, including citizen engagement, smart renewable integration, flexible energy management, sustainable construction workflows, and innovative business models. The project aims to provide comprehensive guidelines and a policy framework to foster the widespread adoption of energy-efficient, circular, and digital practices in the European construction sector.

**Project 'oPEN Lab'.** oPEN Lab is a Horizon 2020 project that aims to transform existing neighbourhoods in Tartu (Estonia), Pamplona (Spain), and Genk (Belgium) into fully functional Positive Energy Neighbourhoods (PENs). The project defines a PEN as an energy-efficient and energy-flexible urban area or group of connected buildings that achieves net-zero greenhouse gas emissions while generating a local or regional surplus of renewable energy on an annual basis. oPEN Lab adopts a living lab approach, combining technological innovation, sustainable design tailored to local conditions, seamless industrial renovation workflows, and renewable energy integration with storage systems. A strong focus is placed on community involvement, with participatory processes guiding the development of each neighbourhood's vision. Beyond the demonstration sites, the project seeks to accelerate the scaling and replication of PEN solutions, supporting the objectives of the EU Renovation Wave and contributing to Europe's climate goals.

**Project 'PROBONO'.** PROBONO is a Horizon 2020 project aiming to drive the transition towards Green Building Neighbourhoods (GBNs) - urban districts composed of zero-carbon, energy-positive buildings integrated with green energy systems, sustainable mobility, and supportive infrastructure. A GBN, as defined by the project, is a delimited neighbourhood where green buildings are combined with energy flexibility, low-carbon mobility, and stakeholder-driven governance to maximise environmental, social, and economic co-benefits. PROBONO focuses on delivering validated solutions for the design, construction, and operation of zero-emission neighbourhoods, leveraging digitalisation, smart technologies, and participatory co-design processes. The project is implemented through six Living Labs across Europe, including two large-scale city-led demonstrators in Madrid and Dublin, and four business-driven sites in Porto, Brussels, Aarhus, and Prague. Together, they serve as real-world testbeds to demonstrate how technological and social innovations can accelerate the shift to sustainable urban districts. With a strong focus on replicability, PROBONO aims to reduce energy consumption, greenhouse gas emissions, air pollution, and embodied energy, while improving indoor environmental quality, reducing renovation costs and time, and fostering inclusive growth within communities.

## 2.3 Comparison and discussion of existing PED definitions

Table 1 extracts a set of key elements in the PED concepts and compares them across the twenty-two programmes and projects under study. Based on the comparison, similarities and differences between the existing definitions are identified. All programmes and projects, except DUT and PED-EU-NET, consider a positive annual energy balance as a criterion: 14 (out of 18) include net zero GHG emissions as an additional target. This reflects the alignment of the PED concept with the EU's mission on climate-neutral and smart cities and enables PEDs one of the transition pathways towards climate-neutrality in the long-term. In terms of the scale of development, the terminology used varies from 'several buildings' and 'groups of connected buildings' to 'district' and 'neighbourhood'. While this versatility highlights the broad applicability of the PED concept, it makes it hard to compare PEDs across different projects as the complexity, challenges and level of achievement often depend on the scale of development. The existing programmes and projects also apply different approaches in the selection of PED boundaries. While some based on rigid geographical boundaries, others adopt a more flexible approach that allows the import of renewable energy outside the geographical boundaries of the district, an extension to the so called "virtual boundaries". The introduction of "virtual boundaries" means that PEDs are not necessarily energy autonomous. This significantly lowers the barrier to PED development (especially for districts where the availability of local renewable resources is limited) and as a result, makes the PED concept more inclusive. Regarding the means to achieve PEDs, the application of renewable energy supplies and energy efficiency measures are essential among all programmes and projects. Buildings are seen as a key component in the PED concept, although many projects also recognise the roles of energy storage, mobility, and ICT. Besides energy-related matters, almost all programmes and projects include social, economic, and environmental aspects in the PED concept. Different non-energy qualities are mentioned (e.g. inclusiveness, affordable living, citizen engagement, etc.) but their descriptions are rather general without concrete requirements.

Table 1: Comparison of key elements in the PED concepts across twenty-two relevant programmes and projects.

| | Scale | Boundary | Types | Energy Balance | GHG emissions | Key Concepts | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Energy | Mobility | Economy | ICT | Social |
| **Horizon Programmes** | Several Buildings | - | - | + | - | ✓ | -- | -- | ✓ | -- |
| **SET-Plan Action 3.2** | District | - | - | + | Net Zero | ✓ | -- | -- | -- | -- |
| **JPI Urban Europe** | Groups of connected buildings | - | - | + | Net Zero | ✓ | ✓ | ✓ | ✓ | ✓ |
| **JRC** | -- | Defined Boundaries | - | + | - | ✓ | -- | -- | -- | -- |
| **EERA JPSC** | District | Geographical, Functional and Virtual | PED-auto<br>PED-dynamic<br>PED-virtual<br>pre-PED | + | Net Zero | ✓ | ✓ | ✓ | ✓ | ✓ |
| **DUT** | Urban areas | - | - | - | Net Zero | ✓ | ✓ | ✓ | ✓ | ✓ |
| **PED-EU-NET** | Groups of connected buildings | - | - | - | Net Zero | ✓ | ✓ | ✓ | ✓ | ✓ |
| **IEA Annex 83** | District | - | - | + | Net Zero | ✓ | ✓ | ✓ | ✓ | ✓ |
| **ATELIER** | District | Geographical and Virtual | - | + | Net Zero | ✓ | ✓ | ✓ | ✓ | ✓ |
| **+CityxChange** | District | Geographical, Functional and Virtual | PED-auto<br>PED-dynamic<br>PED-virtual<br>pre-PED | + | Net Zero | ✓ | ✓ | ✓ | ✓ | ✓ |
| **MAKING-CITY** | District | Geographical, Functional and Virtual* | - | + | Decarboni-sation | ✓ | ✓ | ✓ | ✓ | ✓ |
| **POCITYF** | District | Geographical and Virtual | - | + | - | ✓ | ✓ | ✓ | ✓ | ✓ |

| | Scale | Boundary | Types | Energy Balance | GHG emissions | Key Concepts | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Energy | Mobility | Economy | ICT | Social |
| **SPARCS** | District | Geographical and Virtual | - | + | Net Zero | ✓ | ✓ | ✓ | ✓ | ✓ |
| **syn.ikia** | Groups of connected buildings | Geographical, Functional and Virtual* | - | + | Net Zero | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Zukunfsquartier** | District | - | PED-alpha<br>PED-beta<br>PED-omega | + | Net Zero | ✓ | ✓ | ✓ | ✓ | ✓ |
| **PHVision** | District | Geographical and Virtual | - | + | Net Zero | ✓ | ✓ | ✓ | ✓ | ✓ |
| **ZEN** | Neighbourhood | Geographical and Functional* | - | + | Net Zero | ✓ | ✓ | ✓ | -- | ✓ |
| **NEUTRALPATH** | District | Geographical, Functional and Virtual* | - | + | Net Zero | ✓ | ✓ | ✓ | ✓ | ✓ |
| **ASCEND** | District | Geographical and Functional* | - | + | Net Zero | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Harmonise** | District | - | - | + | Net Zero | ✓ | ✓ | -- | ✓ | ✓ |
| **PEDvolution** | District | - | - | =/+ | Net Zero** | ✓ | ✓ | -- | ✓ | ✓ |
| **InterPED** | District | - | - | - | Net Zero | ✓ | ✓ | ✓ | ✓ | ✓ |
| **ARV** | Urban Area | Geographical | - | -- | Net Zero | ✓ | -- | ✓ | ✓ | ✓ |
| **oPEN Lab** | Neighbourhood | Geographical | - | + | Net Zero | ✓ | -- | ✓ | ✓ | ✓ |
| **PROBONO** | Neighbourhood | Geographical | - | + | Net Zero | ✓ | -- | ✓ | ✓ | ✓ |

* = not explicitly mentioned, authors' interpretation through documents and case study strategies
** = only mentioned in one of the case studies
+ = positive energy balance
✓ = considered in the project's objectives or focus
-- = not considered or mentioned explicitly
- = information not available

The diversity of definitions, boundaries, types and targets presented in Table 1 highlights a fundamental challenge in the current landscape of PED development: the absence of a common framework. Each project applies its own criteria, scopes, and metrics to define and evaluate PEDs, reflecting the varying priorities, local contexts, and stakeholder interpretations.

While this heterogeneity allows for flexibility and adaptation to specific contextual needs, it also poses challenges for comparing projects and establishing broadly applicable framework. This diversity highlights the need for further efforts towards harmonising definitions and methodologies within the PED community. Although developing a common approach goes beyond the scope of this report, it is important to acknowledge this issue. Recognising it not only helps frame the interpretation of the data presented but also points to future research and collaboration towards a more consistent understanding and implementation of PEDs.

## 2.4 Conclusion on main aspects in the framework of definition for PEDs

The concept of Positive Energy Districts has evolved from prior concepts of net-zero energy districts and positive energy blocks to become one of the key pillars underpinning Europe's urban energy transition. At the inception of the PED framework, there was a strong focus on the annual positive energy balance as a distinctive requirement. Earlier programmes and initiatives (including the SET-Plan Action 3.2, JPI UE, JRC and EERA JPSC) as well as the first wave of PED projects funded under Horizon 2020 (including +CityxChange, MAKING-CITY, SPARCS, POCITYF and ATELIER) emphasised on the production and active management of an annual energy surplus at the district level. However, the requirement of an annual positive energy balance sets a high barrier of entry to PEDs. Some practitioners criticise PEDs as an academic concept that is out of line with major urban priorities. Others criticise that the PED concept is exclusive as it is inaccessible for districts with limited opportunities for local renewable energy production.
Over the last six years as the PED concept is being tested on the ground in different urban contexts, there has been a gradual shift in the narrative of PEDs. The annual positive energy balance is no longer considered a definitive criterion in some projects. The expectation of PEDs for bringing positive impacts to the districts/neighbourhoods as well as the wider energy system plays a more important role. The alignment of PEDs with the EU's climate-neutrality agenda and urban policies is another crucial element that has been strengthened in the recent PED development. Despite this alignment, it is important to note that the development of PEDs is primarily supported at the research and innovation (R&I) level and much less in legislation. The EC has provided significant support for PEDs through dedicated funding instruments such as Horizon 2020 and Horizon Europe that helps to foster collaboration, experimentation, and new knowledge creation. The RDI activities have played a key role in developing technologies, social innovations, governance models, and capacity for PEDs across Europe. However, PEDs are not currently supported by any binding regulatory or legislative mandate at the EU level. The absence of a legal framework means there is no obligation for cities, developers, and other key stakeholders to adopt the PED approach, which significantly limits the uptake of PEDs in the energy transition context. To date, the energy transition in EU is largely driven by mandatory measures set out in directives like the Energy Efficiency Directive, the Renewable Energy Directive, and the Energy Performance of Buildings Directive. In contrast, the implementation of PEDs remains voluntary, driven mainly by local leadership, city-level ambitions, and the access to research and innovation funding.
Additionally, there has been more emphasis on the social, financial and governance considerations in the PED process, aspects such as community engagement, sustainable business models, participatory decision-making and so on were discussed in recent projects. The shift in the PED narrative, especially the meaning of "positive" from a narrow definition of a positive energy balance to a broader sense of driving positive urban changes makes the PED concept more inclusive, accessible, flexible and policy relevant. The drawback, however, lies on the vague distinction between PEDs and other existing urban development concepts such as climate-neutral districts or net-zero energy districts.

Nevertheless, the outlook of PEDs is expected to go beyond the conceptual/definition refinement and towards more the practical strategies and approaches for operationalising the PED concept. Although the application of local renewable energy systems, energy efficiency measures, energy storage technologies and energy sharing/flexibility services are all key to the PED implementation, their practicality, performance, economic viability and social acceptance largely depend on the local contexts and boundary conditions. Learnings from existing PEDs (collected in the PED-EU-NET Database: https://pedeu.net/map/) will be an essential next step to support the replication of PEDs in different European cities.

# 3. PED Assessment Methods

## 3.1 Review of assessment methods in existing PED projects

Assessment methods for PEDs vary across projects, as no standardised methodology has been established. In general, these methods differ in two key aspects: (1) energy balance assessment, which determines whether a district qualifies as a PED, and (2) key performance indicators (KPIs), which evaluate various aspects of a district's progress. This section provides a general overview of these assessment methods, highlighting how different projects have adapted them based on their specific priorities and objectives.

### 3.1.1 Energy Balance Calculation

**MAKING-CITY (MC)**

The MAKING-CITY project has developed a structured methodology to calculate the annual primary energy balance (PEB) of Positive Energy Districts (PEDs) [25]. A district qualifies as a PED if it achieves a negative annual PEB, meaning it exports more primary energy than it imports within its defined boundaries, which can be geographic, functional, or virtual.

The calculation process begins with determining the PED boundary, followed by calculating energy needs and energy use within the district. Next, the methodology assesses on-site renewable energy generation and determines the amount of delivered energy required to meet the district's demand. These values are then converted into primary energy, allowing for the calculation of the energy balance. Finally, all energy flows within the district are visualised in a Sankey diagram, providing a clear representation of the PED's energy performance [25].

To determine the annual PEB, both delivered and exported energy are converted into primary energy using country-specific primary energy factors (PEFs). These factors account for the energy consumed throughout the supply chain, distinguishing between renewable and non-renewable sources, with the non-renewable share used in this assessment. The final step visualises all energy flows within the district, ensuring a comprehensive evaluation of the PED's energy performance.

**Zukunftsquartier Wien (future district Vienna, ZQW)**

The ZQW project by UIV Urban Innovation Vienna, similar to the MAKING-CITY project, relies on the calculation of a PEB [16, 26]. The PEB is determined by subtracting the total primary energy imported from the total primary energy exported, with an additional proportional allocation of the renewable electrical energy potential of the country and a mobility compensation term. The assessment boundary aligns with the physical district boundary.

To illustrate using the type "PED Beta" in the project as an example, for a district to be classified as a PED, the PEB must exceed a calculated PEB target value, which scales with the Floor Area Ratio (FAR)—the ratio of the gross floor area (TGFA) to the site coverage area of a building. This adjustable PEB target value is described as the Density Factor, derived using simplified assumptions and results from PV simulations of real Austrian districts with varying site densities.

The annual PEB is determined by calculating the total primary energy exported (TPE) minus the total primary energy imported (TPI) per area within the assessment boundary. Primary energy is derived from final energy use and primary energy factors. In the energy balance, electricity imported from wind power peak shaving (curtailed wind energy) is considered primary energy-neutral, a concept known as Regional Renewable Peak Shaving.

To enhance the regional balance of renewable energy sources, the EE-Credit represents a population-proportional allocation of the country's renewable electrical energy potential to the district. Energy from large-scale renewable power plants—such as wind farms, hydroelectric plants, and biomass-fuelled combined heat and power plants—is first assigned to large consumers and energy uses that cannot be met locally. The remaining energy is then distributed among Austrian residents, and the cumulative EE-Credit of all building residents positively impacts the PEB. When mobility energy demand is included, the total district energy demand increases. To account for this additional requirement, a predefined term, Mobility Plus, is added to the energy balance, positively influencing the PEB.

### 3.1.2 Key Performance Indicators

Key Performance Indicators have emerged as one of the primary tools for assessing the diverse aspects of PEDs. Given the complexity and multifaceted nature of PEDs—ranging from energy efficiency and renewable energy integration to social and economic sustainability— KPIs provide a structured and measurable approach to evaluation. They allow for the clear tracking of progress and identification of areas requiring improvement.

**ZEN.** The pilots of the Norwegian ZEN Research Centre's ZEN share a foundational goal: achieving near-zero energy consumption while maximising the utilisation of renewable energy sources. ZEN emphasises the integration of interconnected buildings within a defined geographical area with careful planning and design to minimise life cycle emissions. ZEN employs 42 key performance indicators across six primary categories—Greenhouse Gas Emissions, Energy, Power, Urban Form and Land Use, Mobility, and Economy—ensuring comprehensive assessment within defined system boundaries [19].

**syn.ikia** [15] evaluates the districts (SPENs) through 44 KPIs across five categories: energy and environmental performance, economic factors, indoor environmental quality, social indicators, and smartness and energy flexibility. This multifaceted approach aims to address the energy trilemma of security, equity, and sustainability while promoting social inclusivity and economic sustainability.

**MAKING-CITY** [27] exemplifies the practical application of Positive Energy Districts, aiming to establish neighbourhoods that achieve net-zero energy import and surplus renewable energy production. The project integrates a multi-faceted approach that addresses technical, social, and regulatory challenges. Utilising 20 key performance indicators across categories such as energy and environment, mobility, governance, and citizen engagement. One of the features that makes MAKING-CITY different than others, is the project's PED-readiness indicator tool. This tool helps municipalities evaluate how ready they are to implement Positive Energy Districts. It offers pre-evaluation indicators for over 6,000 cities across Europe, along with self-evaluation questions that prompt local authorities to consider their current capabilities.

**+CityxChange** [28] aims to develop sustainable urban solutions by creating Positive Energy Blocks (PEBs) that scale up to Positive Energy Districts, ultimately contributing to climate-neutral cities. It focuses on innovative energy strategies such as energy reduction, efficiency measures, local renewable energy generation, energy storage, flexibility in energy use, and peer-to-peer energy trading. The project employs 33 Key Performance Indicators across three categories: Integrated Planning and Design, Common Energy Market, and Community Xchange. A distinguishing feature of the +CityxChange project is the assignment of expected targets for each KPI. This approach allows for specific accountability, setting +CityxChange apart from other initiatives in the field.

**POCITYF** [29] focuses on mixed-use urban areas with cultural heritage, aims to create sustainable and inclusive urban environments by integrating PEBs with grid flexibility, e-mobility solutions, innovative ICT technologies, and citizen engagement strategies, all while preserving urban cultural heritage. The project demonstrates solutions at both building and district levels to increase energy self-consumption, enhance energy savings, and integrate locally produced renewable energy. Key strategies are comparable to those in the +CityxChange project, including energy management, energy storage solutions to support grid flexibility, and the reduction of energy curtailment. Active citizen engagement and co-creation processes are also very important for the project, ensuring that residents are at the centre of decision-making, planning, and problem-solving. To monitor and evaluate progress, POCITYF established 63 Key Performance Indicators, refined from an initial list of 258 potential indicators sourced from the Smart Cities Information System (SCIS), CITYkeys, and other projects focusing on Positive Energy District evaluation. These KPIs are categorised into eight dimensions: energy, environmental, economic, ICT, mobility, social, governance, and propagation.

**SPARCS** [30] project developed a comprehensive set of 197 KPIs to assess smart city initiatives in Leipzig and Espoo. These KPIs were created after analysing established frameworks like SCIS and CITYkeys, focusing on impact areas such as energy, economy, technology, and social factors. The KPI development followed a multi-step process. First, a top-down approach identified 29 core KPIs aligned with SPARCS objectives, 22 adapted from existing frameworks and 7 newly defined. Next, a bottom-up approach involved collaboration between technical experts and city stakeholders, adding 78 KPIs based on local actions. Finally, further consultations with experts and city representatives led to 90 additional KPIs, expanding the framework to include governance, mobility, environment, and citizen engagement. The final KPIs are organised into three types: Intervention, Impact, and Replication, providing a holistic and scalable assessment framework for smart cities.

**ATELIER's** [12] KPI framework consists of 86 KPIs grouped into seven categories: energy, environmental, economic, mobility, citizen engagement, upscaling and replication, and knowledge sharing. These categories comprehensively address the technical, environmental, economic and social aspects of Positive Energy Districts. The KPIs are designed to ensure scalability and replication across different contexts while advancing knowledge sharing and policy development to support the energy transition.

**PEDvolution** [31] employs a unique assessment method that integrates KPIs within various business use cases to ensure a comprehensive evaluation PEDs. The framework consists of 10 distinct business use cases, under which a total of 55 KPIs are distributed. Since many KPIs are relevant to multiple aspects of PED development, some are repeated across different use cases. The assessment method focuses on several key areas including: (1) enhancing market value and financial viability through certification and sustainability verification, (2) optimising energy efficiency and cost-effectiveness by improving building stock and leveraging energy communities, and (3) advancing grid and energy system operations by utilising flexibility and sub-balancing areas. Additionally, the framework emphasises reducing dependency on fossil fuels for district heating and cooling, reinforcing PEDs as a crucial component of the energy transition.

Across the evaluation frameworks, it is clear that social KPIs and community engagement has become increasingly central is monitoring the performance of a PED. For more information on social impact assessment, please refer to Subtask C final report.

## 3.2 Test of selected PED assessment methods

A recent study by Fraunhofer [32] systematically analysed the assessment methods from three projects: MAKING-CITY, Zukunftsquartier Wien (ZQW), and ZEN. These three assessment methods were chosen because they differ substantially from each other and together, they capture a wide variety of possible calculation approaches. They range from simple calculation schemes (MAKING-CITY) to well elaborated calculations considering different urban context factors (ZQW) and assessment using sub-annual data instead of a single annual energy balance (ZEN). The three methodologies were tested using the same set of case studies, the results were compared in terms of the general practicality of the methodologies as well as their fulfilment of the PED objectives. The following section presents a summary of the findings and conclusions derived from this study.

**MAKING-CITY (MC) Methodology**

The MC methodology is straightforward, quick to apply, and easily transferable to different districts. It is seen as coherent and comprehensive, with the use of Sankey diagrams enhancing the understanding of energy flows within districts. One of the strengths of this methodology is its virtual boundary that allows wind power to be counted as on-site generation, facilitating energy sharing beyond physical district boundaries. However, this virtual boundary can lead to issues as energy flows that influence the energy balance can be selectively included, and vice versa. The inclusion of mobility energy demands is another concern, as it is not mandatory within the MC methodology but should be considered in the PED framework due to its significant role in energy consumption. Additionally, the use of Primary Energy Factors (PEFs) has been noted as a challenge, as the values and calculation methods for PEFs vary significantly across EU member states, leading to discrepancies in energy assessments. Despite these challenges, the MC methodology's ability to capture energy sharing and its application of centralised optimisation have consistently yielded better results in case studies, highlighting its potential in promoting PEDs.

**Zukunftsquartier Wien (ZQW) Methodology**

The ZQW methodology aims to capture multiple urban development aspects in a single equation and as a result, the method is more complex and labour-intensive than MC. Its Density Factor, which plays a central role in the methodology, depends heavily on local data availability, making it challenging to adapt and transfer across different cities/countries. While the scaling with the Floor Area Ratio (FAR) compensates higher density development to facilitate PEDs in urban areas, it risks compromising quality of life, which is also a core principle of PEDs. The use of Energy Efficiency Credits (EE-Credit) also presents limitations, as commercial districts with lower populations may be disadvantaged due to higher energy demands. The methodology's inclusion of Mobility Plus, which compensates for additional mobility-related energy demands, is an advantage, though it remains unclear how it should be applied when only a subset of mobility options is considered. Furthermore, the approach towards regional renewable energy imports is problematic, as these imports may not always align with the district's renewable energy needs, and the Regional Renewable Peak Shaving concept raises questions about its feasibility. Like MC, ZQW also faces issues with the use of PEFs, as wind energy imports are not clearly treated as on-site generation, diminishing their potential to incentivise Power Purchase Agreements (PPAs).

**Zero Emission Neighbourhood (ZEN) Methodology**

The ZEN methodology is noted for its coherence and thorough documentation, although its application requires higher level of expertise due to the use of hourly data and the generation of predefined plots. The methodology's reliance on reference projects tailored to each district ensures broad applicability, but its focus on multiple KPIs rather than a single overall indicator makes the results difficult to interpret and compare. Extreme values, such as a peak load resulting from a single moment of high electricity import, can significantly affect some KPIs, complicating the evaluation of energy systems. Despite this, ZEN's use of multiple KPIs helps identify potential design issues within energy systems and provides valuable insights. However, the methodology's reliance on final energy imports and exports without differentiating between energy carriers and their environmental impacts is a limitation. For example, grid electricity and biomass are treated equally, despite having different greenhouse gas emissions. Additionally, ZEN does not use PEFs, which complicates the comparison of energy sources and reduces the incentive for districts to enter into PPAs for renewable energy supply. The disconnection between wind energy imports and on-site generation further diminishes the potential for green electricity imports that might help to reduce the carbon intensity of the district's energy mix.

**Summary**

Each assessment methodology has its own advantages and challenges and there is clearly a trade-off between simplicity and integrity of the assessment methods. MC appears to be universal and simple to apply but does not adequately consider enough contextual factors to capture the PED concept completely. Conversely, ZQW combines multiple contextual factors in a single final equation but can increase the complexity level and make the assessment methodology difficult to apply and hardly adaptable. ZEN utilises a unique approach in comparison to the other assessment methods by comparing a range of KPIs on hourly data against a reference project. However, the results can often be difficult to comprehend and the calculation of multiple KPIs can complicate the application.

In summary, the findings of the study pointed out that: (1) the objective of the assessment should not be solely on limiting the energy import and maximising the export of the district. A PED should be seen as a district that delivers positive impacts to the wider area by optimally utilising its own boundary conditions. Therefore, the assessment should also examine the energy exchanges between the PED and the surrounding energy systems to ensure conducive energy flows and prevent undesirable surplus generation; (2) relying solely on annual calculations (that is common for many PED project) is insufficient to assess the interaction between the district and the wider energy systems. Some energy-related performance indicators are best considered at least partly at an hourly level. Finally, the findings suggest that a positive energy balance might not be considered as a prerequisite of PEDs as this strict requirement sets a high entry barrier for districts that lack the intrinsic factors for surplus renewable energy production. For PED as an inclusive framework, the focus should be on delivering positive impacts for the districts and the wider energy systems; whilst the positive energy balance can be seen as a complementary rather than a mandatory condition.

## 3.3 Conclusion with recommendation on PED assessment methods and the PED framework

This section provides an overview of the PED framework and assessment methods, highlighting their current limitations and challenges. It examines key aspects such as the definition of PED boundaries, the applicability across different settlement types and the evaluation of energy balance within these districts. By analysing these shortcomings, this section aims to identify gaps in current PED assessment approaches and propose recommendations for improvement. The discussion will focus on refining PED boundaries, enhancing assessment methods to accommodate different district characteristics, and improving the evaluation of energy balance and flexibility. Addressing these issues is essential to developing a more standardised yet adaptable framework that can effectively guide PED implementation across various urban and regional settings.

### 3.3.1 Scales and Boundaries

The definition of a district, as outlined by the Cambridge Dictionary, refers to a designated area within a country or city, typically larger than a block or neighbourhood [33]. However, this definition remains flexible, leading to ambiguity in defining Positive Energy Districts. Terms like "urban areas," "blocks," and "neighbourhoods" are often used [34], but they lack clear spatial criteria. While districts are generally considered larger areas, data from the PED EU Net database [10] shows that most PED projects involve fewer than 100 buildings, suggesting that a PED's size should not be strictly defined as long as it meets PED principles. However, energy demands, and renewable energy potential differ significantly between rural and urban areas, making it challenging for all districts to meet their needs within their physical boundaries. The JPI Urban PED definition provides flexibility by allowing both local and regional energy production, helping address energy surpluses and system complexity [6].The concept of Virtual-PEDs remains controversial, as it could prioritise energy balance over actual emissions reductions [25], yet tailored solutions remain essential for achieving climate neutrality.

Another major challenge is mobility-related energy, which extends beyond district boundaries, involving commuters, visitors, and residents. While PEDs can generate their own energy, mobility remains inconsistently integrated due to the lack of standardised performance criteria. Regional variations in emission accounting models further complicate assessments [35]. Despite its role in $CO_2$ reduction and energy storage, mobility is often excluded from PED frameworks, limiting their ability to address transportation energy demands [33].

### 3.3.2 Settlement Types

The success of PEDs depends on local factors such as renewable energy availability, infrastructure, population density, and energy consumption patterns. These variables shape PED design and implementation, requiring tailored solutions for different districts. However, the PED concept does not distinguish between the contexts of urban, rural, new build, existing or historic districts, applying the same requirements to all, despite studies showing that densely populated urban areas with cultural heritage values face significant technical and regulatory challenges [35]. Urban districts often lack space for on-site renewable energy generation, making it difficult to match energy demand with local production [36]. In contrast, rural areas typically have more land and greater flexibility for deploying renewables, making PED implementation easier. Additionally, newly developing districts have a higher potential for PED success than historic areas, where retrofitting faces technical and aesthetic barriers [37].

Given these challenges, energy exchange beyond district boundaries can improve urban PED feasibility. Producing energy externally can be more efficient and cost-effective, which points to the use of virtual boundaries to access external resources [35, 38]. When space is limited, Power Purchase Agreements (PPAs) or Green Energy Certificates offer alternative pathways to climate neutrality, as recognised by Article 19 of the Renewable Energy Directive 2018/2001/EU. While this deviates from the traditional PED model of local production, virtual boundaries provide urban areas an opportunity to achieve PED goals despite the spatial constraints.

### 3.3.3 Energy Balance Calculation

A positive energy balance is a core principle of PEDs often serving as the primary metric for PED qualification. However, energy balance calculations are complex and the lack of a harmonised methodology across Member States further complicates assessment, as primary energy balance calculations vary widely.

PEFs, which reflect energy conversion and distribution efficiency, differ by country, making international comparisons difficult. Some nations assign a PEF of zero for renewables, while others do not, creating inconsistencies [25]. Additionally, as the energy system transitions to renewables, primary energy consumption becomes a less relevant indicator, as reductions in primary energy do not always equate to lower final energy use [39].

A recent study highlights that focusing solely on energy balance overlooks efficiency which explains why districts with high generation potential may still have inefficient systems [32]. Moreover, strict energy balance criteria often exclude many districts from achieving PED status, suggesting that assessment methods should offer flexible pathways to encourage progress toward PED goals. While energy balance is important, it should not be the sole determinant of PED status. Assessments must consider efficiency, system improvements, and climate-neutral strategies, ensuring that all districts, regardless of initial conditions, are recognised in their transition toward sustainability.

### 3.3.4 Assessment Methods

A number of assessment frameworks have been devised for the evaluation of PEDs, each incorporating distinct methodologies and key performance indicators. However, a review of several European PED projects reveals significant inconsistencies and challenges in the existing methods. The assessment frameworks differ in their approaches to defining PED boundaries, applying KPIs, and ensuring comparability across different settlement types, such as urban and rural areas or regions with varying climatic conditions. Data accessibility also remains a major concern, as some methods rely on high-resolution hourly data, which many districts lack the necessary technologies to collect. Furthermore, differences in how KPIs are calculated—such as whether they rely on primary or final energy—complicate the standardisation of assessments, leading to inconsistencies in the evaluation.

Renewable energy, efficiency, and flexibility emerge as the most assessed aspects within PED frameworks, yet each presents unique shortcomings. Renewable energy assessments struggle with geographic disparities, where regions with lower solar or wind resources face difficulties in achieving high renewable energy shares. Similarly, densely populated urban areas have limited space for on-site renewable energy generation, making direct comparisons with rural PEDs problematic. Energy efficiency evaluations also vary significantly, with some relying on historical demand data, which may not account for emerging electrification trends like heat pumps and electric vehicles. Flexibility assessments, often based on peak load reduction, may fail to capture the broader adaptability of energy systems, particularly as electrification increases. Given these challenges, there is a clear need for more standardised yet adaptable PED assessment methods that ensure fairness, accuracy, and applicability across diverse district types.

### 3.3.5 Summary

Given these considerations, assessment methods should be streamlined to ensure consistency across the EU while accounting for the varying limitations of different countries. Not all districts have access to advanced data or measurement technologies, so assessment methods must be flexible and considerate of these challenges. Additionally, the methods should focus on the most critical aspects of PEDs, including renewable energy potential, energy efficiency, and mobility integration, ensuring that districts are assessed on a fair and equitable basis.

In conclusion, this study reviewed the definitions and assessment frameworks of a number of existing PED projects. It is found that, in order to bolster the uptake of PEDs, a PED framework that aligns with the EU's climate neutrality agenda and other urban priorities is key. At the same time, by considering local challenges and promoting a more flexible assessment process, the PED concept will become more inclusive and relevant to local development. This will help to mobilise support of local stakeholders in PED developments and warrant PEDs a pathway towards positive urban changes.

# 4. PED Characteristics and PED Archetypes

This chapter intends to report and visualise the analytical results of existing 60 PED related projects in the Europe about their main characteristics, including geographical information, spatial-temporal scale, energy concepts, building archetypes, finance source, key words, finance model and challenges/barriers.

Section 4.1 summarises the methods and data source. Section 4.2 illustrates the technical components, and section 4.3 characterises the life quality indicators/social aspects. The development of PED archetypes is discussed in section 4.4.

## 4.1 General Characterisation of PEDs

### 4.1.1 Data source and characterisation methodology

The data of PED related projects is collected from the PED booklet [40] by JPI UE updated latest on 2019. The total databank consists of 60 projects' data that have similar goals to PED projects in Europe. However, it has been challenging to understand the energy typology and detailed strategies due to unclear/insufficient information for many projects from the JPI Urban Europe booklet. Due to this insufficient information, external sources, such as the website/publication of those projects, have been studied and reviewed.

Text extraction and mining methods were firstly applied in Python with the aid of the Pandas library (version 1.2.4, GitHub, Inc., San Francisco, USA) [41] to transform this data from an unstructured mix of tables and text into clean and structured data frames. Subsequently, the Natural Language Processing (NLP) method using text mining in Python with the aid of the Natural Language Toolkit (NLTK) libraries (Version 3.5, O'Reilly Media Inc., California, USA) [42] was used to extract the most used words from the 60 projects. Finally, the TextBlob library (Version 0.16.0, Steven Loria, New York, USA) [43] was applied to carry out a sentiment analysis study [44] on the dataset to determine the polarity and subjectivity of the groups of projects. In addition, QGIS software (Version 3.10, Open Source Geospatial Foundation, Beaverton, USA) [45]is a Geographic Information System (GIS) based open-source software used here to display the cities on a map.

### 4.1.2 Results of general characteristics

- **Initiation year**

The section shows the year of initiation of the first phase of all the 60 collected PED related projects in Europe, due to the available data source mostly in the Europe. From Figure 1, the first project was initiated in 1970 and the second project in 1995, both in France. There have been very few projects, less than one project each year until before 2014, where 5 projects took place in that year. The momentum has increased from then with 8 projects in 2016, 9 projects in 2017, 11 projects in 2018, 6 projects in 2019, 4 projects in 2020, and no data for 5 projects.

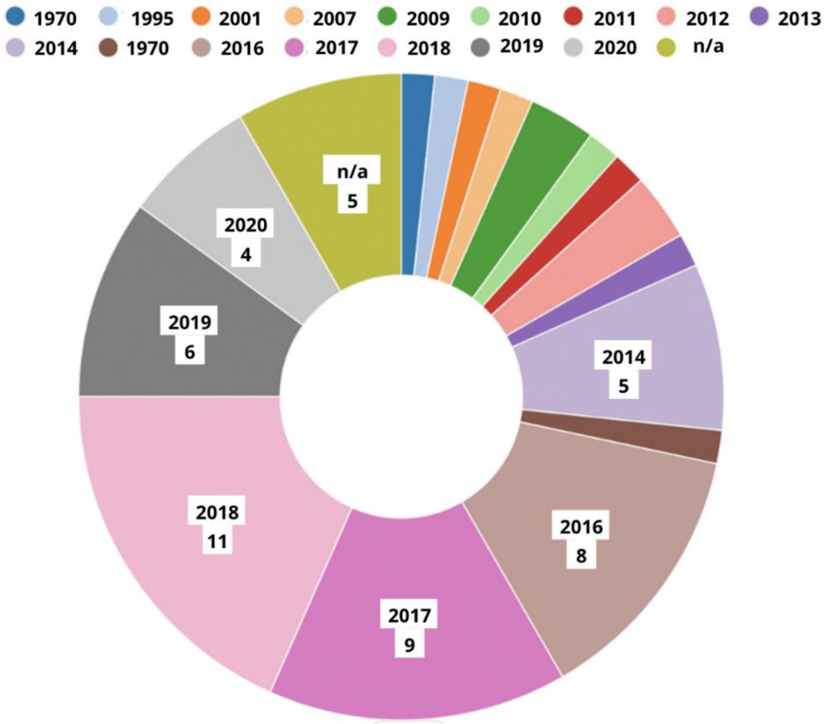


Figure 1: Initiated year of PED related projects

- **Location of Identified 60 PED Related Projects**

The location of the identified 60 PED related projects is displayed in Figure 2. The greatest number of projects are located in Norway, i.e., 9 projects, followed by 8 projects, 7 projects, 6 projects, 5 projects in Italy, Finland, Sweden and The Netherlands, respectively. There are 4 projects in Spain, Germany and Austria, 2 projects in both France and Denmark. There is one project in each of the remaining countries, Portugal, Turkey, Ireland, Belgium, Hungary, Switzerland, Greece, Estonia and Romania.


Figure 2: Location of 60 PED related projects

- **Status of the Identified Projects**

From Figure 3, the results clearly indicate that majority of the projects are under the implementation stage i.e., 26 projects. There are 11 projects under the planning stage, and 6 projects under both the planning and implementation stages. In total, 16 PED related projects are already implemented or in operation, among which 5 projects have completed implementation but have yet to integrate the energy systems into the existing local energy networks of the specific projects, while 11 projects are finally in operation stage. Information is not available for one project.

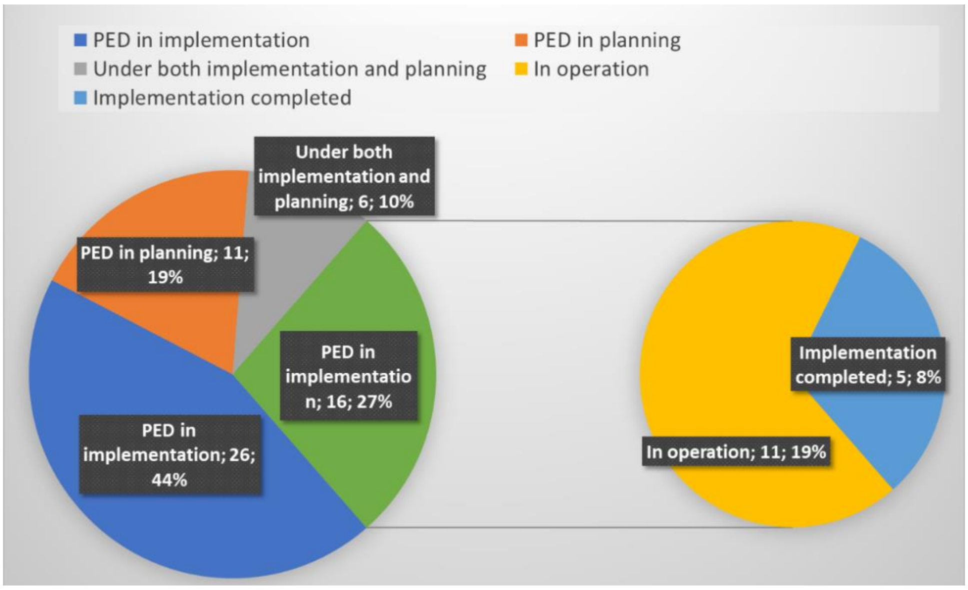


Figure 3: Development stage of collected 60 PED related projects

- **Most commonly used words and Sentiment analysis**

Figure 4 shows the most commonly used words in the project description transcripts according to data source in section 4.1. As seen from the figure, projects that are already implemented (both PED and towards PED) show high use of words like ‘consumption’, ‘passive’, ‘heating’, and ‘industry’. On the other hand, projects that are yet planning (both PED and towards PED) use words such as ‘urban’, ‘solutions’, ‘quarter’, ‘research’, and ‘residential’. Projects that are in implementation (both PED and towards PED) mostly repeat words like ’citizen’, ‘planning’, ‘urban’, heating’, ‘supply’, and ‘cost’. Finally, both implemented and in implementation Towards PED projects use heating, cost and supply words.


Figure 4. Most commonly used words for PED

Figure 5 displays the sentiments portrayed by the 6 groups of projects in the context of polarity (positivity and negativity) and subjectivity-objectivity (opinions-facts). In general, PED implemented projects have very positive feedback, reflected by the text. We see both PED and towards PED implemented projects have higher subjectivity than objectivity, compared to their planning phase counterparts. This could be interpreted as the implemented projects are mostly influenced by diverse factors, such as dynamic data, citizens and other stakeholders, while those projects in planning stages emphasise more on objective learning experience from literature, simulation data and the related estimations.

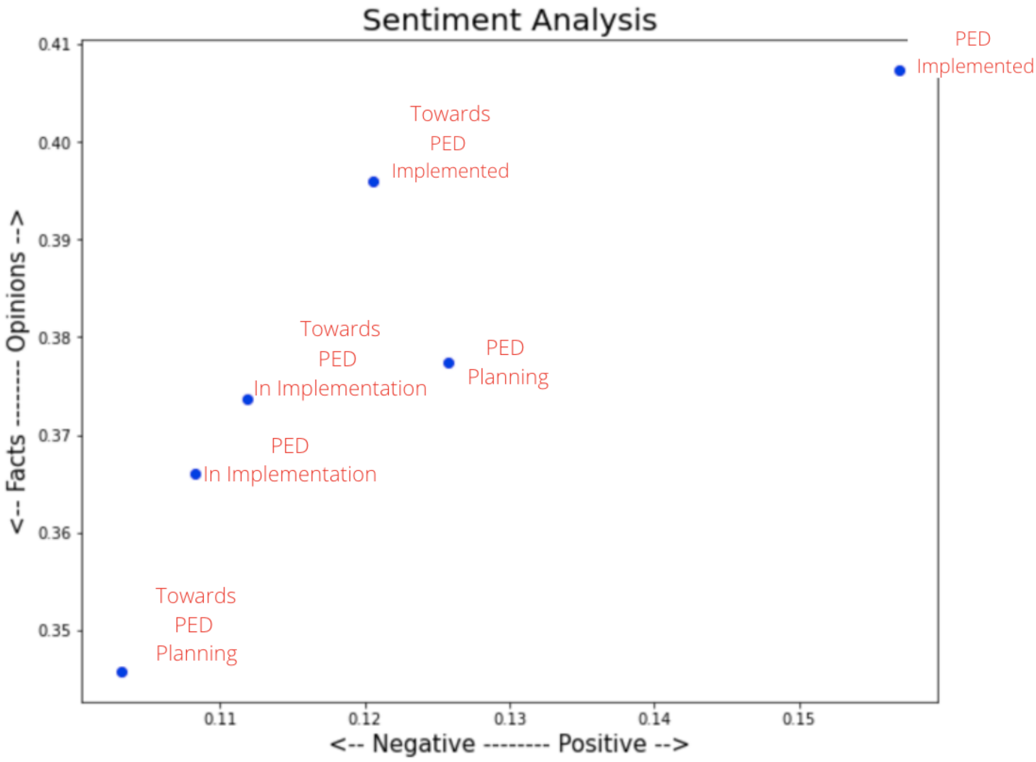


Figure 5: Sentiment Analysis

## 4.2 PED Characteristics: Techno-economic components

### 4.2.1 Results of techno-economic components

- **Projected Area (Spatial Scale)**

The amount of project area (spatial scale) is counted by considering the installation of the planned energy systems in their locality. These energy systems might be installed on the residential, commercial or industrial roofs, or flat ground-mounted in open fields, or even through the virtual presence of an energy system. From Figure 4, most of the projects, i.e., 19 projects are claimed to be using less than 0.2 km$^2$ area, 7 projects between 0.21 and 0.4 km$^2$ area, 8 projects consuming area between 0.81 and 3.0 km$^2$, and there is one project claim to be consuming more than 25 km$^2$ area.

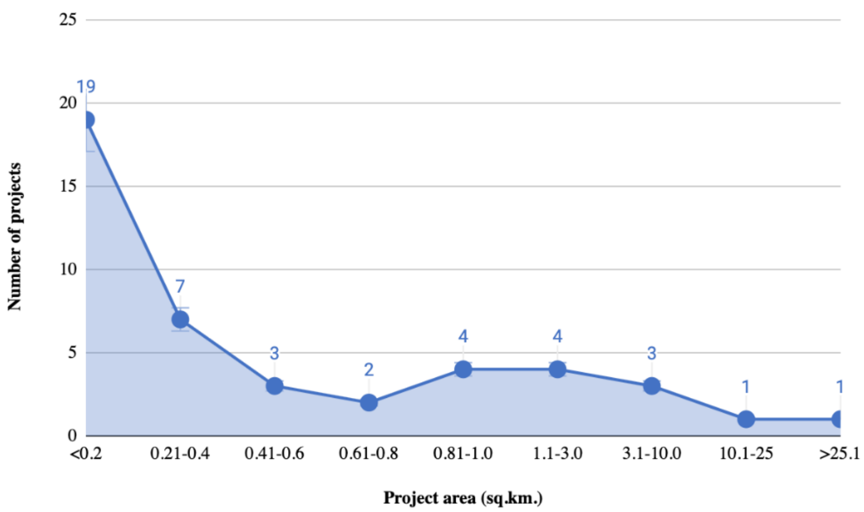


Figure 6: Project area of the 60 PED related projects

- **Finance models used in PED projects**

To meet the project goals and bring clean energy transition, the finance model plays a vital role. Whereas this section demonstrates the common trends being deployed in 60 PED related projects shown in Figure 7. Combination of public, private and others, such as national or regional grants, has been the most common strategy in 20 projects. Only public financing in terms of EU grants or municipality funding is observed in 14 projects out of 60 projects in Europe, 5 projects which solely depend on private financing strategy, and there are 8 projects forwarding with private and public finance combination. However, more than 6 projects which do not have proper information about the finance model in PED booklet by JPI Urban Europe.

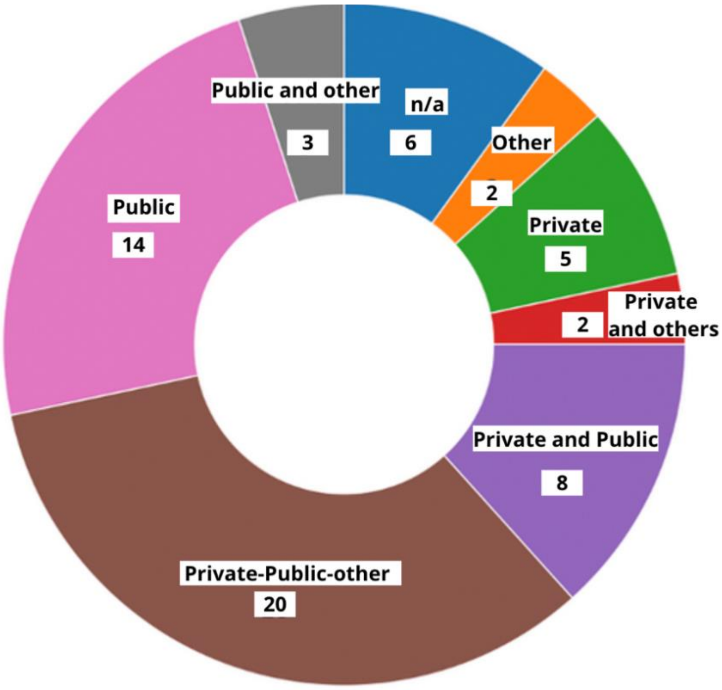


Figure 7: Commonly used type of finance models

- **Type of Buildings Involved**

This section presents the commonly involved building types for installation of energy systems to supply local energy demand and also to generate excess energy to increase energy flexibility according to the specific project goals. Figure 8 illustrates that the residential sector appears to be predominantly used in most of the projects to install energy systems on available roof areas as it is being the primary focus for 39 projects. Office and social buildings are identified to be the focus in around 24 projects and also followed by commercial buildings spaces for more than 20 projects. Other types of buildings such as institutional, cultural etc., are utilised as secondary spaces for implementing the energy systems.

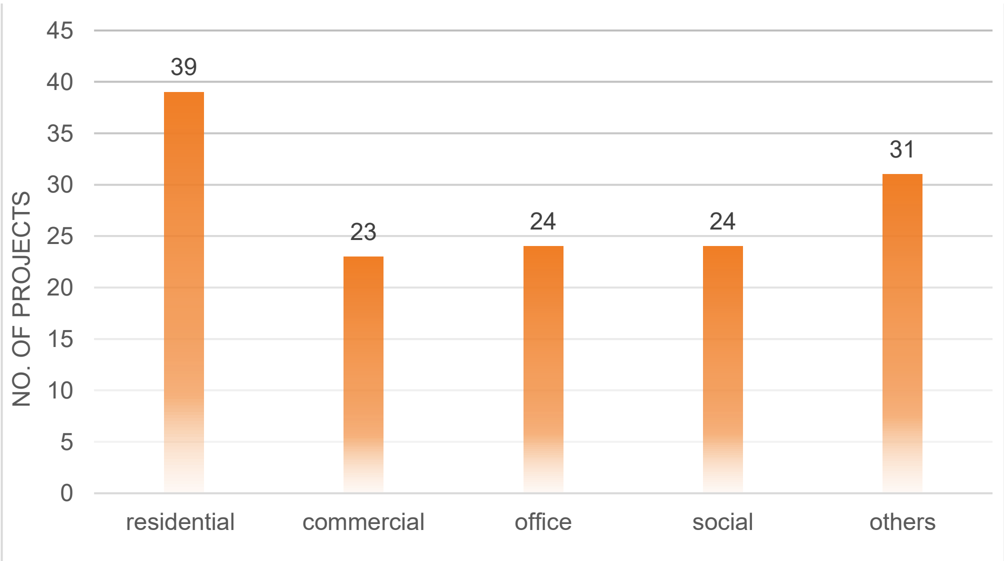


Figure 8: Type of buildings for space utilised by energy systems

It is also observed that almost all the projects have considered a mixture of different building types, depending on the major type of buildings existing in the locality. Residential buildings appear the most in the all PED-related projects. However, the overall trend focuses on involving the citizens as key drivers with the right motivating strategies which eventually address the spatial challenges to install energy systems required for local energy demand.

- **Major Energy Technologies**

The commonly used energy technologies in these PED projects are examined and referred to as the three pillars of Energy Generation, Energy Flexibility and Energy Efficiency. These energy technologies are divided into categories as solar, district heating/cooling, heat pumps, geothermal energy, combined heat and power (CHP), energy storage, wind, e-mobility and others present in the inner circle of the pie chart shown in Figure 9. Solar energy technology is identified to be the primary source of energy supply in almost all projects, specifically photovoltaics (PV) and thermal are the main contributors for producing electricity and heating applications respectively. There are five situations where projects claimed to use solar technology but have not been specific about the type of solar energy. Other new/innovative forms of solar such as hybrid photo-voltaic/thermal (PVT), building integrated photovoltaics (BIPV), floating solar and solar roads technologies also have been considered in few projects.

District heating/cooling has been found in 45 projects, in which heating is used in 43 projects and cooling in 2 projects. Heat pumps, geothermal energy and CHP plant used in 37 projects, 27 projects and 21 projects respectively. Electro-chemical energy battery technology storage for electricity application and seasonal thermal energy storage technology for heating/cooling application are explored as under the energy storage category. Wind energy and E-mobility technologies are identified using in 6 projects and 8 projects respectively. Other technologies, such as bioenergy, green hydrogen, hydropower and natural/mechanical ventilation etc., have also been integrated partly in few PED related projects in Europe.

Figure 9 represents the diversity of energy technologies in each country. Solar energy, district heating/cooling and heat pumps technologies are commonly considered in almost all of the countries, geothermal energy and CHP plant are being used in nearly half of the countries as represented in Figure 8. Wind energy is integrated in a smaller number of countries such as Denmark, Finland, Germany, The Netherlands and Turkey, and energy storage is only seen in few countries such as Austria, Finland, Germany, Italy, Norway and Turkey. Furthermore, the results indicate that Finland, The Netherlands and Norway have high diversity of using more types of energy technologies, followed by Germany, Austria, Italy and Turkey.

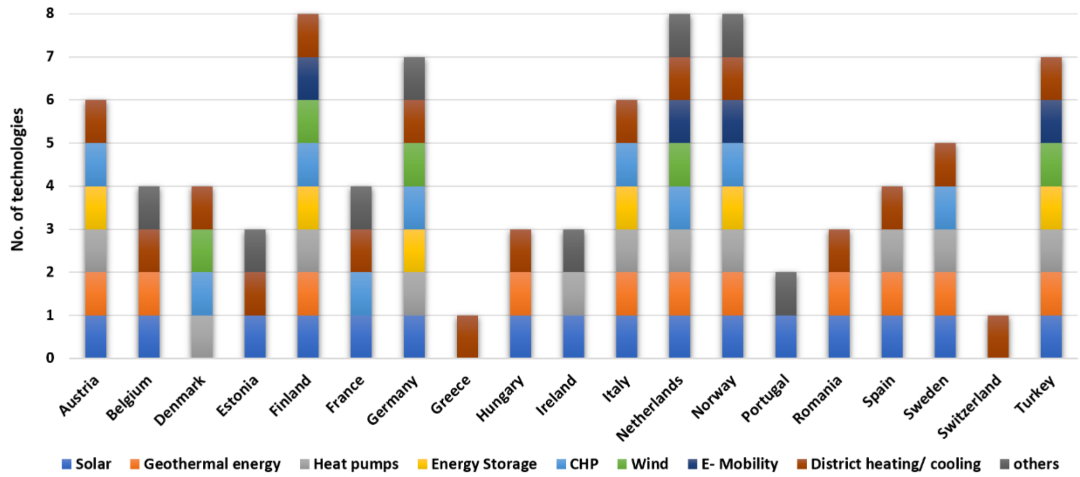


Figure 9: Country-wise approach of energy typology

- **Challenges under different implementation stage**

The data collection focuses on challenges/barriers that are categorised into 'under planning', 'under implementation stage' and 'implemented/in operation' stages shown in Table 2.The gathered information on challenges/barrier reveals the following main topics: Administrative and policy (A&P), Legal and Regulatory (L&R), Technical. Environmental, Social and Cultural, Information and Awareness, Economical and Financial, and Stakeholders interest perspective [46].

Table 2: Challenges and barriers in different stages of PED projects according to the main topics

| Topic | PED in planning | PED in implementation | PED implemented/ in operation |
|---|---|---|---|
| Administration & Policy | Conflicts between different authorities involved in project | Political management | Approvals and permits from municipality and other entities might lead to project timeline extension |
| Legal & Regulatory | | Regulatory framework which governs involved actors throughout Europe | Regulatory barriers for piloting/testing |
| Technical | System boundary conditions defined<br>Coping up with rapid growth of new technologies | Identification and deployment of local feasible clean energy systems | Analysis required for hybrid energy system operations<br>Analysis required for underground seasonal energy storage<br>Energy generation systems is far away from the consumers<br>Thermal mining challenges in the urban areas to reduce the distance from energy generation system far away<br>The electricity supply examined properly above 90 degrees |
| Environmental | | | Disallowing inefficient and high polluting energy generation systems |
| Social & Cultural | | | Cultural differences between different cities involved in the internationally funded projects |
| Information & Awareness | | Local citizen acceptance of new things in rural areas | |
| Economical & Financial | Economic feasibility<br>Finance availing according to the project timeline<br>Overlapping implementation with local ongoing constructions | Finance dependence on private investors<br>Local finance | |
| Stakeholders interest | Encouragement of project drivers like real estate developers<br>Uncertainty in stakeholder's commitment | Stakeholders and involved actor's commitment towards project goals<br>Creating interest in project drivers like building owners and landlords | Conflicts due to lack of common interest between different landowners<br>Strong collaborations needed between energy companies and real estate developers for fast implementation |

| | | | |
|---|---|---|---|
| Others | Active consideration of local knowledge<br>Lack of supporting studies/knowledge for planning | Lack of supporting studies/knowledge for implementation | |

Challenges associated to stakeholders' involvement, administrative, and technical issues had a great relevance in all PED stages. The economic and finance feasibility was crucial in both planning and implementation stages as well as supporting studies or knowledge. However, legal and regulatory barriers were important in implementation and operation stages. Finally, only in operation stage environmental and social and cultural aspects were considered as possible barriers.

### 4.2.2 Discussion of the characteristics of PED

In this report, the projects have been taken from the PED booklet by JPI Urban Europe, which invited voluntary input data over the project experience and knowledge. It should also be noted that this is not an overview of the PEDs in Europe, as countries have contributed unequally to the development of the booklet. Since most of the projects are still under planning and implementation stages (at the time when the PED booklet was published in 2020), it has been challenging to understand the updated information/data of many projects. In addition, due to the insufficient information, there are few data, such as energy technologies for PED, is unclear during data collection. These bring certain uncertainty of the analysis result.

However, it is interesting to examine the main characteristics of the collected 60 PED related projects, and the results shall have certain guidance for final PED definition and the proposal of 'reference PED'. The non-existence of a standard and consolidated definition of the PED concept is in fact one of the main limitations to its development and deployment in European cities, so as to boost the energy transition within a common reference framework [6] for sustainable urban development. So, different approaches and aspects related to the realisation of PEDs will be aligned taking account of European cities diversity.

According to results, the identified 60 projects are constituted in Europe with large number of projects in Norway (9 projects) and Italy (8 projects) respectively. Although the first project took place in 1970, but the momentum for such urban transition goals has started from the year 2014.

According to the database, most of PED related projects choose 'yearly' as the time scale. However, it is not possible to identify the temporal scale for many projects since they are still under planning stage. Regarding the project area (spatial scale), the general trend is to include residential, commercial and industrial buildings for installation of renewable energy systems in a city or district, which is to avoid the deployment of large energy systems in open fields. This might need supporting policies that support direct consumers to involve in adapting implementation on their premises. However, this strategy would need to consider providing economic feasibility or encouraging policies that attracts the private investments. The analysis observes that public, private with regional/national grants is commonly used financial model which reflects active involvement from private sector. In addition, there are some projects that don't have many local renewable energy sources, but they purchase energy from outside of the district boundary (so-called 'virtual PED').

Based on the results, residential, commercial and office/social buildings are highly involved for installation of energy systems, which depends on citizens commitment towards project goals (but the goals might deviate from the designed timeframe of the project). Meanwhile the stakeholders, such as municipality, would need to address overcoming the policy restrictions to further ease the process of adapting the energy system, and also need to conduct necessary activities to bring awareness in consumers and motivate for participation.

The energy mix for projects goals include solar energy, district heating/cooling, wind and geothermal energy are primary technologies, where solar technologies show dominance because of their potential. However, due to unavailability of solar energy during most half of the day and during winter seasons, exploration towards other forms of renewable energy sources, such as geothermal energy, wind etc., yet these may not totally reliably option during peak demands. In this context, energy storage might be the alternative way. Apparently, energy storage has not been part of the major energy strategies, which might be due to unavailability of enough planning, economic feasibility, high maintenance etc. This also might be part of the reason for PED related projects choosing yearly temporal scale rather than daily/monthly or seasonally.

In terms of the mostly used words in the project descriptions, it is observed that projects that are already 'implemented' (both PED and towards PED) tend to concentrate highly on 'consumption', 'production', 'heating'- characteristics that are generally repeatedly showed interest in when the project is implemented and running. On the other hand, projects that are yet 'planning' (both PED and towards PED) tend to concentrate on 'solutions', 'research'- characteristics that are generally repeatedly discussed when a project is being planned. Projects that are in the middle, i.e. 'In Implementation' (both PED and towards PED) mostly repeat words like 'planning' and 'solution', like the 'planning' stage projects, but given they are closer to 'implementation' they also display interest in 'heating' and 'supply'. In the sentiment analysis plot, we deduce that while the X-axis does not reflect a particular pattern, it is observed that projects that are still in the planning phase are more akin to depend on established facts for their documentation, whereas the implemented projects lean towards expressing more opinions (that hint their documentation is developed through experience) and do not have to depend solely on facts. The lessons learned from the preliminary analysis of these PED projects provide a starting point for achieving the objective of reducing the existing research gap in the characterisation of PEDs. A key aspect is facing the complexity of the urban system and the resulting interrelationships between social inclusion, energy systems, infrastructure, circular economy and mobility for sustainable urbanisation. This calls up building or PED-related simulation tools to tackle such challenges.

Moreover, a short summary about a few PED projects with a good level of detailed data has been further analysed in terms of their energy balance/flows. Table 3 provides the main energy concept/flows and some of them in implementation/operation stage have clear energy flows, such as Åland Island in Finland, Stor-Elvdal and Drammen in Norway. The annual energy flows in year 2030 for two scenarios (2030 - 100% Sustainable mobility: 1) 2030 SM Syn scenario - Domestic production of sustainable fuels 2030, 2) 2030 SM El scenario - High Electrification 2030) at Åland Island are illustrated in Figure 10 [47].

It is observed that the major energy contributions vary from district to district. For instance, Åland Island relies on biomass and wind power a lot, while Stor-Elvdal municipality prefers CHP plant, and in Drammen municipalities, heat pump is used mostly. However, these districts are not fully self-sufficient, and they must import energy to cover peaks. For instance, as shown in Figure 10, Åland Island must import 4 or 7 GWh electricity in 2030. It is not easy to judge whether they are PEDs or not at this stage, since there is no standard and KPIs available now. According to the mentioned work from EERA JPSC and JPI UE, four categories of PEDs have been established based on two main aspects: the boundaries and limits of the PED in order to reach a net positive yearly energy balance and the energy exchanges (import/export) in order to compensate for energy surpluses and shortages between the buildings or the external grid.

All the four described categories of PEDs (PED autonomous, PED dynamic, and PED virtual, Candidate-PED) are based on the accomplishment of a yearly positive energy balance, measured in greenhouse gas emissions, with use of renewables within the defined boundaries, and considering both building energy use and non-building energy use in a neighbourhood. Auto-and Dynamic-PEDs are the only categories where a net positive energy balance is achieved, and Candidate-PED should compensate the energy difference with imported certified energy from outside the boundary.

According to the boundaries descriptions aligned to the draft definition of PEDs from EERA JPSC working group and JPI Urban Europe, the net positive yearly energy balance is assessed within the functional or virtual boundaries. Thus, PEDs will achieve a net positive energy balance and dynamic exchanges within the functional/virtual boundaries, but in addition, it may provide a connection between buildings within the virtual boundaries of the neighbourhood.

Table 3: Summary of major energy concepts and flows of a few PED projects

| City/district | Country | Development stage in 2020 | Temporal scale | Major energy flows |
|---|---|---|---|---|
| Åland Island | Finland | Under implementation | Yearly | • Target: 100% self-sufficient and 100% fossil-free.<br>• Solar PV now: 1.7% to 0.7% of power demand.<br>• Wind now: about 20% of total power demand.<br>• Other sources, such as waste heat and CHP, bioenergy, wave power are still under implementation |
| Stor-Elvdal Municipality | Norway | In operation | n/a | • The demand for heat on the campus is covered by on-site heat production through the CHP plant.<br>• One-third of the electricity demand is covered.<br>• The rest is supplied by solar PV with batteries. |
| Drammen | Norway | In operation | Yearly | • 85% of the heating needs are met by the large-scale fjord source heat pump (13 MW). The rest 15% heating needs are met by gas fired boiler.<br>• The average annual energy supply is 67 GWh.<br>• The heat pump is significantly cheaper than a gas heating system, saving the city around €2.7 million a year.<br>• 1.5 million tonnes of $CO_2$ have already been saved by switching from gas to the ammonia heat pump. |
| Oulu | Finland | Under implementation | Yearly | • District heating system supplemented with solar PV and geothermal energy technologies.<br>• PV installations on the roof and geothermal heat pump and thermal borehole storage underneath the shopping mall.<br>• Surplus heat shall be used for refrigeration and seasonal energy storage tanks increasing self-reliance during peak loads. |
| Turku | Finland | Under planning | n/a | • Aim to become carbon neutral by 2029.<br>• 515 solar PV panels installed on new residential buildings will supply energy more than consumption in summer.<br>• Utilising the ground source heat with waste heat recovery extracted from 30 other buildings nearby.<br>• 1MW solar park is installed in the district by energy company, where company rents out solar panels and reduces consumer electricity bills.<br>• Solar thermal collectors are used to produce heat and store underground to use for winter needs.<br>• Further two-way heat trading facility is provided. |
| Tampere | Finland | Under implementation | n/a | • Solar PV farm installed outside the city will be used for energy needs inside the city along with geothermal local district heating and heat pumps. |
| Bodø | Norway | Under planning | Yearly | • Although this municipality has excess power production capacity, distribution networks is the main drawback in several places. Therefore, smart city goals are focused on achieving energy efficiency, creation of stable and sustainable energy systems, and reducing of peak demands.<br>• This energy system uses local renewable energy productions, supply and optimisation with regional, national, Nordic and EU electricity networks |
| Elverum | Norway | Under planning and implementation | n/a | • Firstly, reducing the energy demand in buildings and depending energy production on local renewable energy sources.<br>• Energy storage in the form of batteries or thermal energy storage |

| City/district | Coun-try | Development stage in 2020 | Tem-poral scale | Major energy flows |
|---|---|---|---|---|
| Trondheim | Norway | Under imple-mentation | n/a | • Conventional electricity is being provided by largely Hydro power with 21g $CO_2$eq/kWh, and district heating through burning local waste.<br>• Installation of solar PV arrays, heat pumps integration.<br>• Large 1,500 kWh battery storage would attribute in reaching the energy peak demands and surplus energy supply. |
| Bergen | Norway | Under planning | n/a | • Primarily improving energy efficiency to reduce energy demand.<br>• Individual energy systems based on renewable energy sources such as PV, thermal technologies are developed.<br>• Further surplus power will be supplied to EV mobility solutions |
| Odense | Den-mark | Under imple-mentation | Yearly | • To eliminate fossil fuels by 2025 and reach to top 3 cheapest district heating price in Denmark.<br>• District heating supply with waste heat, energy power production from renewables such as wind power.<br>• Further strategically investing in smaller energy units which include 10-20 MW heat pumps, 30-50 MW biomass boilers and +50 MW electric boilers etc. |
| Osterby | Den-mark | Under imple-mentation | Yearly | • The project aims to reduce the heating costs from district heating with other networks.<br>• Connecting and sharing energy with the large district heating facilities with neighbourhoods reflecting energy flexibility.<br>• 2.07 MWp PV roof mounted installation that will operate the cooling machines in the mall. |
| Lund | Swe-den | Under imple-mentation | n/a | • Producing heat through local waste is enough to provide heating for the whole area.<br>• Large scale district heating is installed to provide low temperature applications with renewable energy systems integration. |
| Lund (Brunnshög) | Swe-den | Under imple-mentation | Yearly | • Existing district heating used by biomass will be replaced by large scale biofuel CHP plant along with geothermal energy unit, waste heat combustion and district cooling heat pumps etc. |
| Lund (Medi-con Village) | Swe-den | Implementation completed | Yearly | • Primarily trying to reduce the energy needs yearly by improving energy efficiency.<br>• Installing solar power on rooftop of buildings for more sustainability. |

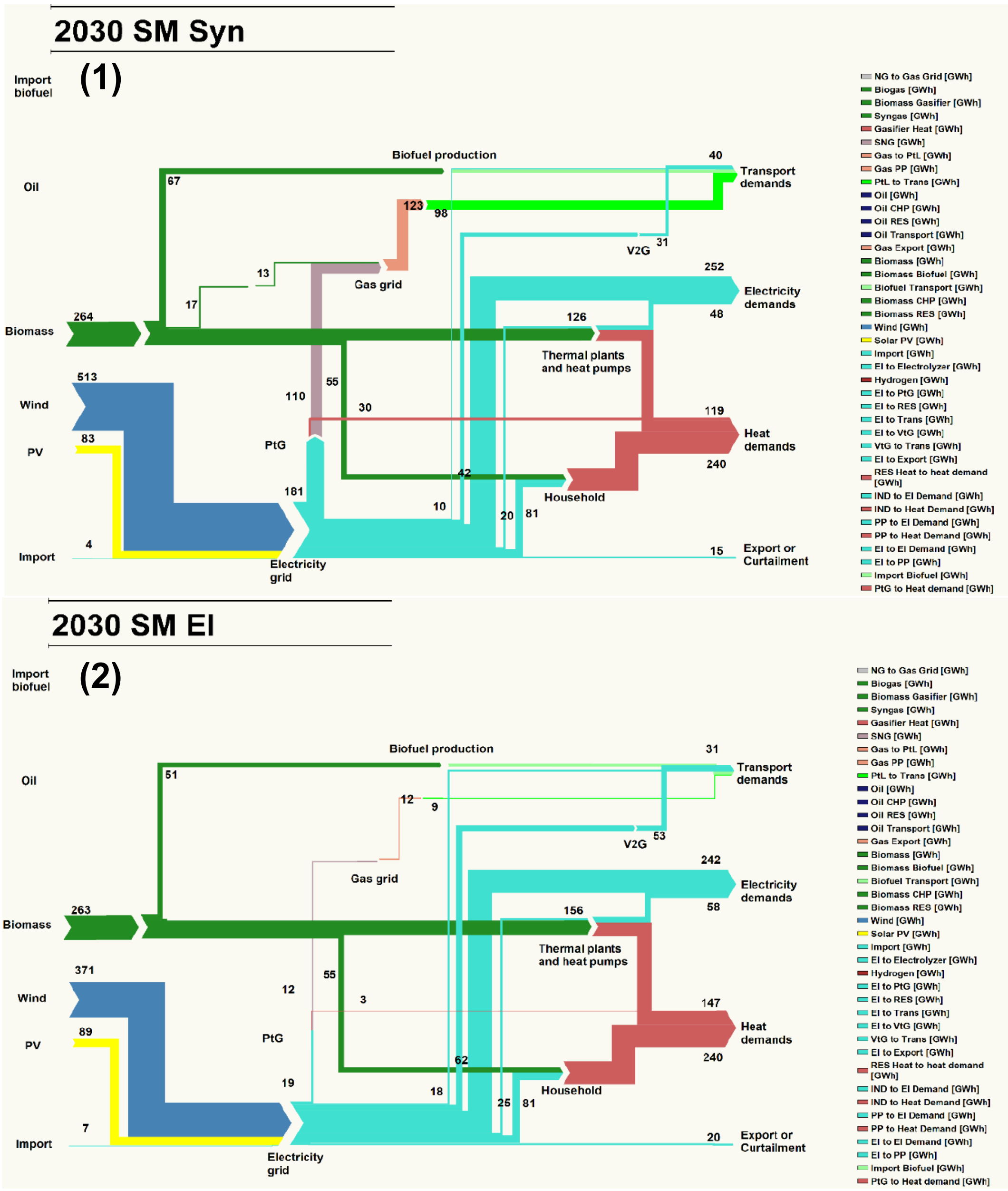


Figure 10: The annual energy flows at Åland Island towards 2030 target - 100% Sustainable mobility for two scenarios: (1) SM Syn scenario - Domestic production of sustainable fuels and (2) SM El scenario - High Electrification [47]

It is necessary to pay specific attention to the differences between cities across different regions, when promoting the development of PED. This is because cities differ from each other at the local, national and international levels from the perspectives of geography, resources, social, economy, culture, infrastructure, and progress for carbon-neutral target. This would bring differences in planning, technology selection/implementation, investment portfolio, stakeholders' involvement, regulations, etc., during the PED development. However, it is important to have a commonly recognised definition of PED, and its related KPI framework for evaluation. By learning the main characteristics from those existing PED projects in EU, it is helpful to define PED or propose 'reference PED' in other cultural and geographical contexts, which will bring significant common values in term of replicability and potential mainstreaming of PED across the globe.

### 4.2.3 Application of artificial intelligence (AI) for PEDs

Renewable energy sources constitute a crucial component of the electricity grid regarding reliability, affordability, and environmental impact [48]. Real-time estimation of produced energy from renewable sources is essential for the planning, management, and operation of electrical power and energy systems. Given the intermittent and unpredictable nature of renewable energy, it is essential to use forecasting as a means of reducing associated risks. This is important for the management and operation of electrical power and energy systems in PEDs. Although applications of machine learning (ML) for renewable energy are mostly related to solar and wind energy predictions, studies that benefit from ML models to model energy production from renewable sources can be found across a wider range, including solar energy, wind, hydropower, geothermal energy, biomass and wave [49]. Meanwhile, NLP approaches have also been applied to develop PEDs by focusing on energy efficiency, energy production, sustainability issues, context, markets, and land use [50], as well as dissemination of PEDs through ChatGPT [51].

Figure 11 illustrates the main application of AI for PED development. In terms of the ML method, it is found that Artificial neural networks (ANNs), support vector machines (SVMs), and tree-based approaches are three representative models for PED. In terms of NLP method, topic modelling, word embedding, and large language model-based semantic modelling are three primary NLP tasks, for instance, the large language mode BERT can be quickly deployed to create a comprehensive picture of a PED and increase semantic interoperability between buildings by analysing building metadata. This modelling framework can directly enable the effective monitoring and optimisation of a buildings' energy use and thus improve energy efficiency. This can be achieved by analysing building occupancy information, user feedback, and real-time sensor data. Word embedding, through its ability to capture semantic relationships between sequential objects, such as words and geographical positions, can enhance the efficiency of information representation. By mapping out the semantic space of discussions and textual information, stakeholders can gain deeper insights into public opinions, concerns, and expectations regarding PED projects. Another example is the way that deep ANN can facilitate the achievement of indoor comfort through system control in a highly intricate environment. By incorporating an ample supply of data, this sophisticated model structure can effectively capture the nonlinearity of a system, thereby enabling smart control actions to be taken. SVMs, renowned for their design phase, stakeholder matching could be used to identify the most effective sustainable design strategies, while evolutionary algorithms could be used to optimise the placement and sizing of renewable energy systems.

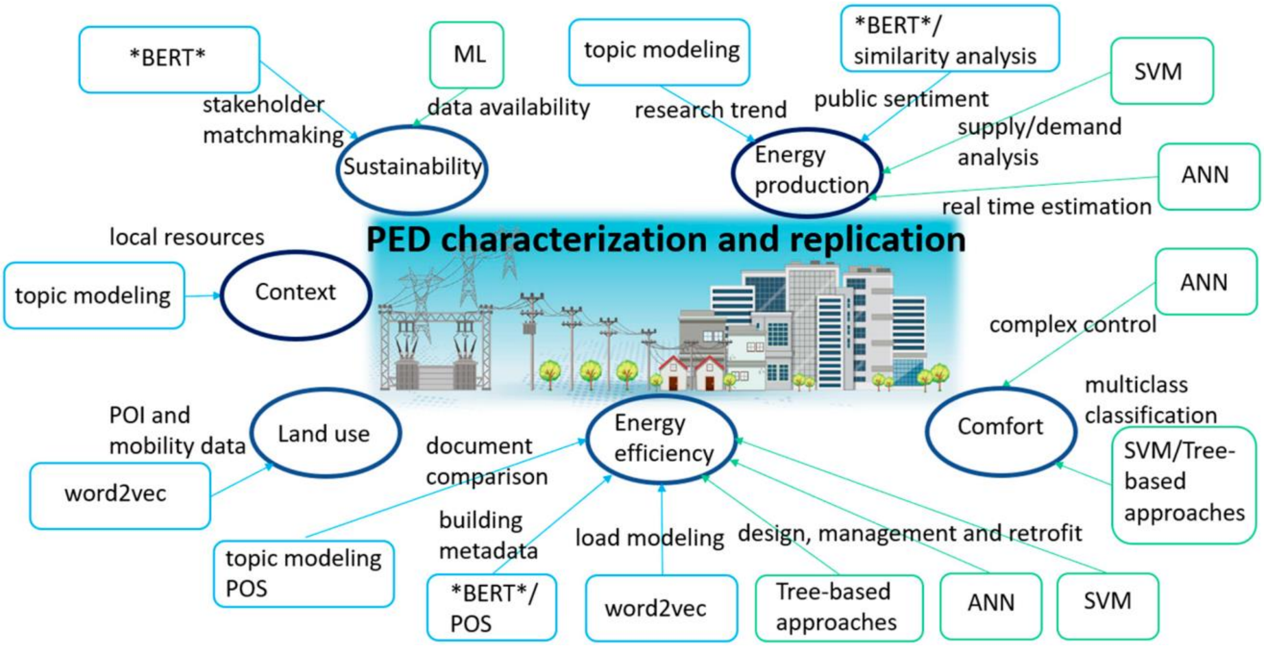


Figure 11: Key features of ML and NLP in PED characterisation and replication

## 4.3 Development of PED archetypes

Climate plays a critical role in creating archetypes for positive energy districts due to its effect on energy generation, systems, and demands. While other factors like district type (urban vs. rural), size, and boundaries matter, **climate directly affects energy needs** and **renewable energy potential** [52]. For example, colder climate requires more energy for heating, while warmer climate demands cooling. These fluctuations must be addressed in PED design to ensure systems are efficient and resilient year-round.
The development of PEDs across Europe is deeply influenced by climatic conditions, local resources, and national energy strategies. To better understand these patterns, four consolidated climate zones, based on the Köppen-Geiger classification, are used to analyse the trends in PED energy generation technologies. The study particularly focuses on the alignment of technological options with regional climate characteristics and energy demands. The climate-oriented grouping reveals how districts approach energy positivity based

on the inherent characteristics of the natural environment and in turn, helps to shape consistent PED archetypes.

This climate-based archetype analysis represents a first step towards understanding how PED design responds to environmental conditions across Europe. The patterns identified here demonstrate how climate significantly shapes technology choices and system configurations. However, this approach is inherently limited to the climatic dimension, as it relies on the most consistently available data across the case studies in the PED-EU-NET database. The findings presented should therefore be seen as a starting point and not a completed framework. Expanding the analysis to include more detailed information on other critical factors such as system boundaries, PED types (autonomous, dynamic etc.), urban density, ownership models, and socio-economic conditions, would enable the development of a more comprehensive archetype framework. Additionally, it is important to acknowledge that the use of the term "archetype" in this context refers specifically to climate-driven patterns of technology adoption and system design. This should not be confused with the established classification of PED types developed by EERA JPSC (Section 2.2.1), which are defined based on energy system boundaries and grid interaction models. The influence of other relevant factors will be further discussed in section 4.3.5.

To conduct this analysis, the 86 PED case studies collected in the PED-EU-NET database were categorised according to their respective climate zones, based on a simplified version of the Köppen-Geiger climate classification, which captures the major climatic variations relevant to energy demand and renewable energy potential across Europe. In order to avoid over-complicating the analysis and to maintain a sufficient sample size within each group, Köppen-Geiger climate classification with similar climatic characteristics and similar observed energy system trends were grouped together. This approach allows for a balance between analytical clarity and statistical robustness. As a result, four consolidated climate zones were identified: Mediterranean, Marine West Coast, Humid Continental, and Continental Subarctic. This grouping enables the identification of common energy system configurations and technological choices that align with the environmental constraints and opportunities within each climate type.

Table 4 Climate Zone Grouping based on 86 PED cases in the PED-EU-NET database.

| PED Climate Archetype | Köppen-Geiger Climate Zone | Number of case studies |
|---|---|---|
| **Mediterranean** | Csa, Csb, Cfa, Cwa | 18 |
| **Marine West Coast** | Cfb, Cwb | 28 |
| **Humid Contentinal** | Dfa, Dfb, Dwa, Dwb, Dsb | 35 |
| **Continental Subarctic** | Dfc, Dfd, Dwc, Dwd | 5 |

In Table 4, each climate zone is listed alongside the number of PED case studies it represents. This provides essential context for interpreting the percentage values of energy technologies used, allowing for a more accurate understanding of how frequently each system appears relative to the total number of case studies per climate type. The following sections present a detailed analysis of each climate-based PED archetype, highlighting the dominant technologies, key design strategies, and how districts respond to their specific climatic challenges.

### 4.3.1 Mediterranean Climate

Mediterranean climate PEDs are the combination of the climates mediterranean (Cfa, Cwa) and Humid tropical (Csa, Csb) climates. PEDs in these climates reflect a shared emphasis on solar energy and climate-responsive design. These regions—includes countries such as Spain, Italy, Portugal, Greece, Balkans and Turkey—exhibit hot summers, mild to cool winters, and high solar irradiance throughout most of the year. While the Mediterranean areas tend to be drier, the humid subtropical zones exhibit higher humidity and slightly greater heating needs in winter. Despite these differences, both climates foster solar-centric PED strategies driven by environmental ambition, urban comfort priorities, and the practicality of decentralised energy production.

The common denominator across these regions is a climate that demands more cooling than heating, especially in urban centers. The hot summers, frequently exceeding 30°C, create strong incentives for shading, passive cooling, and efficient electric cooling systems. Winters, while cooler in humid subtropical areas, are generally mild enough that heavy-duty heating systems—like district heating—are unnecessary or economically unjustified.

One of the defining features of this archetype is the dominance of solar-based energy systems, particularly photovoltaics and solar thermal collectors. This prevalence is the outcome of the region's high solar irradiation levels, often exceeding 2,500 hours of sunshine annually. This makes solar technologies not only abundant but also economically viable and widely supported by EU funding programs and national incentives.

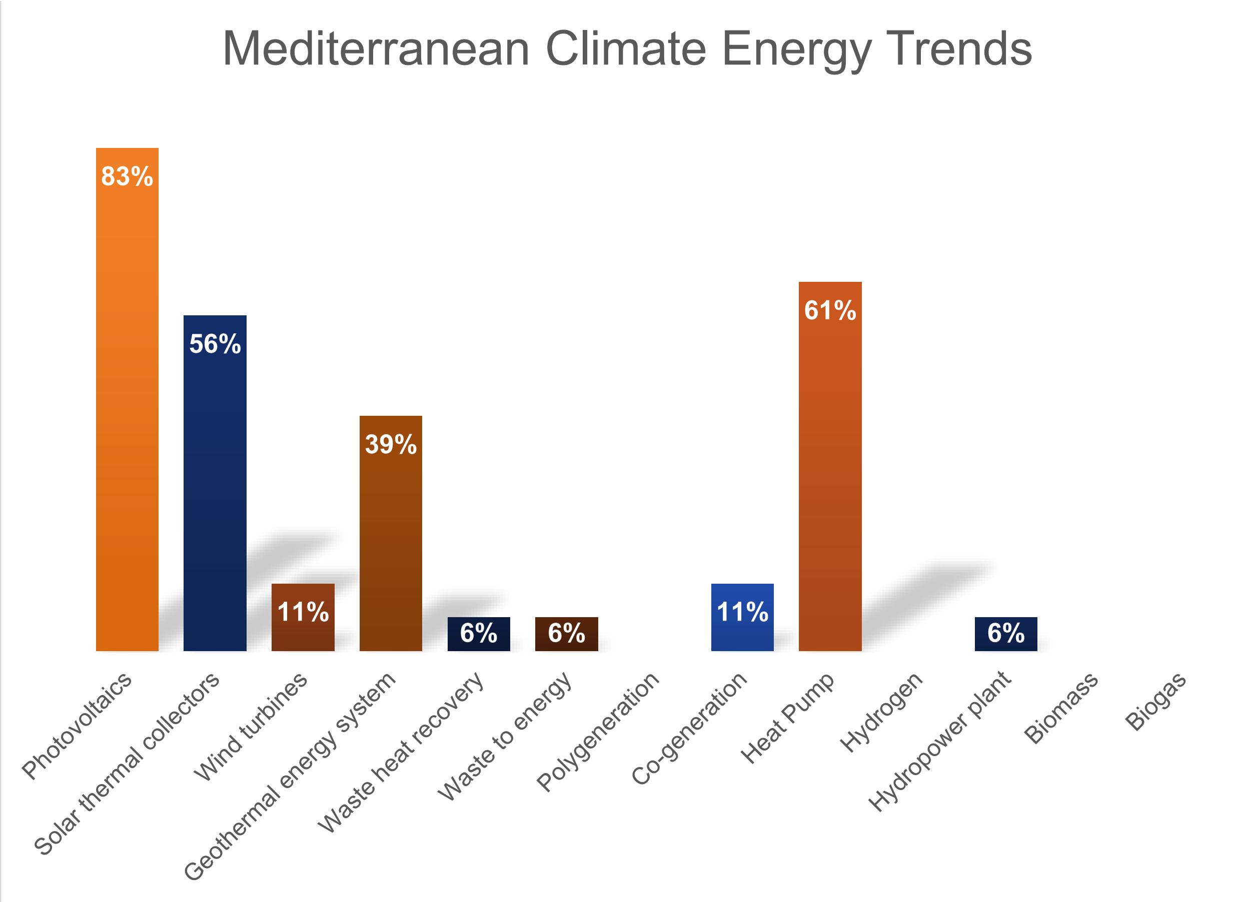


Figure 12: Distribution of Energy Technologies used in Mediterranean Climate

Photovoltaics (PV) are used in 83% of cases, benefiting from consistent solar irradiance and relatively stable daylight hours. Solar thermal collectors, present in 56% of PEDs, efficiently provide hot water and light heating, especially during mild winters. Heat pumps are used in 61% of cases, offering both heating and cooling well-suited to Mediterranean needs. Geothermal systems appear in 39% of PEDs, mainly where large-scale infrastructure is feasible, though their adoption is limited by cost and urban constraints. Less common technologies include wind turbines (11%), constrained by low urban wind speeds and siting issues, and waste-to-energy and hydropower (each 5.5%), limited by scale and environmental factors. Biomass, biogas, hydrogen, and co-/polygeneration see minimal use (0–11%) likely due to emissions, logistics, and technological immaturity.

Overall, Mediterranean PEDs prioritise scalable, solar-driven systems that align with local climate, urban form, and sustainability goals—favouring efficiency, simplicity, and year-round reliability.

### 4.3.2 Marine West Coast Climate

Marine West Coast climate is usually seen in Central and Northern Europe, including parts of Germany, France, the Netherlands, the UK, and Austria. These areas are defined by moderate temperatures, high humidity, and consistent precipitation year-round. Unlike the sun-intensive strategies of the Mediterranean, Marine West Coast PEDs rely on a hybrid mix of generation technologies and demand-side flexibility to adapt to their less predictable climate and mature urban landscapes. The energy generation trends observed in Marine West Coast PEDs reflect this hybrid climatic profile, combining solar, electrified heating, and a range of complementary or backup systems to ensure year-round reliability.

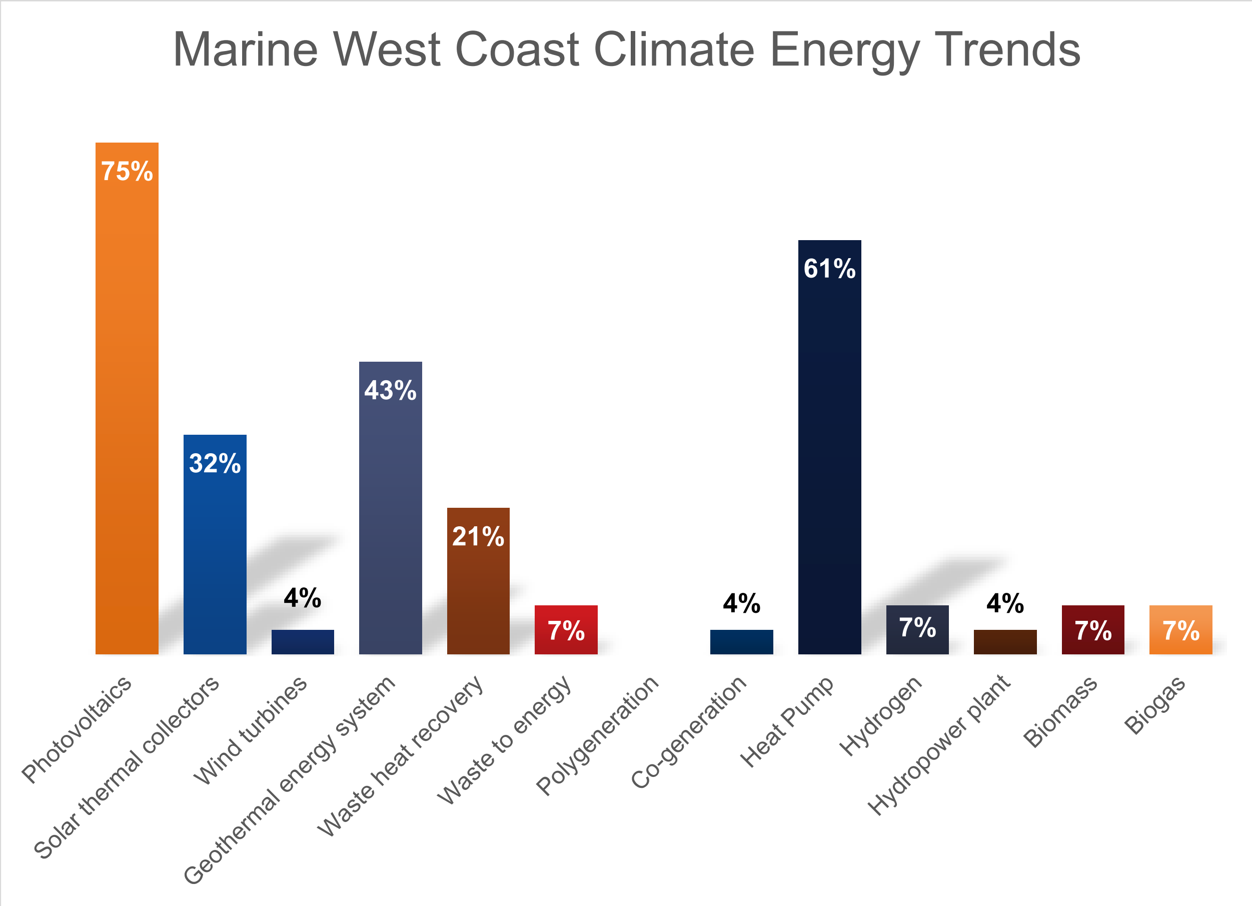


Figure 13: Distribution of Energy Technologies used in Marine West Coast Climate

Photovoltaics (75%) are the most widely used energy system in Marine West Coast PEDs reflecting a strong commitment to decarbonisation through renewable electricity. Despite lower solar insolation compared to Mediterranean regions, the high adoption rate demonstrates how policy support, falling costs, and technological improvements have made PV a feasible and effective solution—even in cloudier climates. Heat pumps (61%) are also heavily used, offering an efficient way to electrify heating in regions where heating demand is steady and long-lasting, though not extreme. Both air-source and ground-source heat pumps are common, with many integrated into district heating networks to improve performance and scalability. Their dual function for heating and cooling also adds year-round utility. Geothermal systems (43%) are increasingly incorporated to provide stable, renewable heat that isn't dependent on weather conditions. Shallow geothermal benefits from suitable soil conditions and established technical expertise. Their use highlights a growing emphasis on climate-resilient systems that complement variable renewable sources like PV.

Several other technologies are moderately present:

- Solar thermal collectors (32%) are used primarily for domestic hot water in buildings with suitable roof space, particularly multifamily housing and public facilities.
- Waste heat recovery (21%) and co-generation (4%) appear in districts where industrial processes or dense infrastructure allow for effective reuse of thermal energy.
- Wind turbines (4%) and hydropower (4%) remain rare due to spatial constraints and limited suitable sites within urban areas.

Other technologies such as biomass, biogas, hydrogen, and waste-to-energy each appear in about 7% of PEDs. These are typically found in municipal or research-led districts and face hurdles including emissions concerns, air quality regulations, cost, and infrastructure readiness. Polygeneration (0%) is entirely absent, likely due to its complexity and redundancy in areas where simpler, modular systems—like PV paired with heat pumps and storage—are sufficient.

In summary, Marine West Coast PEDs exemplify a Balanced Hybrid model. Unlike the solar-centric Mediterranean approach, these districts rely on a blend of technologies tailored to moderate climates with consistent heating needs and variable solar potential. The combination of PV, geothermal, heat pumps, and thermal reuse systems creates a resilient, flexible, and scalable energy concept that can support long-term decarbonisation goals while adapting to seasonal and climatic variations.

### 4.3.3 Humid Continental Climate

Humid Continental regions generally include areas like south of Scandinavia, the Baltics, Poland and parts of Northern and Eastern Germany. These areas are defined by their significant seasonal contrasts—cold winters, warm summers, and moderate precipitation throughout the year. This climatic duality demands a robust, highly adaptable energy system, which has driven PEDs in this zone toward technologically integrated, efficiency-driven solutions that emphasise resilience, low-carbon heating, and smart management systems.

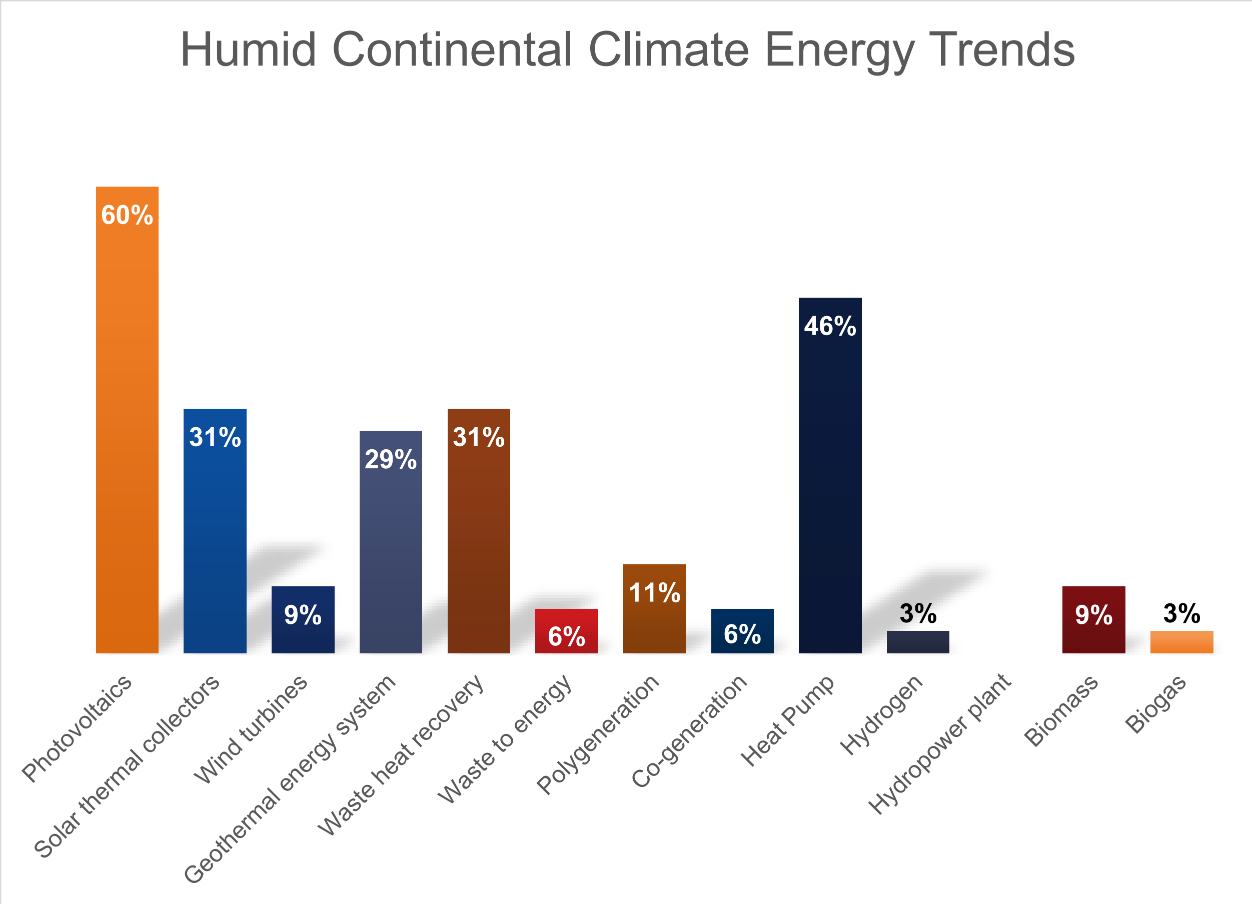


Figure 14: Distribution of Energy Technologies used in Humid Continental Climate

Energy generation trends in this climate reveal a diverse but electricity-oriented strategy, shaped by the dual need for substantial heating in winter and cooling in summer. Photovoltaics (60%) remain the most used generation technology, leveraging long daylight hours in summer to support both building-level and district-wide electricity needs. While solar conditions are less consistent than in Mediterranean climates, generous feed-in tariffs, EU subsidies, and improved PV efficiency have made solar viable even at northern latitudes.

Heat pumps (46%) are also widely adopted, offering an electrified solution to space heating and cooling. Their efficiency and compatibility with building retrofits (e.g., wall insulation) make them a practical option for climate-neutral heating—particularly in residential and public sector applications. The relatively lower adoption rate compared to Marine West Coast PEDs may reflect legacy infrastructure, higher upfront costs, and climatic extremes that challenge heat pump performance during cold snaps. In some cases, hybrid systems are required for backup.

Geothermal energy systems (29%) are deployed in select regions with favourable geological conditions. These systems provide stable, weather-independent heating, which is especially valuable in winter-heavy climates. Adoption is more common in areas with supportive geological conditions and urban planning frameworks, though widespread deployment is often constrained by the complexity and cost of installation in dense urban environments.

Supporting and flexible technologies include:

- Solar thermal collectors (31%), primarily for domestic hot water in multifamily or district systems during summer.
- Waste heat recovery (31%), especially in industrial districts like those in Poland or the Czech Republic, improving thermal efficiency.
- Polygeneration systems (11%), more common here than in other climates, reflecting a desire for multi-output systems to address variable seasonal demands, though complexity remains a barrier.

Other less common but emerging technologies include:

- Wind turbines (9%), biomass (9%), and co-generation (6%), are occasionally used where spatial, economic, or regulatory conditions allow, though biomass is limited by air quality concerns.
- Waste-to-energy (6%), biogas (3%), and hydrogen (3%) are also present but minor. These are often tied to municipal waste management or research-driven projects, rather than mainstream deployment.

In summary, Humid Continental PEDs demonstrate a commitment to electrification and thermal adaptation, forming a flexible response to the region's extreme seasonal variability. The reliance on PV, heat pumps, geothermal systems, and waste heat recovery underscores a drive toward multi-season performance, while emerging technologies continue to evolve in parallel. These PEDs represent a technologically balanced and resilient energy model, optimised for long winters, summer cooling, and a growing demand for sustainable urban development across Eastern and Central Europe.

### 4.3.4 Continental Subarctic

Continental Subarctic climates, encompasses parts of northern Sweden, Finland, Norway, and extreme northeastern European territories such as Siberian Russia. These regions experience long, harsh winters, very short summers, and extreme seasonal variations in daylight, creating unique energy challenges that are met with a holistic, circular approach to resource management, energy recovery, and resilience. PEDs in these areas reflect some of the most technically advanced and thermally efficient systems, driven by strong policy frameworks, high energy standards, and long-standing experience with district heating. The energy systems chosen emphasise reliability, low emissions, and independence from fossil fuels, aligning with both climate demands and progressive national decarbonisation goals.

Photovoltaics (80%) are surprisingly prevalent despite limited winter sun, reflecting significant investment in high-efficiency PV panels, smart energy management, and seasonal compensation strategies. These countries often optimise solar during the summer, storing surplus electricity or using it to reduce grid reliance. Policy incentives and renewable energy targets also support PV uptake, even in high-latitude zones. Solar thermal collectors (80%) are equally common and serve as a primary method for domestic hot water production during the sunnier months. Their popularity reflects both building design practices (which often incorporate thermal storage) and the extensive use of shared systems in multifamily and district-scale projects.

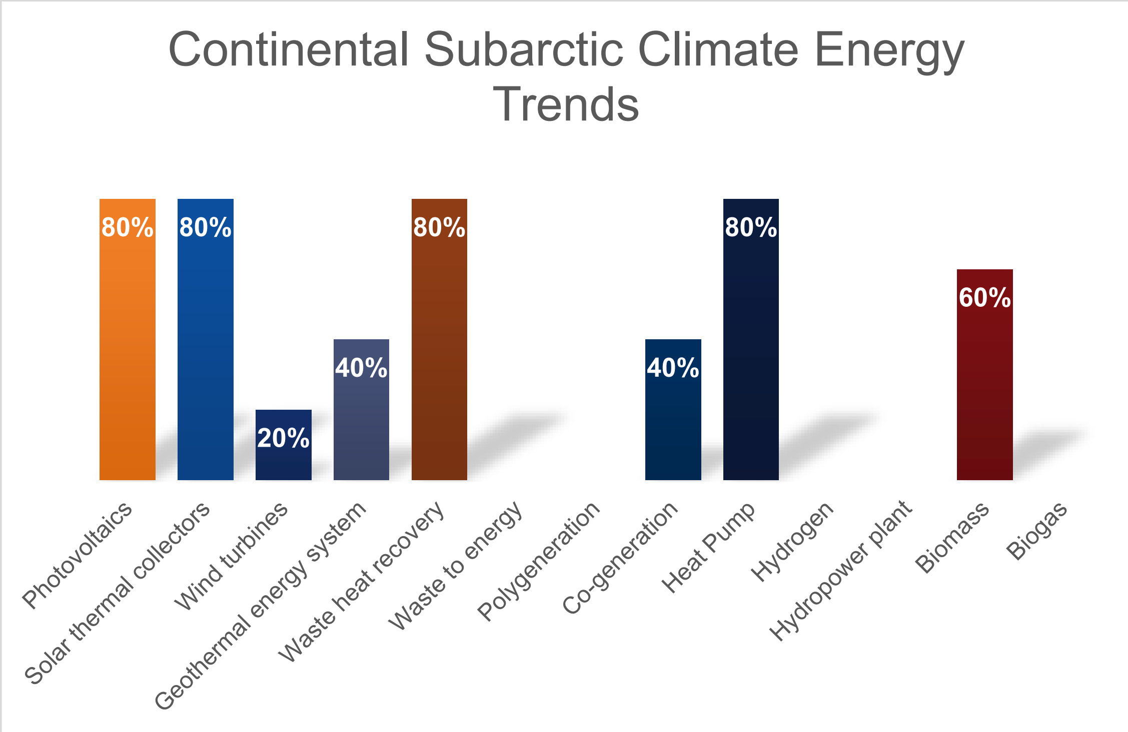


Figure 15: Distribution of Energy Technologies used in Continental Subarctic Climate

Heat pumps (80%) are widely used, offering a low-carbon and efficient heating solution. Their performance is optimised through integration into district heating and energy-positive buildings designed to minimise heat loss. In subarctic climates, these systems often work in tandem with thermal storage or secondary backup systems to manage peak winter loads.

Waste heat recovery (80%) is highly utilised in this archetype, reflecting the maturity of industrial-urban integration in Nordic countries. Big cities in countries like Finland and Sweden have long relied on waste heat from data centres, subways, or industrial processes, capturing this resource into district networks. The high adoption rate signals a circular energy mindset that's deeply embedded in urban planning.

Geothermal (40%) and co-generation (40%) play key roles in subarctic PEDs, especially where district heating infrastructure exists. Shallow geothermal systems are more feasible than deep ones and help reduce fossil fuel use, while co-generation efficiently provides both heat and power in dense urban areas.

Biomass (60%) is a major energy source, widely used in combined heat and power (CHP) plants or as backup heating. Owing to sustainably managed forests in Nordic countries, biomass is considered a carbon-neutral and scalable solution for cold climates, though concerns over emissions and long-term sustainability are growing.

Other technologies are used sparingly:

- Wind (20%) appears mainly in rural or open areas, limited in cities by space and regulation.
- Hydropower, hydrogen, biogas, waste-to-energy, and polygeneration (all 0%) are largely absent due to geographic constraints, lack of infrastructure, or system complexity. Air quality standards also limit combustion-based systems in urban zones.

In summary, Continental Subarctic PEDs exemplify a model of deep thermal efficiency and seasonal energy balancing. They focus on electrified heating, solar-thermal synergy, biomass integration, and advanced district systems to cope with extreme temperature and low solar availability in winter. These districts represent the cutting edge of PED development, not only surviving in harsh climates but pushing the frontier of low-carbon and high-resilience urban energy.

#### 4.3.5 Influences of Other Factors

While the archetypes presented in this study are based on climatic conditions, it is important to emphasise that climate is only one of several key factors influencing the development and configuration of PEDs. The focus on climate stems from the fact that it is the only variable consistently available across all 86 case

studies in the PED-EU-NET database, which enables a sufficiently large and comparable sample size for analysis. Climate has a direct and well-understood influence on both energy demand patterns (particularly for heating and cooling) and the feasibility of different renewable energy sources, making it a logical starting point for an initial archetype analysis.
However, this approach is inherently limited. While climate plays a crucial role, it is only one dimension of PED context and does not capture the full range of factors that shape PED design, operation, and performance. Other contextual characteristics, such as urban morphology, population density, building typologies, and spatial layout, are also highly relevant. For example, PEDs located in dense urban centres may face significant spatial constraints for renewable energy generation, leading to different design choices compared to those in suburban or rural areas. Similarly, building types and usage patterns significantly influence demand profiles and technological configurations.
Additionally, it is important to clarify that the climate-based archetypes developed here are fundamentally different from the commonly referenced PED types, such as PED-autonomous, PED-dynamic, PED-virtual, and Pre-PED. These PED types are defined by the system boundaries and the degree of energy interaction with the wider grid, rather than by contextual environmental conditions. In theory, it would have been highly valuable to integrate this dimension into the analysis—for example, by examining how technology patterns differ between autonomous PEDs and dynamic PEDs, or between geographically bounded and virtually aggregated districts. However, the PED-EU-NET dataset provides very limited information on system boundaries and does not include PED type classification at all. This is primarily because, while PED types are widely recognised in the research community, they are not systematically applied by most PED projects in practice and typically remain an optional information rather than a standardised classification criterion within project reporting. This gap between research and practice is itself a reflection of a broader challenge in the PED landscape, the lack of a common definition and classification framework. As a result, if such an analysis were attempted based on the limited available data on system boundaries, the sample sizes would become too small to support a statistically robust analysis. This limitation is even more pronounced for PED types, where the data is entirely absent from the database. Consequently, this study focuses on the climatic context, which provides the only variable with sufficient coverage to support a meaningful and representative analysis across a large number of PED case studies.

Beyond system boundaries, urban form, and climate, there are several additional factors that significantly influence PED development but were not possible to include in this analysis. These include:

- **Ownership models**, which affect decision-making processes, investment capacities, and stakeholder collaboration.
- **Economic viability**, including funding mechanisms, business models, and return on investment expectations, which directly shape which technologies are selected and how PEDs are operated.
- **Regulatory frameworks**, which can either enable or constrain certain solutions based on local, regional, or national policies, planning regulations, and market rules.
- **Social factors**, such as community engagement, social acceptance, and demographic profiles, which influence demand flexibility, energy sharing, and long-term success.

The importance of incorporating these additional factors is strongly reinforced by recent work from Schneider et al. [53] who propose a comprehensive quantitative framework for defining PEDs based on contextual targets. Their framework introduces the concept of adapting PED energy balance goals to local conditions, including urban density, mobility patterns, renewable energy supply potential, and embodied emissions. This approach also directly aligns with the argument that PED assessment should take into account the specific potential and context of each district. It acknowledges that not all districts can achieve the same performance targets due to physical, geographical, infrastructural, or socio-economic constraints.

Incorporating all these factors into a single archetype analysis, however, would be extremely challenging given the data limitation of PED-EU-NET database. It would either require excluding many case studies due to missing data, which would dramatically reduce the sample size or risk oversimplifying complex variables to maintain consistency. This tension between completeness and complexity highlights the need for balance: while a detailed, multi-dimensional archetype framework is absolutely necessary for long-term PED research and implementation, it also requires a significant improvement in the quality, consistency, and completeness of PED data reporting.

Therefore, one of the key tasks for the PED research community moving forward must be to prioritise filling critical information gaps in PED databases, particularly regarding system boundaries, PED types, ownership models, and socio-economic characteristics. Although this creates additional complexity in analysis, it is a necessary step toward developing a robust, standardised PED framework that accurately reflects the diversity of real-world conditions. This future direction is essential not only for scientific accuracy but also for supporting effective policymaking, funding mechanisms, and planning practices that are sensitive to local constraints and potentials.

In summary, while this study provides a valuable first step in identifying climate-based PED archetypes, it is clear that a more comprehensive and context-sensitive framework is needed. Future research should integrate climate with additional factors such as system boundaries, urban form, ownership models, mobility patterns, and regulatory contexts, as emphasised by Schneider et al. [53]. Doing so will enable the creation of a multi-dimensional PED typology that is not only technically rigorous but also adaptable, equitable, and aligned with the broader goals of climate neutrality and sustainable urban transformation.

#### 4.3.6 Summary

This study analyses 86 Positive Energy District (PED) case studies across Europe to understand how climate conditions influence energy system configurations. The findings reveal clear and consistent patterns, with distinct climate-based PED archetypes emerging across different regions. These archetypes demonstrate how climate directly affects both energy demand—particularly heating and cooling—and the suitability of renewable energy sources.

In **Mediterranean and Humid Subtropical climates**, the **Solar Dominant archetype** prevails, prioritising photovoltaics and solar thermal supported by heat pumps for limited seasonal needs. Heating demands are low, making biomass or co-generation rarely necessary.

The **Marine West Coast climate** shows a **Balanced Hybrid archetype**, where PEDs adopt a mix of photovoltaics, heat pumps, geothermal systems, and moderate waste heat recovery. This diversified strategy reflects the need for flexibility under lower solar availability and consistent heating demands.

In **Humid Continental climates**, characterised by cold winters and warm summers, PEDs follow a **Thermal-Electric Hybrid archetype**. These districts use heat pumps and geothermal alongside biomass, co-generation, and waste heat to meet high heating needs, with photovoltaics contributing significantly in summer.

Finally, in the **Continental Subarctic climate**, the **Arctic Thermal Resilience archetype** emerges. PEDs rely heavily on heat pumps, geothermal, biomass, waste heat recovery, and photovoltaics to ensure resilience in extreme cold. Solar thermal is also common but limited during long dark winters.

While this climate-driven analysis offers valuable insights, it represents only one dimension of PED design. Climate was selected as the primary lens because it is the only variable consistently available across the entire PED-EU-NET database. However, it is crucial to acknowledge that **PED development is not determined by climate alone**.

Each PED is deeply shaped by a combination of local factors, including:

- **Urban morphology and spatial constraints**, which determine the feasibility of deploying technologies like rooftop photovoltaics, geothermal fields, or district heating systems.
- **Existing infrastructure**, such as district heating networks or electricity grid capacity, which influences technology selection.
- **Population density and building typologies**, which shape energy demand profiles and whether solutions are centralised or decentralised.
- **Regulatory and policy frameworks**, which can enable or restrict certain technologies depending on planning rules, grid regulations, or energy policies.
- **Ownership models and economic viability**, affecting investment decisions, business models, and stakeholder engagement.
- **Social factors**, including community acceptance, participation, and demographic profiles, which directly impact operational success and demand flexibility.

This limitation highlights the need for a **multi-dimensional PED framework** that moves beyond climate to incorporate spatial, technical, economic, regulatory, and social factors. Such a comprehensive framework is essential to accurately reflect the diversity of real-world PED contexts and ensure that solutions are not designed as one-size-fits-all but are tailored to local potentials and constraints.

In conclusion, while this study offers a valuable first step in defining climate-based PED archetypes, it also underscores that **climate is only one piece of the puzzle**. PED design and implementation are inherently context-dependent, shaped by a complex interplay of environmental, spatial, economic, regulatory, and social factors. Therefore, building a robust, adaptable, and comprehensive PED framework is essential—not only for ensuring technical success but also for supporting the broader goals of **scalability, replicability, and standardisation**, which are critical for Europe's transition toward climate-neutral, resilient, and sustainable cities.

# 5. PED Processes

As outlined in Chapter 2, the discourse on PED has shifted the last year. The meaning of “positive” has been reinterpreted from a narrow definition of a positive energy balance to a broader sense of driving positive urban changes concerned with a positive development in the quality of life for the people living in a PED. The evolution of the PED concept also necessitates an update of our thinking about the process flow of PED development, how we address the shifting constellation of PED stakeholders to drive PED development as well as PED-related regulations and legal barriers.

## 5.1 Reimagining the process flow of PED development

That ‘a PED is a process, not a product’ has already been acknowledged back in 2020 [54]. Furthermore, its set-up ‘will always involve multiple building blocks and a large number of stakeholders and contributors, which will each have their own ambitions, agendas, interests and constraints'. It is generally accepted to regard PED as a complex process that entails at least four aspects. First, the PED process requires a high degree of coordination due to the multi-stakeholder environment. Second, the PED process involves a disruptive urban transformation at large-scale as it affects blocks of buildings rather than single buildings. Third, the PED process takes into account not only technical but also social, economic, regulatory, legal or financial issues. Finally, the PED process considers scaling and replication factors in order to achieve a relevant impact on the city, aligned within the city strategies integrating pillars of energy systems and spatial planning.

Given its complexity and its intersection among sectors such as construction, energy, real estate, and the built environment in general, the phases of PED development and the levels of granularity are not universal. Phases of PED development would be dependent on whether the PED project is a new build or a refurbishment/ retrofit, the building scale vs. district scale infrastructures, and further juxtaposed against the local social, economic, regulatory aspects.

The conventional thinking has been to regard the key phases of PED development as comprising a series of linear steps (see Table 5). These steps are recognisable stages of a so-called structural-functionalism model which uses the rational planning approach to discuss and analyse the underlying complexities and uncertainties, where visioning and objective-setting, strategy development, implementation and monitoring/evaluation can be neatly planned out.

Table 5 Conventional thinking of key phases in PED development [55]

| | PED as a process |
|---|---|
| I. | Master planning |
| II. | Energy planning (Mobility, Renewables, Flexibility) |
| III. | Construction/Refurbishment planning |
| IV. | Implementation |
| V. | Operation |
| VI. | Monitoring |
| VII. | Post occupancy Evaluation |

With the meaning of ‘positive’ gravitating more and more to a broader sense of driving positive urban changes concerned with a positive development in the quality of life for the people living in them, PEDs increasingly come to represent innovative place-based strategic approaches aimed at advancing our climate goals within the built environment. Achieving human-centric PEDs requires a transdisciplinary collaboration and a co-creation approach, bridging gaps between the public sector, business sector, research and technology sector, and end users [56]. In practice, the PED process flow can more aptly be characterised as more emergent and adaptive – comprising iterative, small steps – rather than the linear deliberate approach. In unravelling the complexities of ongoing PED projects, researchers have been uncovering that conventional planning paradigms are giving way to more adaptive approaches in governance structures where numerous initiatives operate beyond the formal project structure [57]. For example, informal voluntary agreements and the role of social science expertise can be pivotal to the success of a PED development. An informal voluntary agreement (written in accessible language) among the project developer, the city municipality, the architects, and other relevant planners describes the goals and expectations of the PED project (such as management, communication, urban development, buildings, energy, mobility). Not only does such a governance mechanism foster trust and coordination, it also enables new actors to have the same picture, be it to catch up on the project development or whenever questions arise, since stakeholder roles can shift in a PED project. The role of social science expertise in PED projects can also be pivotal as part of the overall governance mechanisms. Sociologists can undertake the work to analyse the neighbourhood infrastructure and development of common areas, as well as to organise community activities and engage residents in the project. The involvement of sociologists can also be regarded as part of the process flow of PED development as it facilitates the integration of non-technical and human-centric aspects into the project, establishing a culture of interdisciplinary collaboration.

Much attention has been given to the pre-implementation and planning/ design phases compared to how PEDs are built, operated and managed once the planning/design are completed. It is also possible to conceive three-prong complementary action areas to the conventional PED phases of development – that of **orienting, engaging and activating** as cross-cutting relevant transition approaches [58]. These relevant transition approaches comprise both rational planning and incremental approaches. **Orienting** refers to the methodical planning to align resources and the use of relevant tools to enable systematic decision making, familiar to most PED researchers and practitioners. **Engaging** can be understood to prioritise comprehensive stakeholder participation throughout all PED phases, including various techniques to sustain stakeholders’ active involvement in order to leverage their experience and competence. **Activating** anticipates focus on the grounding of pilot projects by identifying optimal solutions tailored to diverse intervention scenarios. It involves a thorough analysis to determine the most effective strategies for each specific context.

The process flow of PED development calls for a balanced approach that integrates elements of both rational and incremental planning to navigate the complexities of a PED project. While strategic orientation and planning with clear timelines and responsibilities and alignment with policy and regulations need to be in place, engaging actions pertaining to inclusive governance processes and community engagement are indispensable. A transparent techno-economic analysis detailing cost-benefit assessment to develop viable business models for the solutions and technologies should then ensue. Figure 16 captures the reimagined process flow of PED development.

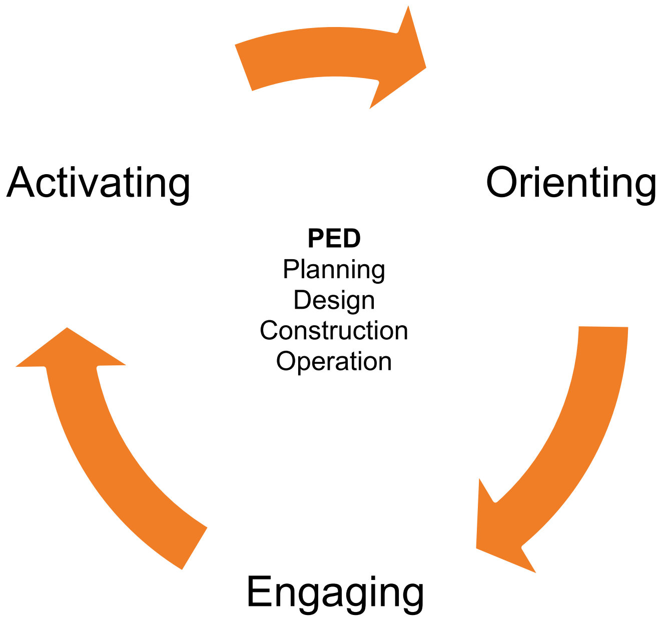


Figure 16 Process flow of PED development

## 5.2 Characterising PED stakeholders as PED actors

The development of Positive Energy Districts (PEDs) is arguably the development of an innovation embedded in a community of organisations and individuals (occupants, inhabitants, citizens) who can affect or are affected by the innovation [55]. PED planning, design, construction and operation is complex given its district dimension, which is still novel to those used to working with the single building scale and those working on the entire city scale. Development of a PED needs to be tailored to its users and types of buildings and its geographical-cum-climate, demographical and cultural contexts and therefore ***an innovation in its own right*** every time one is being conceived, planned and implemented.

The engagement of what has been termed "stakeholders" in the planning and implementation of Positive Energy Districts (PED) has consistently been identified as one of the key challenges and barriers for implementation of PED projects. The stakeholders are not limited to municipalities, real estate developers, building owners, tenants, energy providers for electricity and heating, research institutes and universities, mobility providers, energy system providers, ICT companies, industry, SMEs, non-profits or NGOs, politicians, and last not least citizens and citizen organisations. It has been acknowledged that stakeholder can shift their positions or rethink their involvement when moving from one PED phase to another.

The shifting stakeholder roles can be attributed to at least two factors. First, most PEDs will be confronted with challenges of refurbishment and retrofitting to complement the energy system upgrades and to achieve the necessary demand reduction. Changing any historically grown energy infrastructure at the district or urban scale is more disruptive than transforming individual building installations. Second, regarding the PED's interaction with its surrounding urban and regional energy infrastructures, the meaningful integration of different types of energy assets (e.g. energy production or storage units at the individual-, district- or macro-scale) require an overarching planning exercise that accounts for the entire regional energy landscape, both from a technical and a spatial planning point of view [15]. Merging urban, spatial and energy system planning further adds to the complexity of building PEDs.

To achieve effective decarbonisation of the built environment, the ultimate goal of any PED researcher and practitioner is to have more PEDs on the ground. In this effort, it is helpful to reimagine PED stakeholders. Instead of a faceless entity, PED stakeholder are full-faced actors in that they can affect or are affected by the development of the PED. In other words, stakeholder are actors who act and react in the process whether they are municipalities, real estate developers, building owners, tenants, energy providers for electricity and heating, research institutes and universities, mobility providers, energy system providers, ICT companies, industry, SMEs, non-profits or NGOs, politicians, citizens and citizen organisations.

PED developments can benefit from reimagining PED stakeholders as actors in order to scrutinise them in each local context and condition systematically to involve the community and to increase social acceptance. Changing gears to a more actor-oriented approach, where stakeholders are understood as full-faced external parties with whom the owner or driver of the PED can, or must, interact in PED developments, also open the possibility of relevant tools to better identify, understand and address their needs. To date, the development of PED guides and tools has gravitated towards the technical domain (e.g. energy system simulation, digital planning and energy trading), the development of non-technical and managerial guides and tools is in its infancy.

PED actors can generally be delineated into two types – industry actors and contextual actors. Industry actors are interpreted as those entities that perform value-adding activities or consume the outputs of these activities. Typically, industry PED actors pertain to suppliers such as energy consultants, battery storage suppliers, PV suppliers. Identifying the industry actors can be tedious but doable since their business interests, capacities and agendas are more or less recognisable. Contextual actors are those entities whose behaviour, intentionally or unintentionally, sets the conditions under which the industry actors must operate. The list of contextual actors relevant for PED development is often comprehensive as in-depth local knowledge is required to understand contextual actors. As PEDs become smarter and energy systems more complex, users will need to become more involved in the management of neighbourhood-based systems and can be exposed to technical challenges. The delivered project must match the occupant´s expectations and investments, including environmental, affordability, and functionality benefits. This may include a healthier environment, green housing features, and lower operating costs due to enhanced energy efficiency. The work to map out contextual PED actors is increasingly tedious as the definition of PED evolves.

Whether adopting a top-down or bottom-up approach in PED developments, the consideration of scale on a building level, district level and the city level can also help to make visible the benefits of PEDs for the different categories of actors involved in a more systematic way. This would provide the opportunity to allow respective end-users (i.e. occupants on a building level, inhabitants on the district level, citizens at the city level) to have a stronger say in the specification of their needs.

**Actors** on the building, district and the city scale: It is useful to reimagine PED stakeholders ***as interactive actors*** since stakeholder roles shift during the PED process (design, build, own, operate and use). It is therefore helpful to map them not only according to the process, but also on the building, district and the city scale. This would facilitate keeping in view the diverse *ambitions, agendas, interests and constraints* of industry and contextual actors in order to work towards long-lasting commitment for collaboration and coordination in any PED development. To further understand an actor-oriented stakeholder mapping framework to consider the building, district and the city scale, see [55].

As the definition of PED evolves, a plethora of PED terms can be expected to proliferate in Europe and the world, and this can be very confusing to practitioners. It is both urgent and useful to offer practical advice to PED researchers and practitioners to regard stakeholders not as passive entities but as partners for co-creation towards developing each PED as a unique innovation commensurate with its geographical-cum-climate, demographical and cultural contexts.

## 5.3 PED-related regulations and legal barriers

### 5.3.1 General review of existing regulation and policy

Developed nations made a commitment to combating climate change and made the decision to limit greenhouse gas emissions, particularly $CO_2$, beginning with the 1992 Rio de Janeiro "Earth Summit" and continuing with the 1997 Kyoto Protocol. Europe has taken the lead in regulating and implementing policies that will aid in the reduction of $CO_2$ emissions. Policies have been framed at national level to incorporate renewable energy, and support has been given in the form of incentives [59]. One of the main incentives for the use of renewable energy sources in Europe is a quota system in terms of quota obligation. In Sweden, the Electricity Certificates Act obliges energy suppliers to prove that a certain quota of the electricity supplied by them was generated from renewable energy sources. Energy suppliers shall provide this evidence by presenting tradable certificates allocated to the producers of electricity from renewable sources [60, 61]. Electricity generated from wind energy is eligible for tax privileges consisting of a reduction of the real estate tax as defined in the Act on the Federal Real Estate Tax [62]. Electricity produced in electricity generators with a capacity lower than 50 kW is not taxable [63]. In the case of electricity generated from wind, wave and solar this capacity margin are higher as authorised by the Energy Tax Act. Since 2015, a tax reduction for the micro-production of renewable electricity is in place [64].The producers of electricity from wind [65], biomass and biogas in Finland [66] sell their electricity in the market and receive a variable bonus, which is paid on top of the market price and is equal to the difference between a target price and the market price.

The Renewable Heat Incentive (RHI) is the main instrument for funding RES-H sources in the United Kingdom (UK) by supporting RES-H installations with a fixed amount per kWth produced. The scheme consists of two parts: The Non-Domestic RHI (UK) and the Domestic RHI (the UK and Northern Ireland until 2016) [67]. While the Non-Domestic RHI provides payments to industry, businesses, and public sector organisations, is the Domestic RHI open to homeowners, private landlords, social landlords, and self-builders. In addition, the Department for Business, Energy & Industrial Strategy (BEIS) plans to introduce changes to the Non-Domestic/Domestic Renewable Heat Incentive (RHI) scheme Regulations that came into effect in September 2017. Further amendments are introduced in 2018 [68]

In 2020, the government reinforced Sweden's major transport research and innovation partnership program, The Strategic vehicle research and innovation program (FFI), with 10 million EUR between 2021 and 2022 to support the research and development of work machines to reduce greenhouse gas emissions and strengthen the Swedish automotive industry's competitiveness [69]. In Austria, the investment promotion program supports the deployment of environmentally friendly vehicles, electric mobility, renewable energies, cycling, and mobility management. However, the focus of the program is the support of electric vehicles and the development of the respective infrastructure. Projects are financed by the national environmental promotion program (Umweltförderung im Inland) and the Climate and Energy Funds [70].

In Sweden, the Government intends to introduce a climate declaration requirement when buildings are constructed, which will enter into force on 1 January 2022. It aims to promote the transition towards more sustainable construction with reduced climate impact and to develop a national database that can help set minimum requirements based on a life-cycle perspective [71]. In the UK Heat Pumps have been identified as the key solution for decarbonising homes and will be critical for meeting the UK's commitment to achieving net zero by 2050. The Heat Pump Ready Programme supports the development of innovative solutions across the heat pump sector [72]. In Denmark, building data is combined with consumption data to provide a foundation for data-driven solutions [73]. Incentives are given in Austria for building renovation campaigns in 2021-2022 to switch from fossil fuel-based heating systems to sustainable heating systems, subsidies for thermal renovation of buildings, and upgrade heating boilers in low-income households [74].

### 5.3.2 Electricity sector

Subsidies have been granted for installation and research for the generation of electricity through renewable sources. In Austria, subsidies are granted for PV installations on rooftops and building-integrated installations with a capacity of 5-200 kW [8], and an investment subsidy is granted for off-grid installations that generate electricity from renewable energy sources [70, 75]. The state of Finland provides subsidies for investment and research projects in the field of sustainable energy generation [76], [77] and renewable energy [78]. In Sweden, there is no obligation for a network concession to transfer electricity from one property to another [79]. In Norway facilities producing electricity in Ped's are small enough to be exempt from concessions for installing and connecting [80]. In April 2013, the Carbon Price Floor was introduced in Great Britain. The tax applies to fossil fuels used for electricity generation. Renewable electricity is exempt from paying this tax [81]. In Denmark, the generation of electricity from renewable sources is promoted through a premium tariff system based on bonus payments. The operators of renewable energy plants usually receive a variable bonus, which is paid on top of the market price. The sum of the market price and the bonus shall not exceed a statutory maximum per kWh, which depends on the source of energy used and the date of connection of a given plant [82]. All the technologies presented below have the great potential to contribute to PED system. There is no universal "better" solution—each technology presents specific trade-offs depending on urban morphology, available infrastructure, policy context, and local stakeholder acceptance.

- **Solar**

Solar energy generation is dependent on irradiation. The cost of solar based systems has decreased during the last years (Table) [61]. Concentrated solar power (CSP) is still expensive compared to the PV and solar thermal-based energy system for electricity generation and heat generation, respectively, due to complex design, space requirement and expensive maintenance. A parabolic through type CSP system [62] could be used in limited PED cases, e.g. in a building with a large roof area and a suitable combination of heat and power needs. The benefits of using a PV or solar thermal-based system are that it can be installed even on the building walls. Therefore, PV is still a popular and easy to install technology that is widely used in buildings. Solar thermal popularity is also increasing with time, as more system integrators are entering the market.

- **Wind**

Wind power production is dependent on two main parameters, i.e. wind speed and wind density. All these parameters are dependent on the location, meteorological conditions and surface roughness [64]. The local wind speed and turbulence are difficult to estimate; therefore, it is challenging to estimate the wind energy potential locally. Compared to solar energy, wind energy costs have not reduced significantly. For the onshore wind turbines medium-sized application, the weighted average total cost decreased from 1949 USD/kW during 2010 to 1397 USD/kW in 2021 [61]. The performance of the wind turbine has also increased over the years. This has happened mainly in locations where the wind speed is low. The challenge of wind turbines in the urban and building context is noise and visual pollution. In addition to this, vibration and high investment costs are why large wind turbines are not used on on-site building locations. Vertical wind turbines are more suitable for building scale, but they also face limitations on the efficiency and space compared with PV. But when aiming at a good temporal balance between the energy demand and supply, wind turbines could be a potential solution, especially in more northern locations.

- **Hydro**

Hydropower is one of the well-developed sources of renewable energy. Almost half of the European hydropower potential has been utilised [65]. There can be two types of hydropower plants (a) run of river hydropower and (b) reservoir hydropower [65]. These two plants are highly dependent on geography and climate. The run of river hydropower plants is dependent on the location of the river and the natural water flow. Therefore, the seasonal variations in the precipitation in the upstream area can affect such plants. On the other hand, reservoir hydropower is dependent on the site location where a larger amount of water can be stored. Therefore, the initial costs are highly dependent on the location. Hydropower is a unique technology that can provide cheap electricity compared to fossil fuel-based technology. It can act as energy storage and provide flexibility to the grid. It can also provide services for frequency regulations, reserve and blackout start-ups etc. The issue with hydropower in the building context is that the hydropower plant cannot be built within the building boundary and on-site in most cases. Therefore, it can only be included in the PED in cases while considering virtual / dynamic building boundary.

- **Heat pump**

Heat pumps are also gaining popularity in terms of their utilisation as a renewable energy source to provide clean heating and cooling energy at the building level and beyond. Heat pumps can serve both individual buildings and collective systems (e.g., small scale low-temperature district heating), with significant differences in spatial requirements, efficiency, control strategies, and governance. For instance, in Finland, more than one million heat pumps are installed with up to 7 billion USD that provides clean, combustion-free heating and cooling energy to the houses. This encourages house owners to replace oil heating stove, and the direct electric heating system needed to heat the houses during freezing winters [66]. There are a wide variety of heat pumps available, based on the heat source (e.g. ground, water, air) and the transfer media (air or water). Ground source (or geothermal) heat pumps are divided by the orientation of the pipes to vertical and horizontal systems and to shallow (typically 100–300 m) or deep (typically up to 600–800 m) according to the depth of the wells in vertical systems [67]. The average investment cost for the ground source heat pump is around 1000–1200 USD/kW for building application [68]. Different heat-pump applications are among the most suitable renewable technologies for building level. The operation of heat pumps requires electricity, and that should also ideally come from renewable sources to fulfil the status as PEDs.

### 5.3.3 District heating and cooling

In Sweden, energy and carbon dioxide taxes are levied on the supply, import, and production of fossil fuels for heating purposes [83]. Renewable energy sources are exempt from these taxes [84]. In Denmark, there are different taxes on the production, processing, possession, receipt, and dispatch of fossil fuels for heating. Renewable energy sources are exempt from these taxes [85, 86]. In Finland, A fixed “Heat bonus” is paid for heat produced by CHP (Combined Heat and Power) plant working on biogas and wood fuel [87]. Investment supports are available for the construction of production facilities using renewable energies [88] there is also support available for farmers to support the construction of heat plants working on renewable energy [89].The most substantial form of supporting small-scale RES heating and cooling is provided by the Environmental Assistance in Austria UFI (Umweltförderung im Inland) program. There are special investment incentives for solar thermal installations, heat pumps, and geothermic and biomass heating plants [90]. The Heating Cost Accounting Act regulates the costs based on actual consumption instead of usable floor space [80]. In Norway, there is no obligation for the use of district heating as the heating source for building owners but it’s mandatory to be connected to the district heating network [80].

### 5.3.4 Transport sector

In Sweden Companies supplying, importing, and producing fossil fuels are obliged to pay energy and carbon dioxide taxes However, biofuels are exempted from these taxes [83, 84] .A bonus-malus system ‘Klimat-bonus’ (taxes relief or higher vehicle tax) is applied for cars, light trucks, and light buses with low climate impact (low $CO_2$ emissions with a maximum of 60g/km) from 1 July 2018 (‘Klimatbonusbilar’) [69]. In the United Kingdom, tax and duty measures are mentioned in the 2020 Budget. Battery electric cars will pay no Company Car Tax in 2020/21, just 1% in 2021/22, and 2% in 2022/23 through to 2024/25 [91]. The UK is also aiming to end the sale of new petrol and diesel cars in the UK by 2030 [92]. In Denmark, Biofuels quota systems ensure that the main support scheme for renewable energy sources used in transport is a quota obligation. Companies importing or producing petrol, gas, or diesel fuels are obliged to ensure that biofuels make up a defined percentage of the company’s total annual fuel sales [93]. In Finland too the main scheme used to support renewable energies in the transport sector is a quota obligation. This mechanism obliges companies selling petrol or diesel fuels to ensure that biofuels compose a defined percentage of the company’s total annual sale of fuel [94]. A Mobility Master Plan is put in action in Austria which aims to support e-mobility through purchase subsidies, registration tax benefits ownership tax benefits, company tax benefits, VAT benefits, infrastructure incentives, and free parking [95]. In Norway incentives for electric vehicles like Battery Electric Vehicles (BEV) and fuel cell and electric vehicles (FCEV) are exempted from the registration tax and the Value Added Tax (VAT) [96].

### 5.3.5 Building sector

The Swedish government has supported investment to stimulate renovation and greater energy efficiency of rental housing that achieves at least a 20% improvement in energy performance as well as the quality of the building [71]. In the UK, smart meters put consumers in control of their energy use, allowing them to adopt energy efficiency measures that can help save money on their energy bills and offset price increases [97]. In Denmark, there is a subsidy scheme for energy savings in public buildings, energy renovations in regional and municipal buildings, and buildings heated by oil burners and gas furnaces [98]. Energy performance certificates (EPC) are required in Finland for all new buildings and the sale or rental of existing buildings [99]. In Norway, stricter regulations have been imposed in the building code, especially for energy use from passive house level requirements to close to energy-neutral requirements [100].

# 6. Conclusions

The evolution of the PED concept marks a paradigm shift in how urban sustainability is envisioned and operationalised across Europe. Originally centred on the goal of achieving an energy surplus within urban districts, the PED model has matured into a broader framework—one that emphasises not just technological solutions, but also social, economic, environmental, and regulatory integration.

This report highlights that the future of PEDs depends on flexibility, adaptability, and inclusivity. Rather than enforcing a rigid standard of net-positive energy output, the revised PED framework acknowledges local constraints and encourages tailored approaches that optimise environmental and societal outcomes. This includes accommodating urban areas with limited renewable energy potential through virtual PED boundaries, dynamic KPIs, and context-specific energy strategies. Such a nuanced approach fosters broader adoption, especially in dense urban or heritage-protected districts where conventional energy surpluses are harder to achieve.

Throughout the report, critical challenges are identified—from data accessibility and inconsistent assessment methodologies to regulatory bottlenecks and stakeholder fragmentation. The review of over 60 European PED projects reveals that success is not solely a function of advanced technology, but hinges on supportive policy environments, robust stakeholder engagement, and innovative financing mechanisms. This insight reinforces the understanding of PEDs as complex socio-technical systems, whose implementation must balance ambition with realism.

Furthermore, the development of PED archetypes based on climatic zones offers valuable guidance for designing district-specific energy strategies. These archetypes—ranging from Solar Dominant models in the Mediterranean to Arctic Thermal Resilience approaches in northern Europe—demonstrate the importance of place-based energy planning. They serve as reference points for cities embarking on PED transitions, allowing for replication while preserving local specificity.

The report also emphasises that PEDs should be seen as processes rather than static end-goals. Their development unfolds through iterative planning, implementation, and governance, involving diverse actors whose roles and interests evolve over time. The importance of continuous learning, peer exchange, and adaptive governance structures cannot be overstated.

PEDs represent a critical frontier in the global transition toward sustainable, climate-neutral cities. By embracing their complexity and fostering collaboration across sectors and disciplines, PEDs can deliver lasting energy, environmental, and social benefits. The insights and recommendations of this report aim to serve as a foundation for advancing the PED agenda, both within Europe and globally, under the shared vision of resilient, inclusive, and energy-positive urban futures.

# Subtask A Publications

The following is a list of publications from Subtask A leaders and members that are directly relevant to the work of IEA Annex 83 on Positive Energy Districts


- Zhang X, Penaka SR, Giriraj S et al. (2021) Characterizing Positive Energy District (PED) through a Preliminary Review of 60 Existing Projects in Europe. Buildings 11:318. https://doi.org/10.3390/buildings11080318
- Stryi-Hipp G, Steingrube A, Triebel M-A et al. (2021) Key features of climate-neutral energy systems for municipalities in different climate zones. Journal of Physics: Conf. Ser. 2042 01204. https://doi.org/10.1088/1742-6596/2042/1/012044
- Albert-Seifried V, Murauskaite L, Massa G et al. (eds) (2022) Definitions of Positive Energy Districts: A Review of the Status Quo and Challenges: In: Littlewood, J.R., Howlett, R.J., Jain, L.C. (eds) Sustainability in Energy and Buildings 2021. Smart Innovation, Systems and Technologies. Springer Nature, Singapore
- Sareen S, Albert-Seifried V, Aelenei L et al. (2022) Ten questions concerning positive energy districts. Building and Environment 216:109017. https://doi.org/10.1016/j.buildenv.2022.109017
- Cheng C, Albert-Seifried V, Aelenei L et al. (eds) (2022) A Systematic Approach Towards Mapping Stakeholders in Different Phases of PED Development—Extending the PED Toolbox: In: Littlewood, J.R., Howlett, R.J., Jain, L.C. (eds) Sustainability in Energy and Buildings 2021. Smart Innovation, Systems and Technologies. Springer Nature, Singapore
- Vandevyvere H, Ahlers D, Wyckmans A. The Sense and Non-Sense of PEDs—Feeding Back Practical Experiences of Positive Energy District Demonstrators into the European PED Framework Definition Development Process. Energies. 2022; 15(12):4491. https://doi.org/10.3390/en15124491
- Zhang X, Shah J, Han M (2023) ChatGPT for Fast Learning of Positive Energy District (PED): A Trial Testing and Comparison with Expert Discussion Results. Buildings 13:1392. https://doi.org/10.3390/buildings13061392
- Han M, Shah J, Zhang X (2023) Review of natural language processing techniques for characterizing positive energy districts. Journal of Physics: Conf. Ser. 2600 082024, https://doi.org/10.1088/1742-6596/2600/8/082024
- Alpagut B, Bossi S, Civiero P et al. (2023) A database for positive energy districts (PED). Journal of Physics: Conf. Ser. 2600 082018, https://doi.org/10.1088/1742-6596/2600/8/082018
- Kozlowska A., Guarino F, Volpe R et al. (2024) Positive Energy Districts: Fundamentals, Assessment Methodologies, Modeling and Research Gaps. Energies 2024, 17, 4425. https://doi.org/10.3390/en17174425
- Gondeck M, Triebel M-A, Steingrube A et al. (2024) Recommendations for a positive energy district framework – Application and evaluation of different energetic assessment methodologies. Smart Energy 15:100147. https://doi.org/10.1016/j.segy.2024.100147

- Han M, Canli I, Shah J et al. (2024) Perspectives of Machine Learning and Natural Language Processing on Characterizing Positive Energy Districts. Buildings 14:371. https://doi.org/10.3390/buildings14020371
- Cheng C, Ekambaram A (2024) Characterising the transdisciplinary challenge in the development of Sustainable Plus Energy Neighbourhoods – what do emerging innovations tell us? IOP Conf Ser.: Earth Environ Sci 1389:12008. https://doi.org/10.1088/1755-1315/1389/1/012008
- Turci G, Civiero P, Aparisi-Cerdá I et al. (2024) Transition Approaches towards Positive Energy Districts: A Systematic Review. Buildings 14:3039. https://doi.org/10.3390/buildings14103039
- Civiero P, Turci G, Alpagut B (2024) Operational Insights and Future Potential of the Database for Positive Energy Districts. Energies. 2024; 17(4):899. https://doi.org/10.3390/en17040899

# References


1. Polly B, Kutscher C, Macumber D et al. (2016) From Zero Energy Buildings to Zero Energy Districts: 2016 ACEEE Summer Study on Energy Efficiency in Buildings
2. European Innovation Partnership on Smart Cities and Communities Positive Energy Blocks Infographics
3. Wyckmans A (2018) SET-Plan ACTION n°3.2 Implementation Plan: Europe to become a global role model in integrated, innovative solutions for the planning, deployment, and replication of Positive Energy Districts. https://jpi-urbaneurope.eu/wp-content/uploads/2021/10/setplan_smartcities_implementation-plan-2.pdf
4. European Commission (2017) Horizon 2020 Work Programme 2018-2020: 10. Secure, clean and efficient energy
5. Shnapp S, Paci D, Bertoldi P (2020) JRC Technical Report: Enabling Positive Energy Districts across Europe: energy efficiency couples renewable energy
6. JPI Urban Europe, SET-Plan 3.2 (2020) White Paper on PED Reference Framework for Positive Energy Districts and Neighbourhoods.: Key lessons from national consultations. https://jpi-urbaneurope.eu/ped/
7. Wyckmans A (2019) Strategic Research Agenda of the EERA Joint Programme Smart Cities. https://www.iqs.se/media/4893/eera-jpsc-ped-sra_wyckmans.pdf
8. Wyckmans A, Ahlers D (2019) D9.2 Report on Intra-Project Collaboration, Including Study Visits and Peer to Peer Workshops: +CityxChange | Work Package 9, Task 9.1. https://cityxchange.eu/knowledge-base/report-on-intra-project-collaboration-including-study-visits-and-peer-to-peer-workshops/
9. Driving Urban Transitions Partnership (2024) Thematic Deep-dive Workshop: How to operationalise the PED Framework [PowerPoint slides]
10. PED EU Net PED Database. https://pedeu.net/map/
11. IEA Annex 83 (2024) Workshop on a common PED definition for Annex 83, Pamplona, Spain
12. University of Duesto, Amsterdam University of Applied Science, Paul Scherrer Institute (2020) Atelier Monitoring and Evaluation Framework: Deliverable 9.1: Repository of definitions of terms, key characteristics archetypes, and a set of KPIs
13. Ahlers D, Riedesel K, Dommerholt T et al. (2023) How to PED – The +CityxChange Cookbook: Experiences and Guidelines on Positive Energy Districts. Zenodo
14. Alpagut B, Gabaldón A (2020) Making-City Guidelines for Positive Energy District Design: How to Transform a district into a PED
15. Salom J, Tamm M (2020) Syn.ikia - WP3 Technology Integration in Smart Managed Plus Energy Buildings and Neighbourhoods: D3.1 Methodology Framework for Plus Energy Buildings and Neighbourhoods
16. Schöfmann P, Zelger T, Bartlma N et al. (2020) Zukunftsquartier - Weg zum Plus-Energie-Quartier in Wien. https://nachhaltigwirtschaften.at/resources/sdz_pdf/schriftenreihe-2020-11-zukunftsquartier.pdf
17. IBA - HPVision Heidelberg Project Development of Patrick-Henry-Village. https://iba.heidelberg.de/de/projekte/phvision
18. Wiik MK (2022) ZEN Report No.44: The ZEN definition - a guideline for the ZEN pilot areas. https://sintef.brage.unit.no/sintef-xmlui/handle/11250/3043357
19. Wiik MRK, Fjellheim K, Vandervaeren C et al. (2022) ZEN Report No.45: Zero emission neighbourhoods in smart cities: Definition, key performance indicators and assessment criteria. https://sintef.brage.unit.no/sintef-xmlui/handle/11250/3043357
20. NEUTRALPATH (2024) Co-designed urban solutions for climate neutrality. https://neutralpath.eu/
21. ASCEND (2024) Accelerate poSitive Clean ENergy Districts. https://www.ascend-project.eu/
22. HARMONISE (2024) Hierarchical and Agile Resource Management Optimization for Networks in Smart Energy Communities. https://cordis.europa.eu/project/id/101138595
23. PEDvolution (2024) Interoperable solutions to streamline Positive Energy District evolution and cross-sectoral integration. https://pedvolution.eu/
24. InterPED (2024) INTERoperable cloud-based solution for cross-vector planning and management of Positive Energy Districts. https://cordis.europa.eu/project/id/101138047
25. Moreno Gabaldón A, Vélez F, Alpagut B et al. (2021) How to Achieve Positive Energy Districts for Sustainable Cities: A Proposed Calculation Methodology. Sustainability 13:710. https://doi.org/10.3390/su13020710
26. Schöfmann P., Forstinger V., Zelger T. et al. (2023) Zukunftsquartier 2.0 Replizierbare, thermisch und elektrisch netzdienliche Konzeption von (Plus-Energie-) Quartieren im dichten urbanen Kontext. https://nachhaltigwirtschaften.at/resources/sdz_pdf/schriftenreihe-2023-33-zukunftsquartier-2-0.pdf

27. Rönty J, Känsälä K, Rinne S et al. (2019) Making City: D5.1 City Level Indicators. https://makingcity.eu/wp-content/uploads/2020/09/MAKINGCITY_D5_1_City_Level_Indicators_Final_V1.pdf
28. Hynes W, Sweeney J, Lynch S et al. (2020) CityxChange: D7.1 Approach and Methodology for Monitoring and Evaluation
29. Angelakoglou K, Kourtzanidis K, Giourka P et al. (2020) From a Comprehensive Pool to a Project-Specific List of Key Performance Indicators for Monitoring the Positive Energy Transition of Smart Cities — An Experience-Based Approach. Smart Cities 3:705–735. https://doi.org/10.3390/smartcities3030036
30. Ntafalias A, Papadopoulos P, Kentzoglanakis K et al. (2023) SPARCS: D2.7 Holistic Impact Assessment of Demonstration Activities- updated version 1. https://sparcs.info/en/deliverables/d2-7-holistic-impact-assessment-of-demonstration-activities-updated-version-1/
31. PEDvolution (2024) Deliverable 1.2 Functional and Operational Requirements of the Demo Sites and Reference Use Cases. https://pedvolution.eu/cms/wp-content/uploads/2024/08/PEDvolution-D1.2-Functional-and-Operational-Requirements-2024-08-Intracom-Telecom.pdf
32. Gondeck M, Triebel M-A, Steingrube A et al. (2024) Recommendations for a positive energy district framework – Application and evaluation of different energetic assessment methodologies. Smart Energy 15:100147. https://doi.org/10.1016/j.segy.2024.100147
33. Derkenbaeva E, Halleck Vega S, Hofstede GJ et al. (2022) Positive energy districts: Mainstreaming energy transition in urban areas. Renewable and Sustainable Energy Reviews 153:111782. https://doi.org/10.1016/j.rser.2021.111782
34. Brozovsky J, Gustavsen A, Gaitani N (2021) Zero emission neighbourhoods and positive energy districts – A state-of-the-art review. Sustainable Cities and Society 72
35. Vandevyvere H, Ahlers D, Wyckmans A (2022) The Sense and Non-Sense of PEDs—Feeding Back Practical Experiences of Positive Energy District Demonstrators into the European PED Framework Definition Development Process. Energies
36. Bruck A, Díaz Ruano S, Auer H (2021) A Critical Perspective on Positive Energy Districts in Climatically Favoured Regions: An Open-Source Modelling Approach Disclosing Implications and Possibilities. Energies 14:4864. https://doi.org/10.3390/en14164864
37. Krangsås SG, Steemers K, Konstantinou T et al. (2021) Positive Energy Districts: Identifying Challenges and Interdependencies. Sustainability 13:10551. https://doi.org/10.3390/su131910551
38. Leone F, Reda F, Hasan A et al. (2023) Lessons Learned from Positive Energy District (PED) Projects: Cataloguing and Analysing Technology Solutions in Different Geographical Areas in Europe. Energies 16:356. https://doi.org/10.3390/en16010356
39. Bosch P, Jongeneel S, Rovers V et al. (2017) CITYkeys indicators for smart city projects and smart cities. Unpublished
40. Gollner C (2019) BOOKLET OF POSITIVE ENERGY DISTRICTS IN EUROPE: A compilation of projects towards sustainable urbanization and the energy transition
41. Reback J, McKinney W, Jbrockmendel BJ et al. (2021) pandas-dev/pandas: Pandas 1.0. 3: Zenodo; 2020
42. Loper E, Bird S (2002) NLTK: The Natural Language Toolkit. Accessed 24 Jan 2025
43. Loria S textblob Documentation
44. Agarwal B, Mittal N, Bansal P et al. (2015) Sentiment Analysis Using Common-Sense and Context Information. Computational intelligence and neuroscience 2015:715730. https://doi.org/10.1155/2015/715730
45. QGIS Development Team Geographic Information Systems: Open Source Geospatial Foundation Project. http://qgis.osgeo.org/
46. Zhang X, Penaka SR, Giriraj S et al. (2021) Characterizing Positive Energy District (PED) through a Preliminary Review of 60 Existing Projects in Europe. Buildings 11:318. https://doi.org/10.3390/buildings11080318
47. Child M, Nordling A, Breyer C (2017) Scenarios for a sustainable energy system in the Åland Islands in 2030. Energy Conversion and Management 137:49–60. https://doi.org/10.1016/j.enconman.2017.01.039
48. Aslam M, Lee J-M, Kim H-S et al. (2020) Deep Learning Models for Long-Term Solar Radiation Forecasting Considering Microgrid Installation: A Comparative Study. Energies 13:147. https://doi.org/10.3390/en13010147
49. Zhang X, Penaka S, Giriraj S et al. (2021) Characterizing Positive Energy District (PED) through a Preliminary Review of 60 Existing Projects in Europe. Buildings 11:318. https://doi.org/10.3390/buildings11080318
50. Han M, Canli I, Shah J et al. (2024) Perspectives of Machine Learning and Natural Language Processing on Characterizing Positive Energy Districts. Buildings 14:371. https://doi.org/10.3390/buildings14020371

51. Zhang X, Shah J, Han M (2023) ChatGPT for Fast Learning of Positive Energy District (PED): A Trial Testing and Comparison with Expert Discussion Results. Buildings 13:1392. https://doi.org/10.3390/buildings13061392
52. Stryi-Hipp G, Steingrube A, Triebel M-A et al. (2021) Key features of climate-neutral energy systems for municipalities in different climate zones. Journal of Physics: Conference Series 2042
53. Schneider S, Zelger T, Sengl D et al. (2023) A Quantitative Positive Energy District Definition with Contextual Targets. Buildings 13:1210. https://doi.org/10.3390/buildings13051210
54. Ahlers D, Alpagut B, Cerna V et al. (2020) Positive Energy Districts Solution Booklet
55. Cheng C, Albert-Seifried V, Aelenei L et al. (eds) (2022) A Systematic Approach Towards Mapping Stakeholders in Different Phases of PED Development—Extending the PED Toolbox: In: Littlewood, J.R., Howlett, R.J., Jain, L.C. (eds) Sustainability in Energy and Buildings 2021 . Smart Innovation, Systems and Technologies. Springer Nature, Singapore
56. Cheng C, Ekambaram A (2024) Characterising the transdisciplinary challenge in the development of Sustainable Plus Energy Neighbourhoods – what do emerging innovations tell us? IOP Conf Ser.: Earth Environ Sci 1389:12008. https://doi.org/10.1088/1755-1315/1389/1/012008
57. Kioumarsi M, Shafei B (eds) (2025) The 1st International Conference on Net-Zero Built Environment: Innovations in Materials, Structures, and Management Practices. Exploring Multilevel Governance Networks in Deployment of Positive Energy Districts: Case of Salzburg, 1st ed. 2025. Lecture Notes in Civil Engineering, vol 237. Springer Nature Switzerland; Imprint Springer, Cham
58. Turci G, Civiero P, Aparisi-Cerdá I et al. (2024) Transition Approaches towards Positive Energy Districts: A Systematic Review. Buildings 14:3039. https://doi.org/10.3390/buildings14103039
59. Albulescu CT, Artene AE, Luminosu CT et al. (2020) CO2 emissions, renewable energy, and environmental regulations in the EU countries. Environ Sci Pollut Res 27:33615–33635. https://doi.org/10.1007/S11356-019-06155-1/TABLES/16
60. Act (2011:1200) on electricity certificates Swedish Constitution 2011:2011:1200 tom SFS 2021:670 - Riksdagen. https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/lag-20111200-om-elcertifikat_sfs-2011-1200. Accessed 05 Sep 2022
61. Ordinance (2011:1480) on electricity certificates Swedish Constitution 2011:2011:1480 tom SFS 2022:1362 - Riksdagen. https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattnings-samling/forordning-20111480-om-elcertifikat_sfs-2011-1480. Accessed 05 Sep 2022
62. Financing of infrastructure with tax or fee? The state’s public investigations 2018:13 - Riksdag. https://www.riksdagen.se/sv/dokument-lagar/dokument/statens-offentliga-utredningar/finansiering-av-infrastruktur-med-skatt-eller_H6B313/html. Accessed 05 Sep 2022
63. Act (1994:1776) on tax on energy Swedish Constitutional Collection 1994:1994:1776 tom SFS 2022:1050 - Riksdagen. https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattnings-samling/lag-19941776-om-skatt-pa-energi_sfs-1994-1776. Accessed 05 Sep 2022
64. Inkomstskattelag (1999:1229) Svensk författningssamling 1999:1999:1229 t.o.m. SFS 2022:1072 - Riksdagen. https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/inkom-stskattelag-19991229_sfs-1999-1229. Accessed 05 Sep 2022
65. Renewable energy policy database and support: sources. http://www.res-legal.eu/search-by-coun-try/finland/sources/t/source/src/act-no-13962010/. Accessed 05 Sep 2022
66. RIS - Green Electricity Feed-in Tariff Ordinance 2018 - Consolidated federal law, version of September 5th, 2022. https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnum-mer=20010106. Accessed 05 Sep 2022
67. The Renewable Heat Incentive Scheme Regulations 2011 (revoked). https://www.legisla-tion.gov.uk/uksi/2011/2860/contents. Accessed 05 Sep 2022
68. The Domestic Renewable Heat Incentive Scheme Regulations 2014. https://www.legisla-tion.gov.uk/uksi/2014/928/contents/made. Accessed 05 Sep 2022
69. Ordinance (2017:1334) on climate bonus cars Swedish Constitution 2017:2017:1334 tom SFS 2021:802 - Riksdagen. https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattnings-samling/forordning-20171334-om-klimatbonusbilar_sfs-2017-1334. Accessed 05 Sep 2022
70. Renewable energy policy database and support: sources. http://www.res-legal.eu/search-by-coun-try/austria/sources/t/source/src/ufg/. Accessed 05 Sep 2022
71. Climate declaration for new buildings - Boverket. https://www.boverket.se/en/start/building-in-swe-den/developer/rfq-documentation/climate-declaration/. Accessed 05 Sep 2022
72. Heat Pump Ready Programme - GOV.UK. https://www.gov.uk/government/publications/heat-pump-ready-programme. Accessed 05 Sep 2022
73. Data to promote energy efficiency The Danish Energy Agency. https://ens.dk/ansvarsomraader/ener-gibesparelser/data-til-fremme-af-energieffektivisering. Accessed 05 Sep 2022
74. Get out of oil and gas: environmental promotion Kommunalkredit Public Consulting. https://www.um-weltfoerderung.at/privatpersonen/raus-aus-oel.html. Accessed 05 Sep 2022
75. Renewable energy policy database and support: tools list. http://www.res-legal.eu/search-by-coun-try/austria/tools-list/c/austria/s/res-e/t/promotion/sum/91/lpid/94. Accessed 05 Sep 2022

76. Valtioneuvoston asetus energiatuen myöntämisen… 1063/2012 - Säädökset alkuperäisinä - FINLEX ®. https://www.finlex.fi/fi/laki/alkup/2012/20121063. Accessed 05 Sep 2022
77. 688/2001 English - Translations of Finnish acts and decrees - FINLEX ®. https://www.finlex.fi/en/laki/kaannokset/2001/en20010688. Accessed 05 Sep 2022
78. Valtioneuvoston asetus uusiutuvan energian ja… 145/2016 - Säädökset alkuperäisinä - FINLEX ®. https://finlex.fi/fi/laki/alkup/2016/20160145. Accessed 05 Sep 2022
79. Så kan du dela el i lokala nät - Fastighetsägarna. https://www.fastighetsagarna.se/aktuellt/webbinarier/sa-kan-du-dela-el-i-lokala-nat/. Accessed 05 Sep 2022
80. Policy mapping and analysis of plus-energy buildings and neighbourhoods
81. Finance Act 2000. https://www.legislation.gov.uk/ukpga/2000/17/contents. Accessed 05 Sep 2022
82. Renewable energy policy database and support: tools list. http://www.res-legal.eu/search-by-country/denmark/tools-list/c/denmark/s/res-e/t/promotion/sum/95/lpid/96/. Accessed 05 Sep 2022
83. Renewable energy policy database and support: sources. http://www.res-legal.eu/search-by-country/sweden/sources/t/source/src/act-no-19841052/. Accessed 05 Sep 2022
84. Lag (2010:598) om hållbarhetskriterier för biodrivmedel och biobränslen Svensk författningssamling 2010:2010:598 t.o.m. SFS 2022:170 - Riksdagen. https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/lag-2010598-om-hallbarhetskriterier-for_sfs-2010-598. Accessed 05 Sep 2022
85. Carbon Dioxide Tax on Certain Energy Products - Act 321/2011 - Denmark - Climate Change Laws of the World. https://climate-laws.org/geographies/denmark/laws/carbon-dioxide-tax-on-certain-energy-products-act-321-2011. Accessed 05 Sep 2022
86. Act 1292/2010 (Lov om afgift af stenkul, brunkul og koks m.v. - Google Search. Accessed 05 Sep 2022
87. Laki uusiutuvilla energialähteillä tuotetun… 1396/2010 - Ajantasainen lainsäädäntö - FINLEX ®. https://www.finlex.fi/fi/laki/ajantasa/2010/20101396. Accessed 05 Sep 2022
88. Valtioneuvoston asetus energiatuen myöntämisen… 1063/2012 - Säädökset alkuperäisinä - FINLEX ®. https://www.finlex.fi/fi/laki/alkup/2012/20121063. Accessed 05 Sep 2022
89. Renewable energy policy database and support: sources. http://www.res-legal.eu/search-by-country/finland/sources/t/source/src/decree-no-2412015/. Accessed 05 Sep 2022
90. Renewable energy policy database and support: tools list. http://www.res-legal.eu/search-by-country/austria/tools-list/c/austria/s/res-hc/t/policy/sum/91/lpid/94/. Accessed 05 Sep 2022
91. UNITED KINGDOM. https://ieahev.org/publicationlist/UnitedKingdompage/. Accessed 05 Sep 2022
92. Government takes historic step towards net-zero with end of sale of new petrol and diesel cars by 2030 - GOV.UK. https://www.gov.uk/government/news/government-takes-historic-step-towards-net-zero-with-end-of-sale-of-new-petrol-and-diesel-cars-by-2030. Accessed 05 Sep 2022
93. Act on sustainable bio-fuels and reduction of transport greenhouse gas emissions (No. 674 of 2011). FAOLEX. https://www.fao.org/faolex/results/details/en/c/LEX-FAOC103619/. Accessed 05 Sep 2022
94. Renewable energy policy database and support: tools list. http://www.res-legal.eu/search-by-country/finland/tools-list/c/finland/s/res-t/t/promotion/sum/128/lpid/127/. Accessed 05 Sep 2022
95. HEV-TCP. https://ieahev.org/countries/austria/. Accessed 05 Sep 2022
96. Norwegian EV policy - Norsk elbilforening. https://elbil.no/english/norwegian-ev-policy/. Accessed 05 Sep 2022
97. Smart meters: a guide for households - GOV.UK. https://www.gov.uk/guidance/smart-meters-how-they-work. Accessed 05 Sep 2022
98. Finansloven for 2021. Accessed 05 Sep 2022
99. Implementation of the EPBD in Finland - epbd-ca.eu. https://epbd-ca.eu/ca-outcomes/outcomes-2015-2018/book-2018/countries/finland. Accessed 05 Sep 2022
100. Forskrift om endring i forskrift om tekniske krav til byggverk (Byggteknisk forskrift) - Lovdata. https://lovdata.no/dokument/LTI/forskrift/2015-11-12-1290. Accessed 05 Sep 2022