PED EU NET

COST Action 19126

Positive Energy Districts European Network

Deliverable 3.3

Report on PED Labs characterisation and KPIs

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Due date: 30.12.2024
Final delivery date: 06.03.2025

This publication is based upon work from COST Action Positive Energy Districts European Network (PED-EU-NET), supported by COST (European Cooperation in Science and Technology).

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Executive Summary

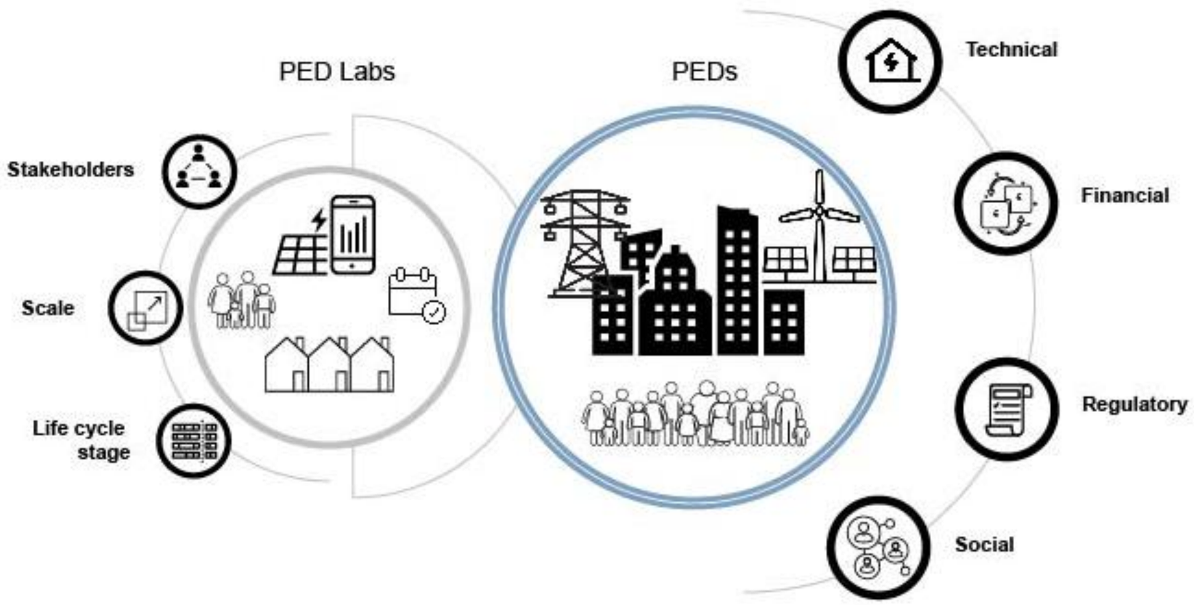
Positive Energy Districts (PEDs) are recognized as a promising approach to achieving energy efficiency and reducing the negative environmental impact of climate change through the surplus of local renewable energy generation. PED Labs, as have been defined by JPI UE in the SET-Plan ACTION n°3.2 Implementation Plan, can serve as «seeding ground for new ideas, solutions and services, will be developed according to place- based needs and local context baselines. PED Labs will follow an integrative approach including technology, spatial, regulatory, financial, legal, social and economic perspectives».

As part of this effort, Task 3.3 aims to consolidate the PED Labs definition based on analysis of implemented cases, by identifying the aspects (technical, social, financial regulatory) and how they influence both implementation and evaluation.

The report presents the analysis of PED Labs and provide guidance on their design and implementation from technological, social, financial and regulatory perspectives. Leveraging this experience and the involvement in the Action, particularly WG 1 and 2, we aim at answering the following research questions:

- Which KPIs are the most relevant for PED Labs implementation?
- How can those aspects be organized to address the appropriate scale and stakeholders?
- Which lessons learned can support the PED Lab implementation, particularly considering existing districts?

The PED Labs provide an opportunity to find ways to address the inherent complexity of the implementation and learn how to overcome the challenges. As part of this effort, this work summarizes the existing PED Labs and provides the key success factors for implementation of PED Labs.



Visual summary of the deliverable

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1. Introduction

Positive Energy Districts (PEDs) are recognized as a promising approach to achieving energy efficiency and reducing the negative environmental impact of climate change through the surplus of local renewable energy generation (Gohari et al., 2024). Despite the potential, the implementation of PEDs faces several challenges. Krangsås et al. (2021) found that the challenges related to governance, incentive, social, process, market, technology and context. PED Labs, as have been defined by JPI UE in the SET-Plan ACTION n°3.2 Implementation Plan, can serve as «*seeding ground for new ideas, solutions and services, will be developed according to place- based needs and local context baselines. PED Labs will follow an integrative approach including technology, spatial, regulatory, financial, legal, social and economic perspectives*». The PED Labs provide an opportunity to find ways to address the inherent complexity of the implementation and learn how to overcome the challenges.

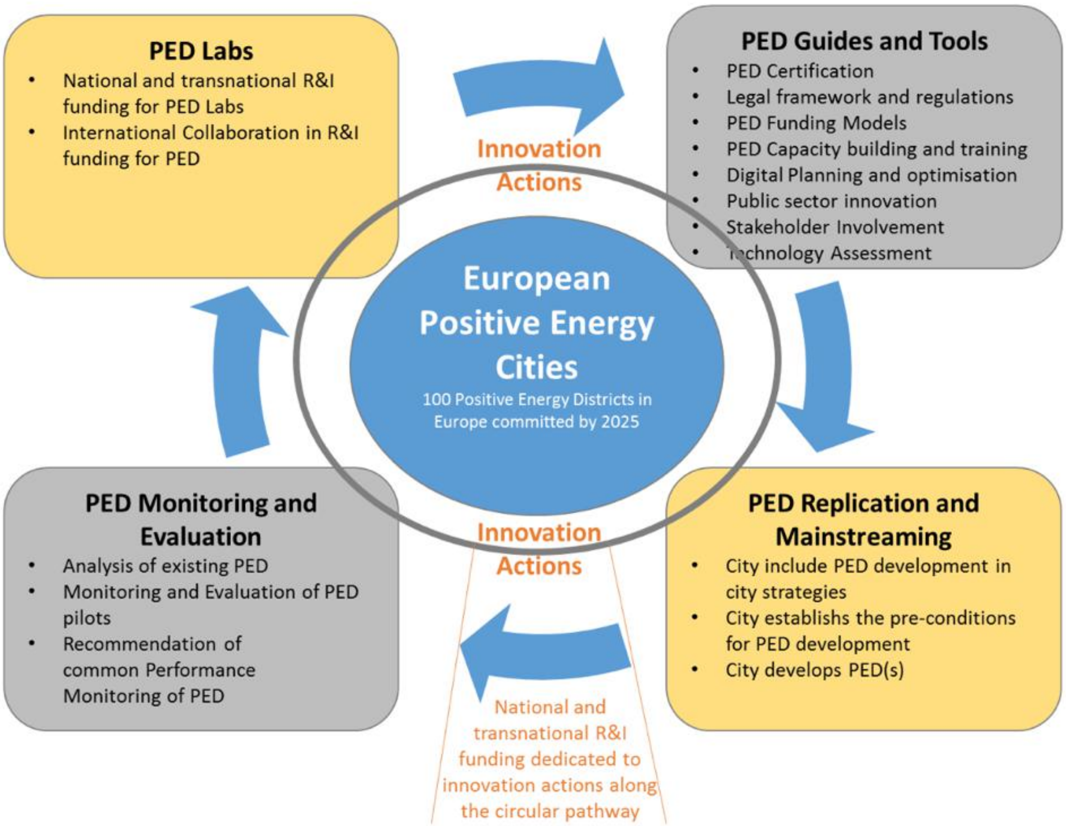

Figure 1. Pathways to Positive Energy Districts in Europe (source: European Commision, 2018)

In line with this overview, WG 3, Task 3.1 positioned the PED labs as a "*subset in the international debate on sustainable urban development, currently led, in Europe, to the two new concepts of Climate Neutral City and New European Bauhaus".* The PED labs are considered as Testing Platforms as Drivers for Positive-Energy Living Laboratories. The experience gained in such urban labs, urban living labs, city laboratories, incubators, etc... to then inform the creation of Positive Energy Districts (ref D3.1 report).

The PED-LAB is simultaneously:

- *A concept referring to a small or medium-scale experimentation, in a risk-controlled environment - especially because it deals with experiments on real urban environments, which allows validating innovative solutions to be replicated later on a larger scale involving entire cities.*
- *A concept referring to the whole of the PED-prototypal experiments, which, by sharing good and bad practices, positive and negative results, constitute an extended laboratory in which integrated solutions are tested and validated in similar or different urban contexts.*

PED-Lab definition regarding the Strategic Energy Technology Plan (SET-Plan Action 3.2): PED Labs will be pilot actions that provide opportunities to experiment with the planning and deployment of PEDs, as well as provide seeding ground for new ideas, solutions, and services to develop. PED Labs will follow an integrative approach, including technology, spatial, regulatory, financial, legal, social, and economic perspectives. (SET and database).

1.1 Objective of the T 3.3

As part of this effort, Task 3.3 aims to consolidate the PED Labs definition based on analysis of implemented cases, by identifying the aspects (technical, social, financial regulatory) and how they influence both implementation and evaluation.
The report presents the analysis of PED Labs and provide guidance on their design and implementation from technological, social, financial and regulatory perspectives. Leveraging this experience and the involvement in the Action, particularly WG 1 and 2, we aim at answering the following research questions:

- Which KPIs are the most relevant for PED Labs implementation?
- How can those aspects be organised to address the appropriate scale and stakeholders?
- Which lessons learned can support the PED Lab implementation, particularly considering existing districts?

2. Methods

1. **Develop framework for the PED Labs Analysis**

   provide a framework regarding PED characteristics and KPIs, considering technological, social, financial and regulatory perspectives. This framework will act as the basis for presenting the consolidated concepts of PED Labs and guidance on their implementation.

2. **Analysis of the PED Lab according to the PED Database classification**

   https://pedeu.net/cast-studies-table-view/?ped_type=lab&phase=&project=

   Based on the definition proposed by the Set Plan Action 3.2 [4], 'PED Labs' are pilot actions that provide opportunities to experiment with the planning and deployment of PEDs. Under this framework, PED labs are considered as urban laboratories where these new proposals, technologies, and services could be developed, modelled, and monitored according to place-based needs and local context baseline. These research infrastructures allow defining integrative solutions that include technological, spatial, regulatory aspects, financial, legal, social, and economic perspectives.

3. **Analyse the PED Labs based on the 4 aspects and the 3 framework dimensions**

2.1 Relation with other WGs

As outlined in **SET-Plan ACTION n°3.2** (European Commission, 2018), **Positive Energy District (PED) Labs** are a fundamental component of the **Pathway to PED Implementation** (Figure 1). They serve as dynamic innovation ecosystems where cities experiment with and refine PED solutions, facilitating the transition towards climate-neutral and energy-positive urban areas.

PED implementation operates at multiple levels. While **PED Labs, replication, and mainstreaming** are primarily **driven by cities**, the development of **PED Guides and Tools (PED III)** occurs at **national and European levels**, ensuring harmonization, scalability, and policy alignment. Meanwhile, **PED Monitoring and Evaluation** plays a critical role in assessing progress, identifying best practices, and refining methodologies to enhance impact and effectiveness.

Given the complexity and interdisciplinary nature of PED implementation, a **cohesive and collaborative approach** is essential. **WP3 (PED Labs & Replication)** serves as a **key interface** between research, technological development, and real-world application, ensuring a seamless transition from theory to practice. In this context, **Working Group 3 (WG3)** plays a pivotal role by integrating key insights from other working groups and work packages:

- **WG1/WP1 (PED Framework & Database):** Establishes a robust **PED Database**, structuring and standardizing PED-related data to support evidence-based decision-making. WP3 relies on these data-driven insights to refine PED Lab interventions and ensure replication efforts follow **standardized metrics, benchmarks, and best practices**.
- **WG2/WP2 (Technological & Non-Technological Tools):** Focuses on developing and aligning tools such as digital platforms, energy models, and governance frameworks. WP3 integrates these tools within PED Labs, testing their **applicability,**

interoperability, and scalability in real urban settings, while also providing feedback for refinement.

- **WP4 (Stakeholder Engagement & Policy Integration):** Ensures that PED replication is **context-specific and aligned with local governance structures**. WP3 contributes by generating **practical insights and implementation experiences**, which WP4 then translates into **policy recommendations, investment strategies, and stakeholder engagement models** to facilitate institutional adoption.

By fostering strong collaboration across these groups, the PED framework evolves into a **systematic, data-driven, and city-led initiative**, accelerating the transformation towards sustainable and energy-positive urban districts.

3. PED database

The analysis of the PED Labs is based on the PED database, developed by WG1, accessible in the Action's website. (https://pedeu.net/cast-studies-table-view/?ped_type=lab&case_study=2105).

The set up of the database is described in (Civiero et al., 2024). Currently, there are 23 PED cases, including both PED/PED-relevant cases and PED Labs, along with 7 PED related projects available. The interconnections among mapped case studies and projects are shown in Figure 2.

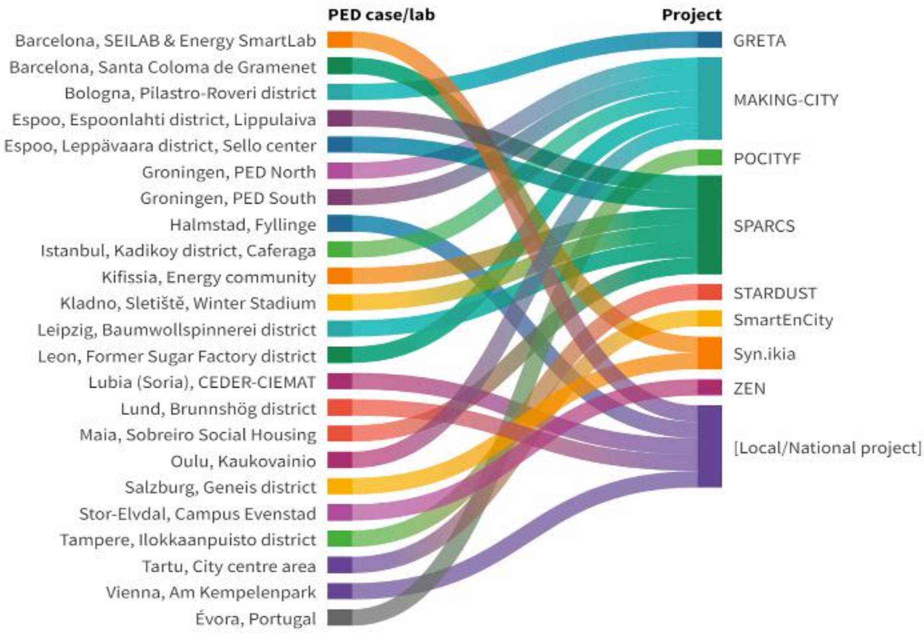

Figure 2. Referenced Case studies/Labs linkage to general Projects/Initiatives'. (source: Civiero et al. 2024).

The database classified the PED labs according to a series of answers to questions. Results shows that researchers seem to be the main interested stakeholders in testing PED labs as infrastructures properly focused on innovation, experimentation, and monitoring aspects. At the same time, public and private sectors have also expressed a strong interest in testing PED Labs as they allow pilots grounding of different innovative solutions and approaches in a controlled and experimental environment.

Section B2 'PED Lab in detail' of the database

The section B2 needs to be filled in if the PED site—according to parameter P003 in section A1—is classified as a PED Lab. Based on the definition proposed by the Set Plan Action 3.2 [4], 'PED Labs' are pilot actions that provide opportunities to experiment with the planning and deployment of PEDs. Under this framework, PED labs are considered as urban laboratories where these new proposals, technologies, and services could be developed, modelled, and monitored according to place-based needs and local context baseline. These research infrastructures allow defining integrative solutions that include technological, spatial, regulatory aspects, financial, legal, social, and economic perspectives. Therefore, with the objective of mapping the facilities, resources, and characteristics of the available laboratories, a series of questions are formulated that make it possible to classify the PED labs.

Table 8. Section B2 'PED Lab in detail'. Source: CA 'PED-EU-NET'.

ID	Parameter Title	Type of Answer				Answer Options	Target			
		O	Cs	Cm	A		Pu	Pr	Re	Ct
B2 P001	Scale of action		•			•Building; •City; •District; •Campus; •Virtual; •Semi-virtual	•	•	•	•
B2 P002	Motivation for developing the PED Lab			•		•Strategic; •Private; •Civic; •Grassroots; •Other, please specify	•		•	•
B2 P003	Lead partner that manages the PED Lab		•			•Research centre/University; •Municipality; •Industry/Company; •Other, please specify	•	•	•	
B2 P004	Collaborative partners that participate in the PED Lab			•		•Academia; •Private; •Industrial; •Citizens, •Public, •NGO; •Other, please specify	•	•	•	
B2 P005	Incubation capacities of the PED Lab			•		•Monitoring and evaluation infrastructure; •Pivoting and risk-mitigating measures; •Tools for prototyping and modelling; •Tools, spaces, events for testing and validation; •Other, please specify	•	•	•	•
B2 P006	Available facilities to test urban configurations in PED Lab			•		•Buildings; •Demand-side management; •Prosumers/P2P; •Renewable generation; •Non-renewable generation; •Energy storage; •Energy networks; •Efficiency measures; •Waste management; •Water treatment; •Lighting; •E-mobility; •Green areas; •User interaction/participation; •Information and Communication Technologies (ICT); •Ambient measures; •Social interactions; •Sustainability processes; •Blockchain; •Business models; •Financial models; •Circular economy models; •Other, please specify	•	•	•	•
B2 P007	Synergies between facilities in the PED Lab	•				[txt]		•	•	
B2 P008	Available tools			•		•Energy modelling; •Social models; •Business and financial models; •Sustainable models; •Decision making models; •Fundraising and accessing resources; •Matching actors; •Other, please specify;	•	•	•	•
B2 P009	Monitoring capabilities			•		•Execution plan; •Available data; •Type of measured data; •Equipment; •Restricted access to facilities; •Other, please specify	•	•	•	
B2 P010	Any accredited laboratory services?		•			•Yes; •No	•	•		•
B2 P011	Replication and scalability framework in the PED Lab	•				[txt]	•	•	•	
B2 P012	Stakeholders accessing the facilities			•		•Academy and students; •Industry; •Research; •Associations; • Other, please specify	•	•	•	•
B2 P013	Stakeholders' accessibility framework to facilities			•		•Under contract; •Collaborative project; •Internships allowed; •Other (open text)	•	•	•	•

"•" is used for categorising each parameter according to the type of answer required (O, Cs, Cm, A) or the target Type (Pu, Pr, Re, Ct). Instead in the column "Answer Options" is used for bullet list.

Figure 3. Section B2 'PED Lab in detail'. Source: CA 'PED-EU-NET'. (source (Civiero et al., 2024), Table 8)

In the database there are currently 10 cases classified as PED Labs. Those cases were analysed within the framework of this task, with the objective of mapping the facilities, resources, and characteristics of the available laboratories, a series of questions are formulated that make it possible to classify the PED labs (Civiero et al., 2024).

Table 1. PED Labs in the PED-EU-NET database

PED Lab	from project	category	picture
Vantaa, Aviapolis	NEUTRALPATH – Pathway towards Climate-Neutrality through low risky and fully replicable Positive Clean Energy Districts	PED Case Study / PED Relevant Case Study / PED Lab	
Aarhus, Brabrand	BIPED – Building Intelligent Positive Energy Districts	PED Case Study / PED Relevant Case Study / PED Lab	
Évora, Portugal	POCITYF – A POsitive Energy CITY Transformation Framework,	PED Relevant Case Study / PED Lab	
Groningen, PED North	MAKING-CITY – Energy efficient pathway for the city transformation: enabling a positive future	PED Lab	
Groningen, PED South	MAKING-CITY – Energy efficient pathway for the city transformation: enabling a positive future	PED Lab	
Maia, Sobreiro Social Housing	SPARCS – Sustainable energy Positive & zero cARbon CommunitieS	PED Lab	
Lubia (Soria), CEDER-CIEMAT		PED Lab	
Tartu, City centre area	SmartEnCity – Towards Smart Zero CO2 Cities across Europe	PED Relevant Case Study / PED Lab	
Barcelona, SEILAB & Energy SmartLab		PED Lab	
Genk, OpenLab	oPEN Lab-Living Lab Genk	PED Lab	

4. Framework

The framework follows the organization suggested by WG2, Task 2.5. Even though it primarily focused on identifying the tools (Natanian et al., 2024), it provides guidance how to analyse the PED Labs as well, as the Tools and the Labs are linked with regards to PED implementation. In this approach the KPIs are central in the framework, as they determine the aspects that the tools address.

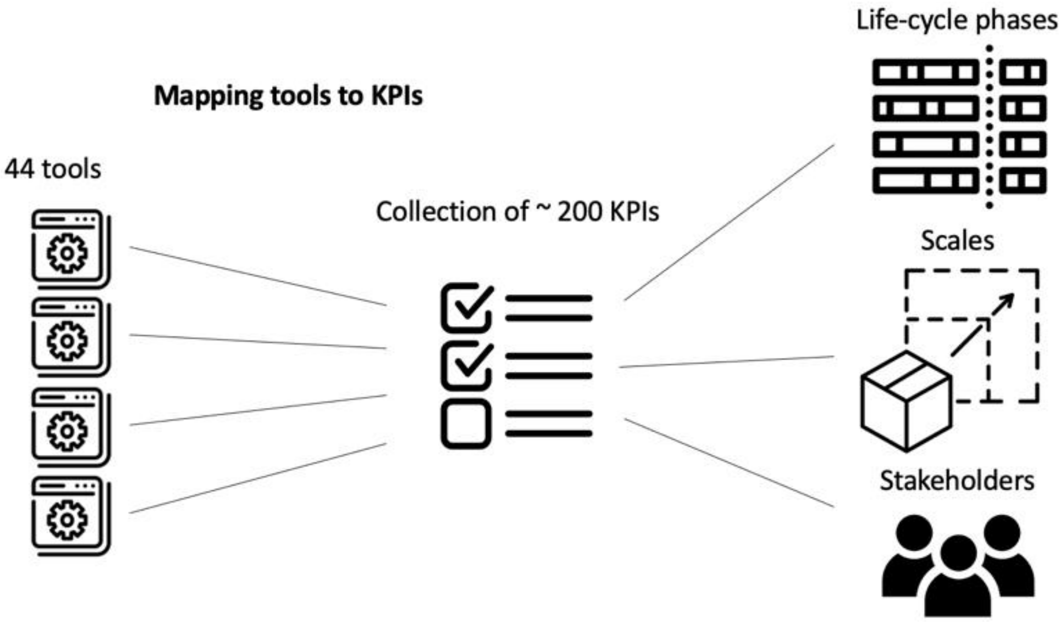

Figure 4. overview of the framework for mapping the tools, developed by WG2, T2.

Areas	Key Tools/ Technologies answer in areas	Implementation domains	Engagement phase	Engagement scale	Stakeholder
1. Safety & Security, 2. Health, 3. Education, 4. Mobility, 5. Energy, 6. Water, 7. Waste, 8. Economic development, Housing and Community.	*Ref. to all* Areas (1,2,3, …)	1. Technologies in built environment 2. Energy supply system, 3. Water disposal system, 4. Waste disposal system, 5. Mobility system, 6. Public space, 7. Regulatory framework.	1. Planning, 2. Design, 3. Construction, 4. Management.	1. Functional unit, 2. Building, 3. Block of buildings, 4. Infrastructures (material/ immaterial), 5. Environment (physical/social).	1. Government, 2. R&I, 3. Financial/Funding, 4. Analyst, IT project and Big Data, 5. BPM, 6. Urban Services, 7. Real Estate, 8. Design/ Construction, 9. Social/Civil Society, 10. eCommerce.

Figure 5 Analysis model for implementation of the Smart Sustainable District solutions (Cellurale, 2019)

Table 2. KPIs Categories (source: Orova, M. and A. Reith (2024).

Main category	Subcategory
Energy	Energy generation
	Usage factors
	Energy balance
	Energy efficiency
	Energy savings
	Active management
	Flexibility
Environmental Performance	Emission
	Emission reduction
	Resilience
Economic performance	Cost
	Cost reduction
Society and Residents	Participatory approach
	Life quality of users
	Inclusiveness
	Affordability
Mobility	Mobility
Materials and Resources	Materials
Governance	Scalability
	Local context

Deliverable 3.2 defined different indicators particularly for the PED Labs. In alignment with WG1, as shown in Table 2 (Demir, Alpagut, and Soutullo Castro, 2022). They refer to Energy, Mobility, Environment, Economy and Social.

Particularly for Task 3.3, the framework to analyse the PED labs aimed at including the technological, social, financial and regulatory perspectives. The KPIs categories as shown in Table 2 link to those aspects in different ways. In this respect, mapping the key stakeholders, as well as on which scale and phase the decisions are made will be part of the analysis. As a result, the proposed framework provides a relation between the 4 key aspects:

- **technological,**
- **social,**
- **financial and**
- **regulatory**

and the 3 dimensions:

- **Stakeholders,**
- **Life-cycle phase and**
- **scale.**

4.1 Stakeholders

The role of the diverse stakeholders in the PED Labs and the potential implementation is undeniable. Gohari et al. (2024) reported on the commitment, communication and coordination of the different actors as an enabling factor.
"Uncertainty and ambiguity in planning and decision-making processes due to a lack of knowledge and resources, particularly in the context of PED, can increase challenges. Municipal interests or political agendas may determine site choice rather than technical aspects. Lengthy bureaucratic and political processes can demotivate citizens. Municipal hierarchies can complicate the decision-making process due to a lack of communication. There may be a low transfer of knowledge".
Therefore, it is important to take into account the objective of the stakeholder´s contribution, their motivation, the degree of commitment they are willing to assume, the type of activity or the model of affiliation with the laboratory. The involvement and cooperation of all stakeholders requires an open, transparent and participatory process that enhances relationships, partnerships and collaborations among actors.

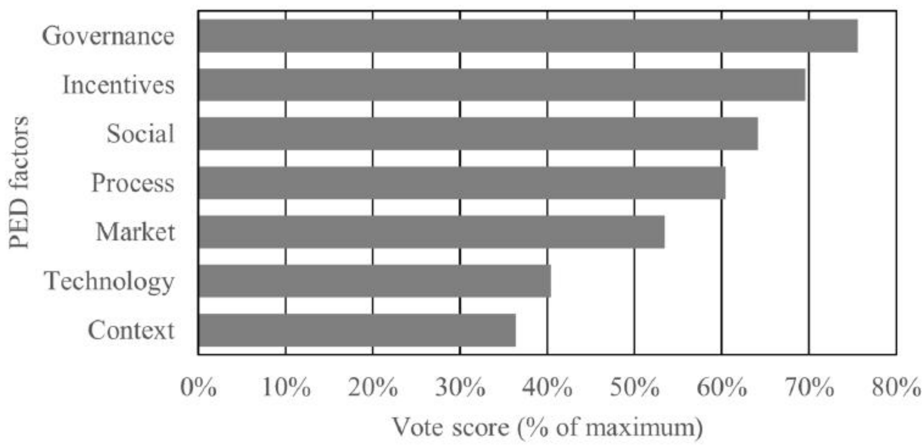

Figure 6 Stakeholder analysis.in PEDs (Krangsås et al., 2021)

With regards to stakeholder, the analysis should look on their role and objectives, as well as the challenges they encountered in the PED Labs. As part of the analysis framework, categories of stakeholders are used.
Stakeholders can be clustered into different categories, depending on their role, influence and implementation/decision-making agency. The Quadruple Helix involves representatives from all members of society; public authorities, industry, academia and citizens (Lindberg et al., 2014).

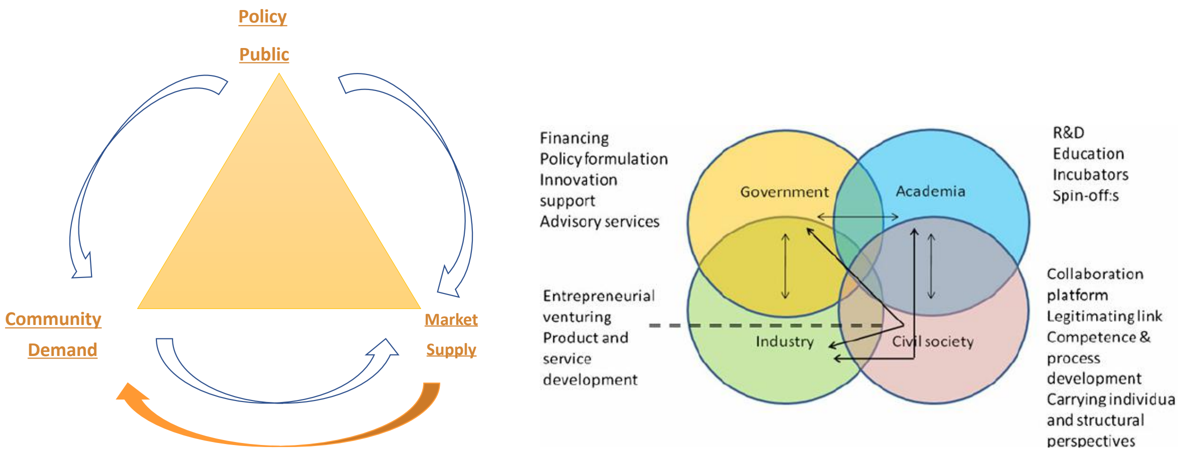

Figure 7 Examples of stakeholders categorization according to Quadruple Helix (Lindberg et al., 2014)

In the context of Smart and Sustainable cities, Cellurale (2019) defined a comprehensive list including the following stakeholders' groups. 1. Government, 2. R&I, 3. Financial/Funding, 4. Analyst, IT project, and Big Data, 5. BPM, 6. Urban Services, 7. Real Estate, 8. Design/ Construction, 9. Social/Civil Society, 10. eCommerce.

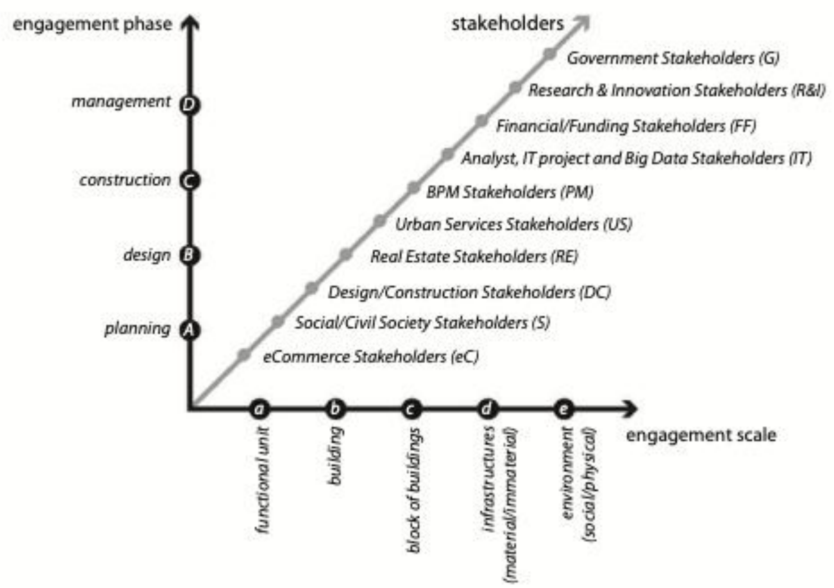

Figure 8 The dimensions of the transformation and implementation of the SCC solutions: engagement phase/scale with stakeholders. (Cellurale, 2019), figure 1.

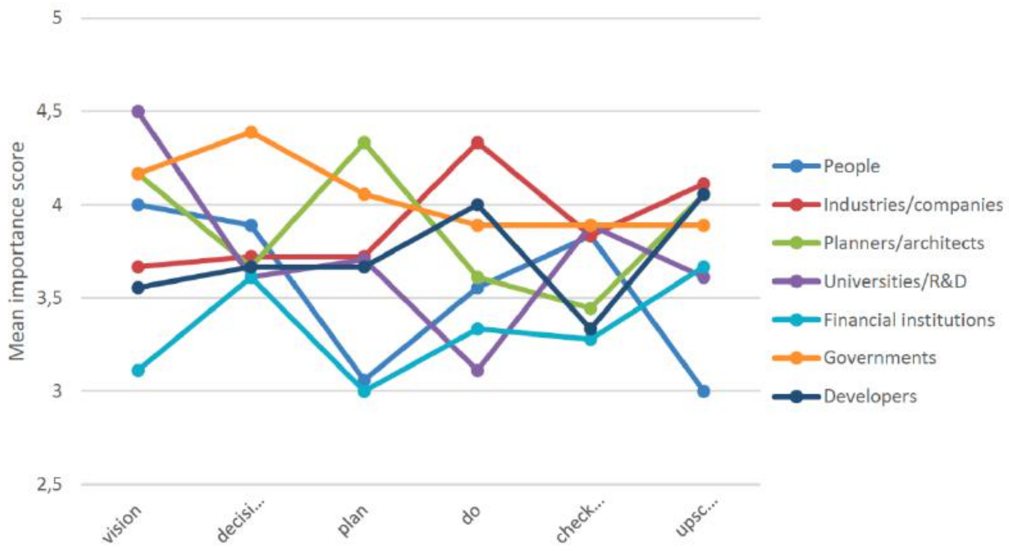

Figure 9 Stakeholders and their perceived importance as analysed by focus groups in T3.1

Based on this discussion T3.3 framework was adopted to the following stakeholders categories:

1. *People/Citizens*
2. *Industries/Companies*
3. *Planners/Architects*
4. *Universities/R&D*
5. *Financial institutions*
6. *Governments*
7. *Developers*

4.2 Life-Cycle phases

During its lifetime, a neighbourhood will go through many project phases. The three project phases and to be assessed in the ZEN definition (Wiik et al., 2024) are the Strategic planning phase, Implementation phase, Operational phase. Particularly for the PED labs, WG3, T3.1 defined the following process phases, which can also been seen in figure above:

- *VISION phase: the participation of University and R&D sector is determinant as well as that of Government and Planners. Consultation of citizens is also a high priority.*
- *DECISION phase: the Government is the main actor, supported by citizens.*
- *PLAN phase: here the Planners manage this phase in support of the Government assisted by Industry, Universities and Developers.*
- *DO Phase: Industry and Developers are the main actors in this phase within a framework promoted by the Government, which also sees the growth of financial institutions in their role as investors.*
- *Check/Act Phase: All stakeholders have to be involved in this phase in various ways.*
- *Upscale/replicate phase: This phase links to the DO phase and sees a similar distribution of roles. The lack of presence of citizens in this phase is surprising. Aspect to be further investigated.*

For the purpose of the T3.3, which is about consolidating the PED Labs definitions, we will use the 3 main phases identified by (Wiik et al., 2024), and add a phase between implementation and operation, when the project is completed, marking the observation of the performance.

1. *Planning phase*
2. *Implementation phase*
3. *Completed*
4. *In operation*

4.3 Scales

{Soutullo, 2020 #1827} has identified the building as the smaller scale of action in PED labs and listed a number of facilities and technologies, such as heat pumps, thermal storage, and PV that have been implemented to the buildings. For this reason, we will also consider the component scale as part of the framework, to be able to include decisions on the component level. Furthermore, we adopt the scales classification as defined by {Cellurale, 2019 #1431}

1. Components
2. Building
3. Block of buildings,
4. Infrastructures (material/ immaterial),
5. Environment (physical/social).

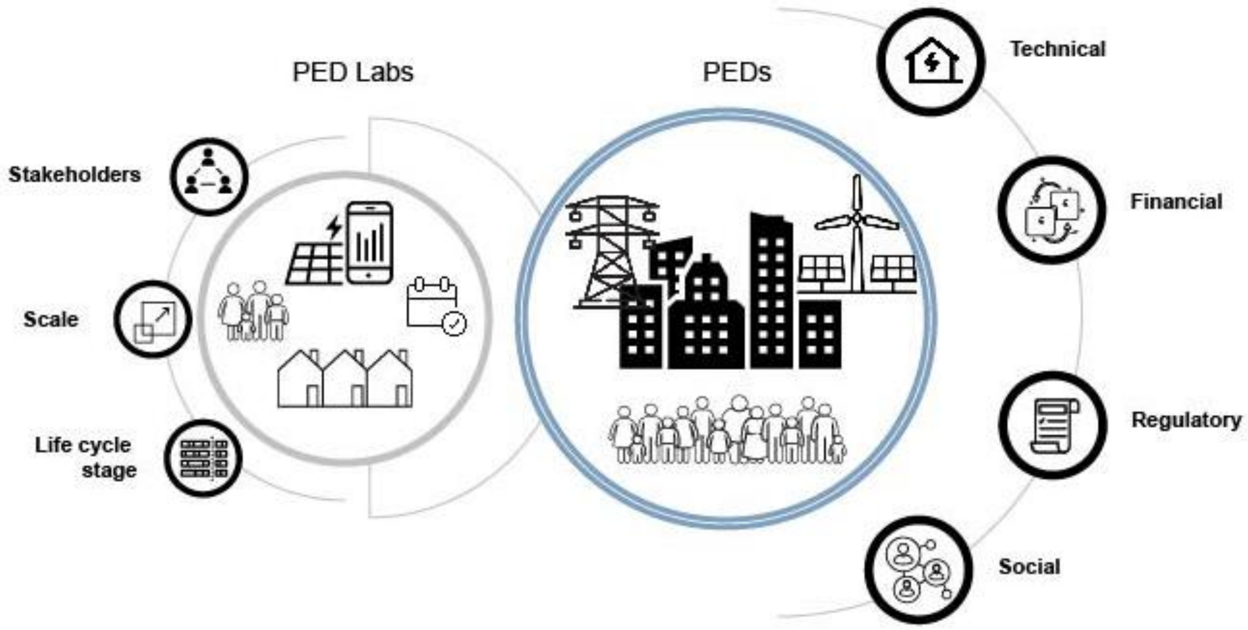

Figure 10 PED Lab Framework overview

5. Template to analyze the PED Labs

The analysis template will follow the structure of the above explained framework.

The extended version in excel formal was used for the analysis. Table 3 gives an overview of the PED Labs in the database.

Table 3. Overview of PED Labs

Name	Vantaa	Aarhus	Évora	Groningen	Groningen	Maia, Sobreiro	Lubia (Soria)	Tartu	Barcelona	Genk PED Lab
Location	Aviapolis	Brabrand	Portugal	PED South	PED North	Social Housing	CEDER-CIEMAT	City centre area	SEILAB & Energy SmartLab	Genk, BE
PED case study	yes	yes	no	no	no	no	no	no	no	yes
PED relevant case study	yes	yes	yes	no	no	no	no	yes	no	yes
PED Lab.	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes

This section investigated in depth how the three dimensions of stakeholders, project phase, and scale influenced the technical, financial, regulatory and social aspects of the PED Lab.

Short analysis of the specific case

Stakeholders: their role objective and decision making

- Which were the main decision makers for the PED?
- Which actor was responsible for implementing?
- Who was the key user of the PED and how the PED influenced their life quality?
- Who has financial savings/benefits (value, revenue)?

Life-cycle phase

- In which phase were the technical interventions decided
- Which phases were monitored and how were the outcomes used?
- How and when will the investment pay back?
- In which phase did the community engage?

Scale

- At which scale was the technology implemented?
- Which other scales did the technology influence/interacted with?
- Which scale was the community engagement relevant for and in which capacity? EG. Building/dwelling, urban, energy community etc.?

Three PED Labs are described her in more detail as shown in Table 4.

Table 4. Three PED Labs with detailed analysis

Name	Maia, Sobreiro Social Housing«×»	Lubia (Soria), CEDER-CIEMAT«×»	Genk PED Lab
Location	CM Maia, IPMAIA, NEW, AdEP.	CIEMAT. Data detail	Genk, BE
PED Lab	Strategic	Strategic	Strategic

6. Results of the PED Labs Analysis

In principle all PED Labs were analysed. Three PED Labs were analysed in more detail and results are presented in the following section.

6.1 Short analysis of three specific case studies

CEDER-CIEMAT PED Lab

The Centre for the Development of Renewable Energy (CEDER) [http://www.ceder.es/redes-inteligentes] is placed in the middle-north region of Spain (Soria) and it is specialized in applied research, development and promotion of renewable energy. This PED Lab is located in the CIEMAT facilities (Spanish public research center) and operates as an energy district, covering an area of 640 hectares.

Figure 11 Aerial image of the CEDER-CIEMAT Lab facilities [Source: CEDER website]

The district consists of six office buildings and two energy networks, one electrical (operational) and one thermal (under implementation). The electrical network integrates a 50 kW wind turbine, eight photovoltaic systems with a total generation capacity of 116 kW, a 100 kVA engine generator, a reversible hydraulic system and storage systems through batteries and flexible loads. The thermal network currently consists of two 300 kW biomass boilers and 90 kWh water tanks for thermal storage. However, this network is being expanded through the incorporation of a low temperature ring (90°C) and a high temperature ring (150°-250° C), both interconnected through an oil/water heat exchanger. Several thermal storage systems are also being incorporated through boreholes, phase change materials, geothermal exchange or the use of zeolites.

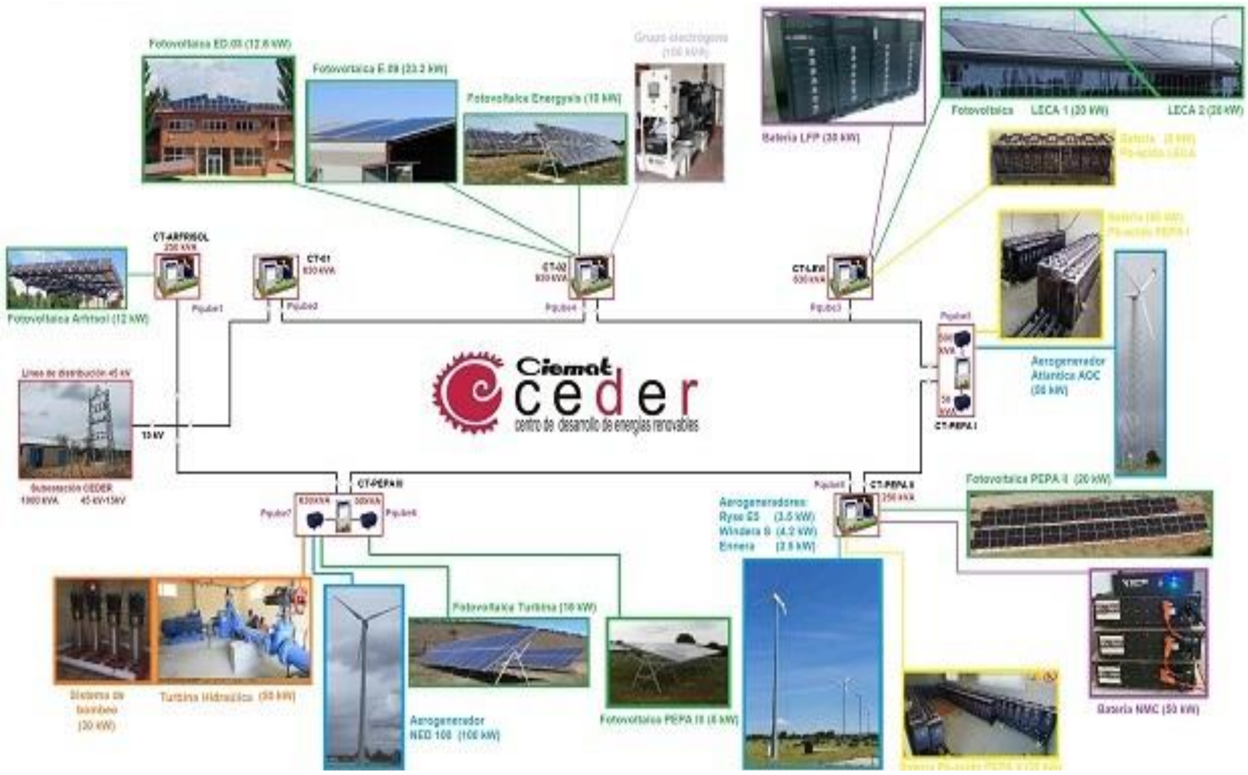

Figure 12 Diagram of electric network elements installed in CEDER-CIEMAT Lab [Source: CEDER website]

The main actor of this PED Lab is CIEMAT, since it is the owner and responsible for the implementation and operation, achieving a flexible facility that produces renewable energy and enhances efficiency through energy networks and adapted buildings. However, the engagement of technical and industrial companies, suppliers and governmental and political actors is crucial to the decision-making and financial processes. In addition, it is essential to involve the local community both to identify its energy behavior (determining user profiles) and to achieve its acceptance in these urban solutions.
This laboratory measures climatic, building and network values, generating datasets processed by a central control system that makes it possible to design and test strategies and solutions or perform virtual analysis related to building and district scale. Although being a laboratory, the change to real urban scale still poses technical and logistical challenges.
Therefore, among the main challenges faced by this laboratory are the need for investment in technology and innovation, cooperation between stakeholders balancing their interests and processing of the monitored data to be translated into results applicable in industrial applications and urban planning.

Table 5. Overview of CEDER-CIEMAT PED Lab dimensions

Dimension	Technological	Social	Financial	Regulatory
Stakeholders	CIEMAT, Universities from Castilla y Leon (Spain), Suppliers, Technological Companies (e.g. Geoter, Gaptek), Technological centres (e.g. CARTIF Foundation)	CEDER-CIEMAT Staff, Spanish Technological Platforms	CIEMAT, Spanish Ministry of Science and Technology, Spanish Centre for the Development of Industrial Technology (CDTI), National and international projects	National Government of Spain, Regional Government of Castilla y Leon, municipality of Soria
Life-cycle Phase	Building retrofit measures and electrical network are defined in the planning phase. Thermal network characteristics are proposed in the implementation and operation phases.	Occupants' behaviour patterns start in the planning phase but are modelled during the operation phase	As a Public Research Body facility, it requires funding at all stages of the process and throughout its life-cycle to keep it in operation.	Aligning the lab's innovations with evolving energy policies at the local, national and European levels requires constant adaptation at all phases
Scale	Interventions are executed at building and district scales. The implementation of IoT systems and smart meter sensors will enable the future development of a virtual PED Lab.	CIEMAT staff engagement occurs at the building scale. The future virtual PED Lab plans to expand this participation at district level in CEDER	In a public Body, funding and savings obtained are not accounted for in economic terms, but are considered in energy terms	This public PED Lab operates within regional and national regulatory frameworks, allowing for replication across different urban zones

Genk PED Lab

oPEN Living Lab Genk is part of the project oPEN Lab which is funded under the European Union's Horizon 2020 Research and Innovation and will focus on identifying and demonstrating replicable, commercially viable solution packages enabling to achieve positive energy buildings and neighbourhoods. oPEN Living Lab Genk is located in Genk, Belgium in the suburban residential neighbourhood called "Waterschei". This neighbourhood consists of two distinct areas: a former miners' district constructed in the 1920s and a more recent social housing district called "Nieuw Texas" built in the 1990s. Together with the suburban context, a very high level of social housing ownership (85%) in Nieuw Texas, and the nearby presence of former mines, represent a unique opportunity for large-scale, real-life demonstrations of promising technology, renovation processes, and social innovation toward the creation of a Positive Energy Neighbourhood.

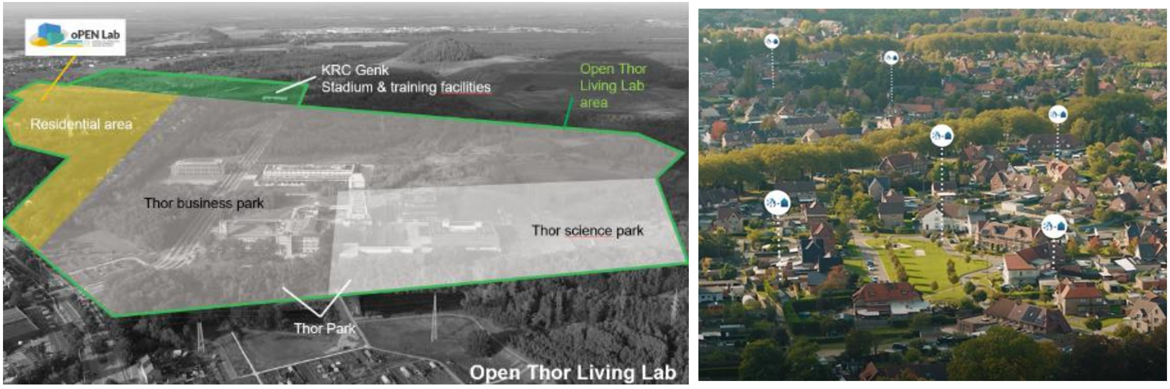

Figure 13 Genk PED Lab overview

The oPEN Living Lab Genk identified all the actors of the quadruple helix stakeholders, which is mainly composed by private owners and social housing owners, the City Council of Genk, the technology providers and the researchers involved in oPEN Lab as project partners. Within the first target audience, private owners need a holistic approach on made renovation for single owners, taking into account their financial requirements and a package to guide them on appropriate new financing models of energy usage, without the need to make investments upfront.

In Nieuw Texas, inhabitants were invited to participate to the oPEN Lab renovation activities on a voluntary basis. In mid-2022, 27 households were selected. In parallel, technical project partners (industrial partners, research institutes) prepared innovative technical design criteria in topical working groups. Simultaneously, Wonen in Limburg (formerly Nieuw Dak) and VITO initiated the process of appointing an external design team, applying for building permits and preparing tender documents for the execution of the construction works, integrating the inputs from the topical working groups. On top of this, there is a macro-level approach, being the oPEN Thor Living Lab. One challenge lies in the alignment of the stakeholders of oPEN Lab and Open Thor Living Lab which are not completely the same group of stakeholders. Some of the oPEN Lab partners are not directly involved in the Open Thor Living Lab and vice versa.

Since the beginning, co-creation sessions were organised by Wonen in Limburg, together with VITO, the City of Genk and Stebo involving tenants and partners (public sector, industrial actors and researchers) with the aim of investigating ways of turning a neighbourhood, a street or a house into a positive energy district. PED-related regulations – particularly those aimed at reducing GHG emissions in buildings, electrifying heating systems and giving buildings a more active role in the energy system – fall under a Flemish remit due to Flanders' regional authority in energy and climate matters.

Table 6. Overview of Genk PED Lab dimensions

Dimension	Technological	Social	Financial	Regulatory
Stakeholders	VITO,IMEC and KU Leuven as academia representatives. Van Roey and Habenu van de Kreeke are two contractors providing support from the building sector, while FUTECH, DCinergy, Cast4all, LITO and Daikin each provide specific technologies.	City Council of Genk , WIL and Stebo.They are responsible for the citizens' engagement.	For social housing companies Flanders has various VKF subsidies (Vlaams Klimaatfonds Subsidies). Research institutes and WIL have also invested in lab facilities.	City Council of Genk ,Flemish government. Flanders has adopted a Local Energy and Climate Plan (LEKP), a pact for local energy and climate action signed by Flanders and the local governments
Life-cycle Phase	Building retrofit measures and feasibility studies identifed at planning phase. The montiroing is done via an energy management platform during operation.	Community engagement started in the planning phase (co-creation sessions) and continues through implementation and operation.	Investment decisions were done during planning; operational savings and data capturing as important assets for replication.	Constant modification at all phases. In progress to transpose different concepts of energy sharing into the Flemish Energy Decree.
Scale	Interventions are completed both at building level and at district-level (neighbourhood shared services).	Engagement happens at dwelling level and expands to neighbourhood-level through the Living Lab approach.	Savings are realized at the social housing dwellings but also at energy and CO_2 emissions terms.	The PED Lab operates within municipal and regional regulatory frameworks that enable replication.

Maia Sobreiro Social Housing

In Maia, the primary decision maker was the Municipality of Maia, led by the city's leadership and coordinated through it's Strategy Development and Innovation Office (NEDI), and working closely with the technical divisions like the Division of Energy and Mobility and partners such as AdEPorto (Energy Agency), EDP NEW R&D (Industry partner) and the University of Maia(Sá et al., 2024). The Municipality set the overall vision, aligned with the City Vision 2050(Melo et al., 2024), and formulated policies driving the development.

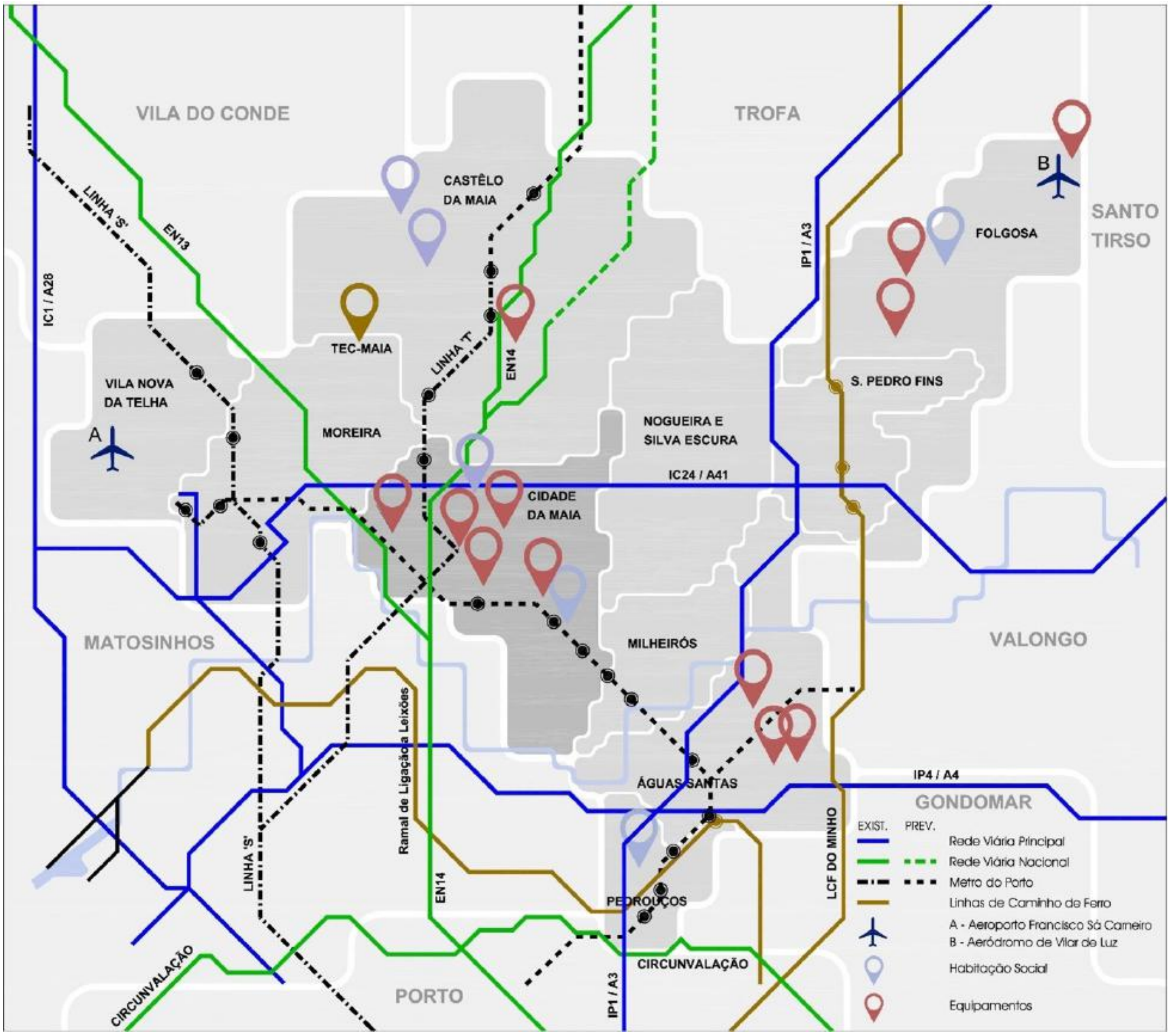

Figure 14 Maia PED Lab overview

Implementation was executed by the municipal social housing company, Espaço Municipal which retrofitted social housing blocks and was overseeing other interventions like PV and smart meter installations. They also collaborated with technical partners like AdEPorto, and EDP NEW R&D, who supported with feasibility studies and technical assessment. The key users of the PED are the residents of the Sobreiro Social Housing. For them, the project aimed to enhance quality of life by improving thermal comfort, developing a sense of community, reducing energy poverty and turning them into prosumers. The financial benefits primarily accrue to the residents, Municipality and Espaço Municipal through reduced energy bills for public buildings and communal areas. The energy community model enables the sharing of revenue from surplus energy, while outcome-based PV contracts guarantee renewable production lowering bills, and minimizing upfront risks(Sá et al., 2024). Efficiency measures in the buildings cut consumption, accelerated payback reduced energy poverty and generated revenue streams for the residents.

Technical interventions were decided during the planning and scoping phase via comprehensive feasibility studies assessing the building stock, public infrastructure and

renewable potential. Monitoring occured throughout the implementation and operational phases using smart meters. Continuous data collection enabled real-time adjustments to retrofit measures and operational strategies ensuring that KPIs were met.
Renewable installations and the refurbishment are both indicated as cost-effective, with short payback periods, driven by savings already mentioned. Energy community in Sobreiro has a payback period of 4,4 years and a favourable 490% return on investment (Sá et al., 2024).
Community engagement began in the early planning phases, through public consultations and co-design workshops and continued into operation via regular meetings and digital platforms. Technological interventions were applied mostly at the building level (social housing blocks and municipal buildings) and aggregated to eventually form a district scale virtual PED. These measures also influence the broader urban scale as part of the "Maia Positive City" vision. Community engagement operates at multiple scales, from individual dwellings to neighbourhood-wide energy community efforts, ensuring both technical and social dimensions are addressed.

Table 7. Overview of Maia PED Lab dimensions

Dimension	Technological	Social	Financial	Regulatory
Stakeholders	Technical partners (AdEPorto, EDP NEW R&D, University of Maia) provide feasibility studies, assessments, and integration tools.	Residents of the Sobreiro Social Housing District engage in co-design and REC formation, influencing comfort and quality of life.	Municipality and Espaço Municipal benefit from reduced energy bills; industry (e.g., Sonae) gains via enhanced sustainability.	Municipality sets policies and coordinates with national bodies to enable the REC model and ensure compliance.
Life-cycle Phase	During planning, feasibility studies define retrofit measures (e.g., PV installations, smart meter deployments); monitored through an energy management platform in operation.	Community engagement starts in the planning phase (public consultations, workshops) and continues through implementation and operation.	Investment decisions (e.g., outcome-based contracts) are made during planning; operational savings accumulate to achieve rapid payback.	Permitting and policy formulation occur in planning, with ongoing compliance monitoring during the operational phase.
Scale	Interventions are executed at the building level (individual social housing blocks and municipal buildings) and aggregated into a district-scale virtual PED.	Engagement occurs at the building/dwelling level and expands to neighbourhood-level via collective actions in the REC; results inform urban-scale replication.	Savings are realized at the communal level (public buildings, social housing) and scaled up through broader municipal investments.	The PED Lab operates within municipal and national regulatory frameworks that enable replication across different urban zones

6.2 Short analysis of PED Labs in database

As shown in Table 6, researchers, coming both from academia and R&I centres, seem to be the main interested stakeholders in testing PED labs as infrastructures properly focused on innovation, experimentation, and monitoring aspects. At the same time, public and private sectors have also expressed a strong interest in testing PED Labs as they allow pilots grounding of different innovative solutions and approaches in a controlled and experimental environment. In this section the PED Labs from the PED database were analysed. It uses the same framework as described above with a specific focus on targets of the PED Lab, Data availability (A1P009), Ownership of the PED Lab (A1P016), Financing - PUBLIC - National funding (A1P022e),

economic targets (A1P023). But also further details of the PED Lab like operator of the installation (B2P004), motivation for developing the PED Lab (B2P007), lead partner that manages the PED Lab (B2P008), available facilities to test urban configurations in PED Lab (B2P011), incubation capacities of PED Lab (B2P012), monitoring measures (B2P014), Key Performance indicators (B2P015), and available tools (B2P019) were collected and used for comparison.

This information draws a complete picture of the important aspects and dimensions as described in Table 8.

Table 8. PED Labs database

Dimension	Technological	Social	Financial	Regulatory
Stakeholders	Data availability (A1P009)	Ownership of the PED Lab (A1P016)	economic targets (A1P023)	Targets of the PED Lab (A1P004)
Life-cycle Phase	Monitoring measures (B2P014)	Lead partner that manages the PED Lab (B2P008)	Incubation capacities of PED Lab (B2P012)	Available facilities to test urban configurations in PED Lab (B2P011)
Scale	Key Performance indicators (B2P015)	motivation for developing the PED Lab (B2P007)	operator of the installation (B2P004)	Available tools (B2P019)

Table 9. Overview of the A1P004: Targets of the PED Lab

Name	Vantaa	Aarhus	Évora	Groningen	Groningen	Maia, Sobreiro	Lubia (Soria)	Tartu	Barcelona	Genk
Location	Aviapolis	Brabrand	Portugal	PED South	PED North	Social Housing	CEDER-CIEMAT	City centre area	SEILAB & Energy SmartLab	Belgium
Climate neutrality	yes	yes	no	yes	yes	yes	no	yes	no	no
Annual energy surplus	no	yes	yes	yes	yes	no	no	no	no	yes
Energy community	no	yes	yes	yes	yes	no	no	no	yes	yes
Circularity	yes	no	no	yes	yes	no	no	yes	no	yes
Air quality and urban comfort	no	no	no	no	no	no	yes	no	no	yes
Electrification	no	no	no	no	no	no	no	yes	yes	no
Net-zero energy cost	no	no	no	no	no	no	no	no	no	no
Net-zero emission	no	yes	no	yes	yes	no	yes	yes	yes	no
Self-sufficiency (energy autonomous)	no	no	no	no	no	no	yes	no	yes	no
Maximise self-sufficiency	no	no	no	no	no	yes	no	yes	no	yes
Other	no	no	no	no	no	no	no	no	yes	yes

Table 10. Details of the PED Lab

City	Vantaa	Aarhus	Évora	Groningen	Groningen	Maia	Lubia (Soria)	Tartu	Barcelona	Genk
Location	Aviapolis	Brabrand	Portugal	PED South	PED North	Sobreiro Social Housing	CEDER-CIEMAT	City centre area	SEILAB & Energy SmartLab	Belgium
A1P009: Data availability	General statistical datasets, GIS open datasets	Open data city platform – different dashboards, General statistical datasets, GIS open datasets	Open data city platform – different dashboards	Monitoring data available within the districts, Open data city platform – different dashboards, GIS open datasets	Monitoring data available within the districts, Open data city platform – different dashboards, GIS open datasets	Monitoring data available within the districts, Open data city platform – different dashboards, Meteorological open data, General statistical datasets, GIS open datasets	General statistical datasets	Monitoring data available within the districts, Open data city platform – different dashboards	General statistical datasets	Monitoring data available within the districts
A1P016: Ownership of the PED Lab	Mixed	Mixed	Mixed	Mixed	Mixed	Public	Public	Private	Public	Mixed
A1P022e: Financing - PUBLIC - National funding	no	no	no	yes	yes	yes	no	yes	no	yes
A1P023: Economic Targets	Positive externalities, Boosting local businesses, Boosting local and sustainable production	Boosting local and sustainable production		Boosting local businesses, Boosting local and sustainable production	Boosting local businesses, Boosting local and sustainable production	Positive externalities, Boosting local and sustainable production	Boosting local and sustainable production, Boosting consumption of local and sustainable products	Positive externalities	Job creation, Boosting local and sustainable production	Boosting local and sustainable production

Table 11. Further details of the PED Lab

City	Vantaa	Aarhus	Évora	Groningen	Groningen	Maia	Lubia (Soria)	Tartu	Barcelona	Genk
Location	Aviapolis	Brabrand	Portugal	PED South	PED North	Sobreiro Social Housing	CEDER-CIEMAT	City centre area	SEILAB & Energy SmartLab	Belgium
B2P004: Operator of the installation	The City of Vantaa manages the lab, working closely with landowners and other stakeholders such as energy companies, solution providers, universities and citizens.			The Municipality of Groningen is Manager of the lab but works closely with other parties such as the university, university of applied sciences, research institute TNO and several other parties.	The Municipality of Groningen is Manager of the lab but works closely with other parties such as the university, university of applied sciences, research institute TNO and several other parties.	CM Maia, IPMAIA, NEW, AdEP.	CIEMAT. Data detail in contact: mariano.martin@ciemat.es and oscar.izquierdo@ciemat.es		IREC	VITO-WIL
B2P007: Motivation for developing the PED Lab	Strategic	Strategic		Civic	Civic	Strategic	Strategic	Strategic	Strategic, Private	Strategic
B2P008: Lead partner that manages the PED Lab	Municipality	Research center/University		Municipality	Municipality	Municipality	Research center/University	Municipality	Research center/University	Research center/University
B2P011: Available facilities to			Buildings, Demand-side	Buildings, Demand-side	Buildings, Demand-side	Buildings, Demand-side	Buildings, Demand-side	Buildings, Prosumers, Renewable	Demand-side managemen	Demand-side managemen

test urban configurations in PED Lab			management, Prosumers, Renewable generation, Energy storage, Energy networks, Waste management, E-mobility, Social interactions, Circular economy models	management, Energy storage, Energy networks, Waste management, Lighting, E-mobility, Information and Communication Technologies (ICT), Social interactions, Business models	management, Energy storage, Energy networks, Waste management, Lighting, E-mobility, Information and Communication Technologies (ICT), Social interactions, Business models	management, Prosumers, Renewable generation, Energy storage, Efficiency measures, Lighting, E-mobility, Information and Communication Technologies (ICT), Ambient measures, Social interactions	management, Prosumers, Renewable generation, Energy storage, Energy networks, Efficiency measures, Information and Communication Technologies (ICT), Ambient measures, Social interactions	generation, Energy networks, Lighting, E-mobility, Green areas, User interaction/participation, Information and Communication Technologies (ICT)	t, Energy storage, Energy networks, Efficiency measures, Information and Communication Technologies (ICT)	t, Energy storage, Energy networks, Efficiency measures, Information and Communication Technologies (ICT),Social interactions
B2P012: Incubation capacities of PED Lab			Monitoring and evaluation infrastructure, Tools for prototyping and modelling, Tools, spaces, events for testing and validation	Tools for prototyping and modelling	Tools for prototyping and modelling	Monitoring and evaluation infrastructure, Tools, spaces, events for testing and validation	Monitoring and evaluation infrastructure, Tools for prototyping and modelling	Monitoring and evaluation infrastructure, Pivoting and risk-mitigating measures	Monitoring and evaluation infrastructure, Tools for prototyping and modelling, Tools, spaces, events for testing and validation	Monitoring and evaluation infrastructure, Pivoting and risk-mitigating measures

B2P014: Monitoring measures				Execution plan, Available data, Type of measured data, Equipment, Level of access	Execution plan, Available data, Type of measured data, Equipment, Level of access	Execution plan, Available data, Type of measured data	Equipment	Available data, Life Cycle Analysis	Equipment	
B2P015: Key Performance indicators	Energy, Environmental, Social, Economical / Financial	Energy, Environmental, Sustainability, Social, Economical / Financial	Energy	Energy, Social, Economical / Financial	Energy, Social, Economical / Financial	Energy, Environmental, Social, Economical / Financial	Energy, Environmental, Economical / Financial	Energy, Sustainability, Social, Economical / Financial	Energy, Environmental	Energy, Environmental, Social, Economical / Financial
B2P019: Available tools	Energy modelling	Energy modelling, Decision making models		Energy modelling, Social models, Business and financial models	Energy modelling, Social models, Business and financial models	Energy modelling, Social models, Business and financial models, Fundraising and accessing resources, Matching actors	Energy modelling	Social models	Energy modelling	Energy modelling, Decision making models

6.3 Summary of findings from detailed PED Lab analysis

The results from the detailed PED Lab analysis can be summarized in the following table 12.

Table 12. Summary of results from the detailed PED Lab analysis

Dimension	Technological	Social	Financial	Regulatory
Stakeholders	Technical partners provide feasibility studies, assessments, and integration tools.	Residents engage in co-design and REC formation, influencing comfort and quality of life.	Municipality benefit from reduced energy bills; industry (e.g., Sonae) gains via enhanced sustainability.	Municipality sets policies and coordinates with national bodies to enable the REC model and ensure compliance.
Life-cycle Phase	During planning, feasibility studies define retrofit measures (e.g., PV installations, smart meter deployments); monitored through an energy management platform in operation.	Community engagement starts in the planning phase (public consultations, workshops) and continues through implementation and operation.	Investment decisions (e.g., outcome-based contracts) are made during planning; operational savings accumulate to achieve rapid payback.	Permitting and policy formulation occur in planning, with ongoing compliance monitoring during the operational phase.
Scale	Interventions are executed at the building level (individual social housing blocks and municipal buildings) and aggregated into a district-scale virtual PED.	Engagement occurs at the building/dwelling level and expands to neighbourhood-level via collective actions in the REC; results inform urban-scale replication.	Savings are realized at the communal level (public buildings, social housing) and scaled up through broader municipal investments.	The PED Lab operates within municipal and national regulatory frameworks that enable replication across different urban zones

6.4 Summary of findings from PED Lab database

The results from the PED Lab database analysis can be summarized in the following table 13.

Table 13. Summary of the results of the PED Lab database analysis

Dimension	Technological	Social	Financial	Regulatory
Stakeholders	Monitoring data available within the districts, Open data city platform – different dashboards, Meteorological open data, General statistical datasets, GIS open datasets	4 x mixed ownership 5 x public ownership	Positive externalities, Boosting local businesses, Boosting local and sustainable production	Targets see Table 10
Life-cycle Phase	Life Cycle Analysis, Execution plan, Available data, Type of measured data, Equipment, Level of access	3 x Research center/University 5 x Municipality	Monitoring and evaluation infrastructure, Tools for prototyping and modelling, Tools, spaces, events for testing and validation, Pivoting and risk-mitigating measures	Buildings, Demand-side management, Prosumers, Renewable generation, Energy storage, Energy networks, Efficiency measures, Information and Communication Technologies (ICT), Ambient measures, Social interactions
Scale	Energy, Environmental, Sustainability, Social, Economical / Financial	Civic Strategic private	3 city/municipality 3 research company	Energy modelling, Social models, Business and financial models, Fundraising and accessing resources, Matching actors

6.5 Existing gaps in PED Lab

While PED Labs are making significant strides in promoting sustainable urban development, there are still some key knowledge gaps that need to be addressed to accelerate the transition towards Positive Energy Districts.

Standardized Methodologies and Metrics:

- There's a lack of standardized methodologies for assessing and comparing the performance of PEDs. This makes it difficult to benchmark progress and share best practices effectively.
- We need more comprehensive metrics that go beyond energy balance and consider other crucial aspects like environmental impact, social equity, and economic viability.

Long-Term Performance and Resilience:

- Most PEDs are relatively new, and there's limited data on their long-term performance, especially regarding energy efficiency, maintenance, and resilience to climate change.
- We need to better understand how PEDs can adapt to changing conditions, such as evolving energy technologies, climate patterns, and societal needs.

Integration and Scalability:

- Optimizing energy performance at the district level is complex, requiring sophisticated modelling and simulation tools that consider interactions between buildings, energy systems, and infrastructure.
- Scaling up PED initiatives from pilot projects to widespread implementation poses significant challenges, requiring innovative business models, financing mechanisms, and policy frameworks.

Social and Behavioural Aspects:

- Understanding user behaviour and engaging residents in PED initiatives is crucial for their success. We need more research on how to promote energy awareness, encourage sustainable practices, and ensure social acceptance of new technologies.
- It's important to ensure that the benefits of PEDs are distributed equitably across all segments of society, including vulnerable populations.

Technological Innovation and Integration:

- We need to keep abreast of emerging technologies in areas like renewable energy, energy storage, smart grids, and building automation and management, and explore how they can be integrated into PEDs.
- Integrating various technologies and systems at the district level requires advanced planning and coordination to ensure interoperability and optimize performance.

Policy and Regulatory Frameworks:

- Supportive policies and regulations are essential to create an enabling environment for PED development. We need to identify and address policy gaps and barriers that hinder the adoption of PEDs, avoiding misalignment between short-term plans and long-term targets.
- Streamlining planning and permitting processes for PED projects can reduce costs and accelerate implementation.

7. Discussion: PED Lab characteristics and KPIs

7.1 Learnings from PED Labs

PED Labs are research infrastructures that enable the analysis of new prototypes, the implementation of multi-objective urban solutions as well as the co-creation and piloting of new concepts related to Positive Energy Districts.
It is not always possible to distinguish between "PED Labs" as they might relate to Positive Energy Districts (PEDs) and how that differs from actual PED case studies or projects**.** Table 14 tries to summarize them regarding focus, purpose and characteristics.

Table 14. Comparison of PED Labs and PED cases regarding focus, purpose and characteristics

	PED Labs (Hypothetical/Experimental)	PED cases (Real-World Projects)
Focus	• PED Labs are primarily focused on research, development, and testing of technologies, methodologies, and policies related to PEDs. • They are controlled environments where innovative solutions can be experimented with before real-world implementation. • They often involve simulations, modeling, and small-scale prototypes.	• PED cases are actual, implemented PED projects in real-world settings. • They involve the integration of various technologies and strategies to achieve positive energy balance in a defined area. • They are subject to real-world constraints, such as regulations, budgets, and public acceptance.
Purpose	• To identify and address knowledge gaps, test new technologies, and develop best practices. • To minimize risks and optimize performance before large-scale deployment. • To provide a platform for collaboration and knowledge sharing.	• To demonstrate the feasibility and benefits of PEDs in real-world conditions. • To provide examples of best practices and lessons learned for future PED projects. • To contribute to the transition to a sustainable energy system.
Characteristics	• May involve controlled simulations, laboratory testing, and small-scale pilot projects. • Emphasis on data collection, analysis, and validation of new approaches. • May involve a higher degree of flexibility and experimentation than real-world PED projects.	• Involve large-scale implementation of energy technologies and infrastructure. • Subject to real-world constraints, such as climate, demographics, and existing infrastructure. • Emphasis on long-term performance, resilience, and socio-economic impacts.

These laboratories must have monitoring and control devices to manage the performance of the system according to the objectives set. Therefore, when introducing PED Labs it is important to take into consideration:

Focus on PEDs: Their core mission is to facilitate the creation of PEDs, which are areas or groups of buildings that generate more renewable energy than they consume annually.

Collaborative Approach: They emphasize collaboration among diverse stakeholders, recognizing that achieving PEDs requires a holistic approach involving various perspectives and expertise.

Real-World Testing: PED Labs involve real-world testing and demonstration of innovative technologies and solutions in actual urban settings. This allows for practical evaluation and refinement of these approaches.

Knowledge Sharing: They serve as platforms for knowledge sharing and learning, disseminating best practices and lessons learned from PED projects to accelerate the transition towards sustainable urban development.

Supporting Policy Development: PED Labs contribute to the development of supportive policies and regulations that enable the widespread adoption of PEDs.

Innovative business models: PED Labs leverage innovative business models, to ensure financial sustainability and scalability, reinforcing the viability of PEDs

7.2 Guidelines for PED Labs

While some PED Labs might have a physical space, the term "lab" in this context refers more to a collaborative and experimental approach than a traditional brick-and-mortar laboratory. The table summarizes the differences between a PED Lab and laboratory.

Table 15. Comparison between physical labs and PED Labs

Physical lab	PED Lab
These are physical spaces equipped with tools and equipment for conducting experiments and research. Think of science labs with beakers and microscopes.	PED Labs are more like a network or platform that brings together various stakeholders, including researchers, city planners, businesses, and citizens.
often involve hands-on testing and prototyping of technologies and solutions.	They foster collaboration and knowledge sharing to develop and test solutions for creating PEDs.
While valuable, physical labs might have limitations in replicating the complexities of a real-world urban environment.	PED Labs often involve real-world demonstration projects in actual urban settings, allowing for testing and refinement of solutions in a complex environment.
	Some PED Labs might have a dedicated office or meeting space, but the "lab" itself is more about the collaborative process and the network of people involved.

PED Labs serve as «seeding ground for new ideas, solutions and services, will be developed according to place- based needs and local context baselines. PED Labs will follow an integrative approach including technology, spatial, regulatory, financial, legal, social and economic perspectives». The PED Labs provide an opportunity to find ways to address the inherent complexity of the implementation and learn how to overcome the challenges. A summary of the existing PED Labs provides the basis for development of a framework to analyse the PED labs. It mapped the key stakeholders and included the technological, social, financial and regulatory perspectives. As a result, the proposed framework provides a relation between the 4 key Aspects: technological, social, financial and regulatory and the 3 dimensions: Stakeholders, Life-cycle phase and scale as the key success factors for implementation of PED Labs.

Finally, some knowledge gaps could be identified that need to be addressed in future **PED Lab design**. It could be shown that addressing these knowledge gaps will require collaborative efforts from researchers, policymakers, industry stakeholders, and communities. By investing in research, developing standardized methodologies, and fostering knowledge sharing, we can accelerate the transition towards Positive Energy Districts and create more sustainable and resilient cities.

This work as shown that overcoming knowledge gaps regarding **standardized methods and metrics** for PED Labs is a multifaceted challenge that requires collaborative efforts from various stakeholders. Key PED Lab guidelines include a collaborative development of standards**,** data sharing and open access, education and training, further research and development and continuous improvements.

Addressing knowledge gaps concerning the **long-term performance and resilience of PED Labs** requires a comprehensive and forward-thinking approach. Key PED La guidelines include long-term monitoring and data collection, simulation and modelling, research on component durability and degradation, adaptive design and flexibility, establishing long-term policy frameworks that provide clear guidelines and incentives for the development and operation of resilient PED Labs and addressing issues such as grid integration, energy storage, and cybersecurity, as well as the development of standardized methods and certification programs for evaluating the long-term performance and resilience of PED Labs.
The implementation of comprehensive monitoring systems that capture data on energy production, consumption, storage, and grid interaction over extended periods are necessary to be able to develop longitudinal datasets that track PED Lab performance over decades, allowing for the identification of trends and patterns (see also D3.5).
In order to do that we need to create sophisticated simulation models that can predict the long-term performance of PED Labs under various scenarios, including climate change, grid disruptions, and technological advancements. These models can help to conduct stress testing and scenario analysis to evaluate the resilience of PED Labs to extreme events, such as heatwaves, floods, and cyberattacks but also can they help to conduct research on the long-term durability and degradation of PED Lab components, such as solar panels, batteries, and smart grid technologies.

Addressing the knowledge gaps around the **integration and scalability of PED Labs** is crucial for their widespread adoption. The PED Lab guidelines to tackle these challenges include the development of standardized frameworks and protocols and data exchange formats to ensure seamless interoperability between PED components, promotion of modular design principles that can easily be scaled up or replicated, establishing a common metric and key performance indicators (KPIs) for evaluating PED performance, development and deployment of advanced grid management systems that can effectively integrate and manage distributed energy resources (DERs) within PEDs.

Addressing the social and **behavioural aspects of PED Lab**s is critical for their successful implementation and long-term sustainability. The PED Lab guidelines to overcome the existing knowledge gaps include interdisciplinary research where social scientists, psychologists, and behavioural economists are incorporated into PED research and development. In general, the adoption of user-centred design approaches that prioritize the needs and preferences of residents and stakeholders is seen as a key to ensure that PED Labs are designed to be user-friendly, comfortable, and socially acceptable. Another key is the early and inclusive engagement of the local communities early in the PED Lab planning and development process. It includes research to understand consumer behaviour related to energy consumption, renewable energy adoption, and smart grid technologies, social impact assessments to evaluate the potential social and behavioural consequences of PED projects, as well as developing governance models that promote community ownership and participation in PED Lab management.

Overcoming knowledge gaps **in technological innovation and integration** within PED Labs demands a concerted effort across multiple fronts. The key PED Lab guidelines include encouraging collaboration between engineers, IT specialists, urban planners, and material scientists by establishing open innovation platforms that facilitate knowledge sharing and collaboration between research institutions, industry, and startups. Further it needs standardized interfaces and communication protocols to ensure interoperability between different PED Lab components and standardized data formats and exchange protocols to facilitate data sharing and analysis. With the clear strategy of development and deployment of smart grid technologies, such as advanced metering infrastructure (AMI), demand response systems (DRS), and distributed energy resource management systems (DERMS) we can utilize data analytics and artificial intelligence (AI) to optimize PED operation and performance.

Addressing the knowledge gaps in **policy and regulatory frameworks** for PED Labs is crucial for their widespread and effective implementation.
We can approach this by promoting the development of integrated policy frameworks that align energy, building, and urban planning regulations; establishing clear and consistent definitions and standards for PEDs; modernizing grid regulations to enable seamless integration of PED Labs with the existing electricity grid; designing effective incentive structures that encourage PED Lab development and investment; establishing regulatory sandboxes to test and evaluate new policy and regulatory approaches for PEDs; Increasing collaboration between energy, urban planning, and environmental departments within governments.

8. Conclusions

The report presents the analysis of PED Labs and provide guidance on their design and implementation from technological, social, financial and regulatory perspectives. We aimed at answering three research questions by leveraging this experience and the involvement in the Action.

- We reviewed KPIs for PED Labs and identified the most relevant for PED Labs implementation. As part of this effort, this work summarizes the existing PED Labs and provides the key success factors for implementation of PED Labs.
- Our analysis showed that PED Labs provide an opportunity to find ways to address the inherent complexity of the implementation and learn how to overcome the challenges and how those aspects should be organized to address the appropriate scale and stakeholders.
- The lessons learned resulted in some guidelines for PED Labs that show how to support the PED Lab implementation.

By implementing these PED Lab guidelines within **PED Lab framework** which provides a relation between the 4 key aspects of PED Labs along the 3 dimensions, we can create a more supportive policy and regulatory environment for PED Labs, enabling their widespread adoption and contribution to a sustainable energy future.

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ANNEX 1: Questionnaire Template

This template is prepared taking into account the common features of different projects. Some of them have more detail some less.

Aspect	Sub aspect (link to KPI)	Dimension		
		Stakeholder	**Life-cycle stage**	**Scale**
Technical	Which technology was implemented in the PED Lab?	Which were the main decision makers for the PED?	In which phase were the technical interventions decided?	At which scale was the technology implemented
		Which actor was responsible for implementing?	when was this actor involved?	which other scales did the technology influence/interacted with?
			Which phases were monitored and how were the outcomes used?	
Social	What is the social context?	Who was the key user of the PED and how the PED influenced their life quality?		Which scale was the community engagement relevant for and in which capacity?
		How was the community engaged?	In which phase did the community engage?	EG. Building/dwelling, urban, energy community etc.?
Financial	What are the financial motives to the PED lab?	Who invested in the technology implmentation	How and when will the investment pay back?	
		Who has financial savings/benefits (value, revenue)?		

ANNEX 2: PED Lab guidelines

Challenge	Key PED Lab guidelines
This work as shown that overcoming knowledge gaps regarding standardized methods and metrics **for PED Labs is a multifaceted challenge that requires collaborative efforts from various stakeholders.**	Key PED Lab guidelines include a collaborative development of standards**,** data sharing and open access, education and training, further research and development and continuous improvements.
Addressing knowledge gaps concerning the long-term performance and resilience of PED Labs **requires a comprehensive and forward-thinking approach.**	Key PED La guidelines include long-term monitoring and data collection, simulation and modelling, research on component durability and degradation, adaptive design and flexibility, establishing long-term policy frameworks that provide clear guidelines and incentives for the development and operation of resilient PED Labs and addressing issues such as grid integration, energy storage, and cybersecurity, as well as the development of standardized methods and certification programs for evaluating the long-term performance and resilience of PED Labs.
	The implementation of comprehensive monitoring systems that capture data on energy production, consumption, storage, and grid interaction over extended periods are necessary to be able to develop longitudinal datasets that track PED Lab performance over decades, allowing for the identification of trends and patterns (see also D3.5).
	In order to do that we need to create sophisticated simulation models that can predict the long-term performance of PED Labs under various scenarios, including climate change, grid disruptions, and technological advancements. These models can help to conduct stress testing and scenario analysis to evaluate the resilience of PED Labs to extreme events, such as heatwaves, floods, and cyberattacks but also can they help to conduct research on the long-term durability and degradation of PED Lab components, such as solar panels, batteries, and smart grid technologies.
Addressing the knowledge gaps around the integration and scalability of PED Labs **is crucial for their widespread adoption.**	The PED Lab guidelines to tackle these challenges include the development of standardized frameworks and protocols and data exchange formats to ensure seamless interoperability between PED components, promotion of modular design principles that can easily be scaled up or replicated, establishing a common metric and key performance indicators (KPIs) for evaluating PED performance, development and deployment of advanced grid management systems that can effectively integrate and manage distributed energy resources (DERs) within PEDs.

Addressing the social and behavioural aspects of PED Labs **is critical for their successful implementation and long-term sustainability.**	The PED Lab guidelines to overcome the existing knowledge gaps include interdisciplinary research where social scientists, psychologists, and behavioural economists are incorporated into PED research and development. In general, the adoption of user-centred design approaches that prioritize the needs and preferences of residents and stakeholders is seen as a key to ensure that PED Labs are designed to be user-friendly, comfortable, and socially acceptable. Another key is the early and inclusive engagement of the local communities early in the PED Lab planning and development process. It includes research to understand consumer behaviour related to energy consumption, renewable energy adoption, and smart grid technologies, social impact assessments to evaluate the potential social and behavioural consequences of PED projects, as well as developing governance models that promote community ownership and participation in PED Lab management.
Overcoming knowledge gaps in technological innovation and integration **within PED Labs demands a concerted effort across multiple fronts.**	The key PED Lab guidelines include encouraging collaboration between engineers, IT specialists, urban planners, and material scientists by establishing open innovation platforms that facilitate knowledge sharing and collaboration between research institutions, industry, and startups. Further it needs standardized interfaces and communication protocols to ensure interoperability between different PED Lab components and standardized data formats and exchange protocols to facilitate data sharing and analysis. With the clear strategy of development and deployment of smart grid technologies, such as advanced metering infrastructure (AMI), demand response systems (DRS), and distributed energy resource management systems (DERMS) we can utilize data analytics and artificial intelligence (AI) to optimize PED operation and performance.