Benchmark and categorisation of PEN organisational models

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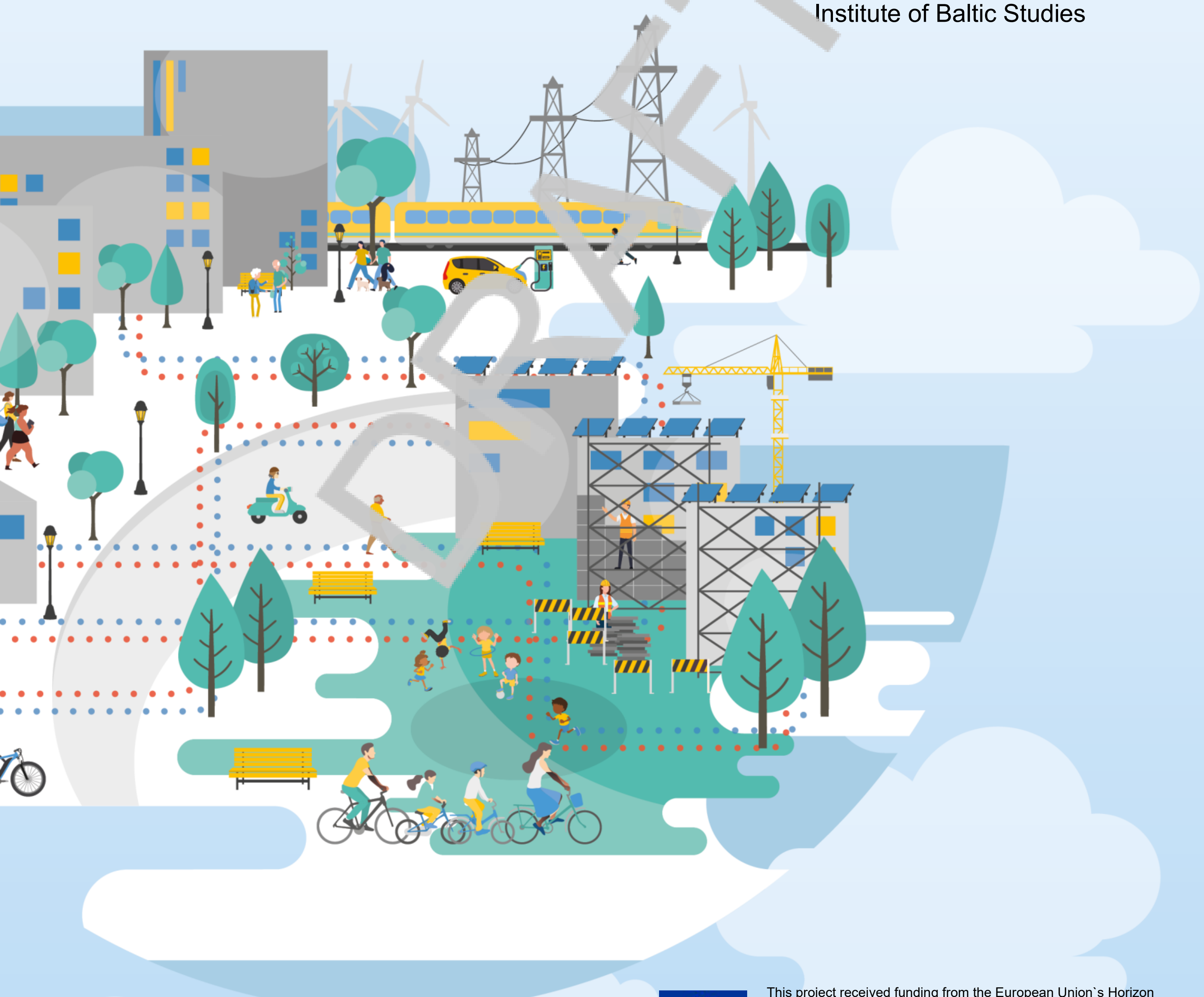

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Abbreviations and Acronyms

Acronym	Description
AI	Artificial Intelligence
AR/VR	Augmented Reality / Virtual Reality
BIM	Building Information Model
BIPV	Building Integrated Photovoltaics
BMS	Building Management System
DSO	Distribution System Operator
EMS	Energy Management System
EPC	Energy Performance Certificate
EPBD	Energy Performance of Buildings Directive
ESCO	Energy Service Company
EU	European Union
EV	Electric vehicle
GHG	Greenhouse gas
GWP	Global Warming Potential
HMI	Human-Machine Interfaces
HVAC	Heating, Ventilation and Air-Conditioning
ICT	Information and Communication Technology
LEKP	Local Energy and Climate Pact
LTRS	Long-Term Renovation Strategy
NBRP	National Building Renovation Plans
NGO	Non-Governmental Organisation
NZEB	Nearly Zero-Energy Building
PED	Positive Energy District
PEN	Positive Energy Neighbourhood
PPP	Public-Private Partnership
PV	Photovoltaics
RaaS	Renovation as a Service
REC	Renewable Energy Community
RES	Renewable Energy Sources
SECAP	Sustainable Energy and Climate Action Plan
SME	Small and Medium-sized Enterprise

Executive Summary

As European cities move towards climate neutrality, neighbourhoods and districts have emerged as a **key scale for integrated energy transition and decarbonisation of the building stock**. However, the novelty and complexity of Positive Energy Neighbourhoods (PENs) have led to diverse interpretations and implementation approaches. Differences in local governance systems, regulatory frameworks, stakeholder structures and market conditions shape how PENs are conceived and managed. This report seeks to respond to these variations by benchmarking emerging organisational models in the oPEN Lab project and identifying patterns as well as enabling factors that support effective PEN deployment.

This report, *Benchmark and categorisation of PEN organisational models*, provides an analytical framework for understanding how PENs are **organised, governed and sustained** across different urban contexts in Europe. It contributes to the wider oPEN Lab project objective of identifying transferable approaches for implementing and scaling energy-positive neighbourhoods, drawing on evidence from three case studies – Genk (Belgium), Pamplona (Spain) and Tartu (Estonia).

The **main objectives** of the report are to:

- Examine the organisational and governance models underpinning the emerging PENs in oPEN Lab;
- Categorise and compare these models across different urban and national contexts in the example of Genk, Pamplona and Tartu;
- Identify barriers, drivers and success factors influencing PEN developments;
- Derive recommendations to guide cities and stakeholders in replicating and adapting effective organisational setups in PENs.

The **methodology** combines literature review, policy analysis and empirical evidence from the three oPEN Lab cities. Each case study is analysed according to a set of guiding questions, ensuring comparability while acknowledging contextual specificities.

Methodologically, the deliverable **contributes to PEN research** by operationalising a three-level analytical framework that connects local context, intermediary Living Lab structures and emerging PEN models and organisations. The combined use of dual archetype typologies - organisational and systemic - provides a novel comparative lens for understanding how diverse European cities interpret and operationalise the PEN concept under varying conditions.

The benchmarking confirms that all three cases represent **transitional systems rather than completed organisational models**. Their current configurations reflect early organisational, technical and social experimentation, which are important stepping stones towards the establishment of fully operational PENs. Given this early stage of development, the report does not attempt to benchmark their maturity; instead, it recognises that each pilot is still in formation and progressing at a pace shaped by local governance, regulatory conditions and stakeholder dynamics.

1. Introduction

The **Positive Energy Neighbourhood** (PEN) concept has emerged as a key component of sustainable urban development, aiming to create urban districts that produce more energy than they consume. A PEN integrates various elements, including energy-efficient buildings, local renewable energy generation, smart grids and active energy management to achieve a net-positive energy balance. Beyond technological integration, however, the concept places a strong emphasis on community involvement, governance structures and business models that support long-term sustainability.

Within the oPEN Lab project, a **PEN is defined** in the following way [1, p. 15]:

"A positive energy neighbourhood (PEN) is characterised by a group of buildings and public spaces with connected infrastructure, within a geographical area. A PEN aims for energy-efficient and energy-flexible groups of connected buildings and urban areas which produce net zero greenhouse gas emissions from energy use on an annual basis and actively manage an annual local or regional surplus production of renewable energy. PENs seek an integrated, participatory, neighbourhood-based approach to maximise the benefits of innovative energy systems."

This definition highlights some **key principles** of a PEN:

- a focus on decarbonisation and energy efficiency at the neighbourhood scale;
- active management of renewable energy production and consumption;
- stakeholder collaboration, ensuring social and economic sustainability.

1.1. Organisational PEN models

Organisational PEN models describe the **governance, operational, financial and collaborative arrangements** that enable PENs to function and evolve over time. Rather than prescribing a single blueprint, such models provide a structured way to understand how different ecosystem stakeholders – including public authorities, citizens, utilities, technology providers and financiers – interact to deliver neighbourhood-scale energy transition. In this sense, an organisational PEN model captures the roles and responsibilities of stakeholders, decision-making processes, financial flows and operational mechanisms that together shape the effective implementation and long-term sustainability of PENs within their specific local contexts.

For the purpose of this report, an **organisational model** thereby answers **key questions** such as:

- Who governs and manages the PEN? (e.g. municipalities, energy cooperatives, public-private partnerships (PPP))
- What are the key operational mechanisms? (e.g. energy generation, distribution and storage models)
- How is financing structured? (e.g. public funds, private investments, cooperative contributions)
- What business and ownership models are applied? (e.g. service-based energy models, community-owned systems)

Importantly, organisational PEN models are inherently context-dependent. Local governance specifics, market conditions, regulatory frameworks and community characteristics shape how such model emerge and operate. As such, organisational diversity is a defining feature of PEN development.

1.2. oPEN Lab approach to organisational PEN models

The oPEN Lab project aims to **test and refine different pilot PEN models** across three cities: Genk (Belgium), Pamplona (Spain) and Tartu (Estonia). This report aims to capture the complexity of the emerging PENs through exploring the specific organisational models attached to each of the PEN projects through case studies. Each of these case studies reflects a distinct approach to PEN organisation, shaped by local governance, economic structures, regulatory conditions and stakeholder involvement. To systematically conceptualise and compare these models, a structured methodology based on existing literature, stakeholder engagement and real-world implementation is followed. This approach considers:

- **Governance structures** – defining roles and responsibilities among stakeholders.
- **Operational models** —how energy generation, storage, distribution and energy use are managed, including investments in energy efficiency, building retrofits and heating, ventilation and air-conditioning (HVAC) systems that shape neighbourhood-level performance.
- **Financial models** – financing mechanisms and revenue streams.
- **Ownership structures** – who owns and operates the infrastructure.

In the oPEN Lab project, different aspects of **governance, organisational and capacity-building models** are explored (see Figure 1). There are reports that focus more exclusively on the governance of living labs (e.g. *Mid-project progress report of Living Labs operations and management* [2], *Implementation plans for the oPEN Living Labs* [3], and *Capacity-building handbook and mentoring report* [4]) and others on aspects steering PEN regulatory drivers and barriers influencing their potential rollout (e.g. *Outline of the oPEN Lab policy roadmap* [1]). This report is dedicated to understanding **how PENs are organised and how they function**. This involves studying the **ecosystem of stakeholders, governance structures and operational frameworks** that enable PENs to develop. To achieve this, the project examines real-world examples from the three pilot cities, each representing a different approach to PEN organisation. The findings are compiled into a **benchmark and categorisation of organisational PEN models**, providing insights that can help guide future neighbourhood-scale energy initiatives.

In the context of the oPEN Lab project, a distinction also needs to be made between **PENs and Living Labs,** as well as their close interrelation. As also stated in oPEN Lab's policy roadmap [1], the PEN refers to a group of buildings and shared spaces that work together to achieve high energy performance, flexibility and renewable energy generation at neighbourhood level. The Living Lab is the platform that brings together residents, the municipality, companies and other actors to jointly design, test and refine the technological, financial and social solutions needed for such a neighbourhood. Therefore, the PEN delivers the physical transformation and the Living Lab provides the participatory and organisational structures that make it possible. The PEN describes what is being transformed, the Living Lab describes how this transformation is organised and supported.

Figure 1 illustrates how the **different elements of the oPEN Lab approach** jointly shape both the PEN and the Living Lab. The Living Lab configuration provides the collaborative environment, stakeholder engagement and real-life test setting. In parallel, the organisational PEN model examines how neighbourhood energy systems function within their regulatory, social and market context. Business model development focuses on how PEN-related solutions and services can be taken up and sustained. Together, these components contribute both to the physical transformation of the neighbourhood (the PEN) and to the participatory and organisational structures that make this transformation possible (the Living Lab).

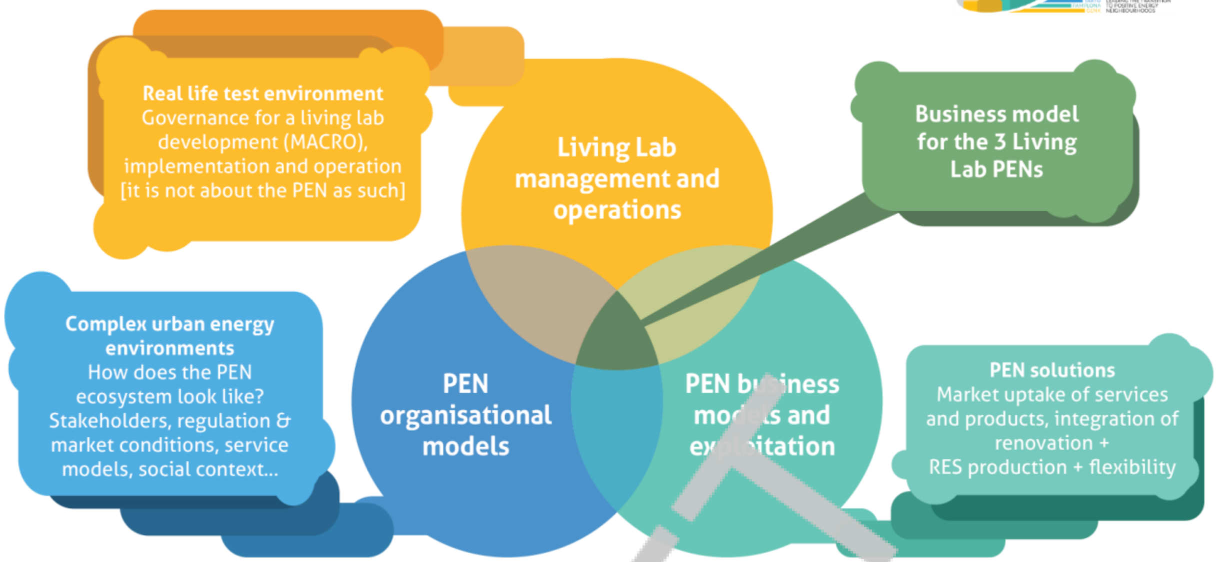

Figure 1: Conceptual interrelations in oPEN Lab. Source: Authors based on VITO and internal discussions with the research team.

When considering the **three layers of Living Labs** [5] (see also Figure 2) oPEN Lab operates on the meso level as an innovation project using Living Lab methodologies, i.e. beyond the micro level (individual research steps and activities), but not reaching the macro level (Living Lab constellation consisting of organised stakeholders).[1]

[1] *"When creating a Living Lab, organisations often begin with what they know already: project management. They often enter the Living Lab world by a single project such as oPEN Lab (MESO), discover and test different methods and tools during the project life cycle (MICRO). Once the project is finished, organisations have the strategic choice whether to continue using participative methods and tools but without a dedicated structure or to develop a specific structure for this type of activity (MACRO). This becomes an example of institutionalisation of the Living Lab, which is the more advanced phase when mastering the Living Lab concept and to ensure longevity. The first steps to institutionalisation are establishing a governance and business model."* (quoted in Zimmermann et al. [4, p. 22])

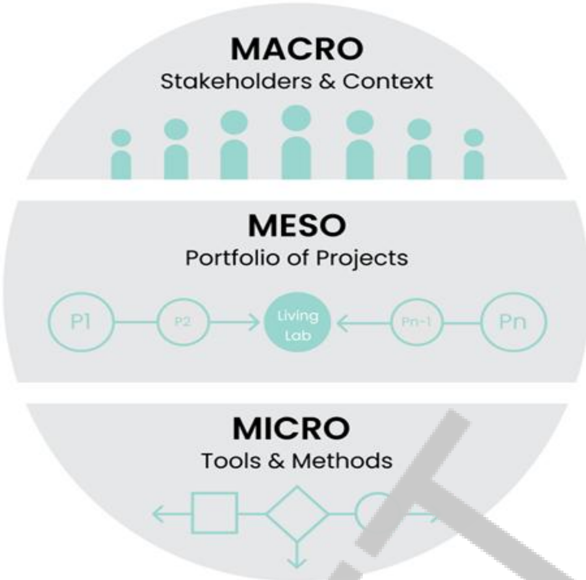

Figure 2: Three-layer model of Living Labs. Source: Zimmermann et al. [4], adapted from Schuurman [5].

While the oPEN Lab project provides a structured framework for testing and understanding the organisational dimensions of PENs, may it also be already stated that the pilot areas in Genk, Pamplona and Tartu are still in **early and experimental stages of development**. None of the three sites can yet be characterised as a fully realised PEN in the technical or organisational sense. Rather, they represent **emerging ecosystems** where governance structures, financing mechanisms and stakeholder collaborations are progressively taking shape. The focus of this report is therefore not on assessing mature, operational PENs, but on examining the **foundations and trajectories** through which such neighbourhoods may evolve in the future. By analysing the current configurations and identifying enabling and constraining factors, the study provides an outlook on how the three pilot neighbourhoods could be gradually **transitioning towards sustainable, replicable and scalable PENs** within their respective local contexts.

1.3. Structure of the report

As a report that seeks to investigate the organisational side of the complex PEN ecosystems developing in the three oPEN Lab pilot cities, the **following chapters** will explore:

- The **policy context** shaping PEN development in Europe.
- The **evolution and common definitions** of PENs.
- A **review of existing PEN ecosystems** based on literature.
- A **methodology overview**, outlining how PEN organisational models are approached in the oPEN Lab project.
- Detailed case studies of **Genk, Pamplona and Tartu**, showcasing different PEN organisational models.
- A **comparative analysis** of these models, identifying PEN organisational archetypes and key takeaways.

The report offers a reference framework and practical insights for those involved in developing or supporting PEN initiatives. Its primary audience includes **local and regional policymakers, urban planners and practitioners working with energy systems and neighbourhood-**

scale renovation (e.g. energy agencies, utilities, distribution system operators (DSOs), service providers). The aim is to help these actors understand how PENs can be organised in practice and what kinds of governance, operational, financial and partnership arrangements can support (or hinder) their replication or scale-up.

2. Understanding the foundations of PENs

This chapter establishes the **conceptual and contextual basis** for analysing PENs and the emerging PEN organisational models within the oPEN Lab project. It reviews the policy frameworks shaping PEN development in Europe, explores ongoing efforts to move towards a common definition and summarises the key characteristics of PEN ecosystems as described in existing literature. The chapter further examines PEN business considerations and provides an overview of how PEN or Positive Energy District (PED) initiatives have evolved across Europe. Together, these components create a shared understanding of the policy, conceptual and practical dimensions of PENs, which informs the methodological approach and the case study analysis framework presented in the next chapters.

2.1. Policy context[2]

As cities are on the frontlines of global climate change, they are also well-positioned to play a leading role in addressing it. The European Union (EU) aim is to be **climate-neutral by 2050**, which requires a full decarbonisation of the existing building stock [6]. One priority must be to decarbonise the existing building stock, making cities future-proof with no adverse impact on climate change and with a minimised environmental footprint, while having a positive impact on society.

The first major EU-level articulation of neighbourhood-scale energy transition came through the Strategic Energy Technology Plan Action 3.2 *Smart Cities and Communities* [7], which introduced the **concept of PEDs**. PEDs are urban districts that achieve annual net-positive renewable energy production while maintaining high levels of liveability and climate resilience. According to the White Paper on PED Reference Framework [7], the Implementation Working Group of Smart Cities of the Strategic Energy Technology Plan established in 2018 stated the mission to bring about **100 urban districts or neighbourhoods in Europe by 2025** with a clear commitment to sustainability, liveability and going beyond carbon neutrality by becoming energy positive. Although initially framed within a European context, PEDs have since evolved into a global research and innovation topic, notably through the IEA EBC Annex 83 [8], which brings together cities and researchers from Europe, North America and Asia to advance PED definitions, design principles and monitoring frameworks.

Related concepts have emerged around similar ambitions but different scales or entry points. The **Net-Zero Energy District** refers to districts or urban areas aiming to balance or exceed their annual energy consumption with locally generated renewable energy - a model that focuses primarily on energy supply-demand balance at district scale [9]. In parallel, over the last decade, several European research and innovation initiatives, including Horizon 2020 and Horizon Europe projects, have adopted and refined the concept of **Positive Energy Districts and Neighbourhoods (PEDs/PENs)** to represent a broader, more holistic and place-based approach. PEDs/PENs integrate buildings, public space, mobility infrastructure, energy generation and flexibility, and embed social, regulatory and governance innovation into the urban process.

A major recent policy development relevant for PENs is the introduction of **district and neighbourhood renovation approaches** in the 2024 recast of the Energy Performance of Buildings Directive (EPBD) [10]. The EPBD explicitly recognises that renovation strategies should move beyond the individual building and consider buildings as part of a wider urban system. The directive encourages Member States to plan and report on neighbourhood-level

[2] For a comprehensive overview of the European policy landscape, neighbourhood-level renovation frameworks and the development of PED/PEN concepts, see the oPEN Lab *Policy Roadmap* (2024) [1].

renovation programmes, integrate district-level technical solutions, and address social and environmental aspects linked to local contexts. This marks a structural shift towards scaling up renovation in clusters, enabling shared renewable energy systems, collective flexibility, and more inclusive engagement with local communities and stakeholders. The district/neighbourhood approach implies different types of policies, funding instruments and information schemes, aimed at supporting coordination between multiple actors and overcoming ecosystem-level barriers considering financing, governance complexity, and uneven access to information.

2.2. Moving towards a common PEN definition[3]

There is still a good amount of ambiguity in the literature concerning PEDs/PENs and their key energy concepts, which is said to **hinder their full potential**. Definitions of the related concepts tend to vary depending on local contexts, interests and goals of stakeholders. A review of various PEDs and related definitions revealed the following common aspects: [11]:

- Most definitions specify that the surplus of energy or energy production must be from **renewable and/or local energy sources**.
- Usually, definitions do not specify the energy carrier, but if they do, the most mentioned are **electrical and thermal** ones.
- Almost all definitions allude to energy activities related to **production and high energy performance and energy flexibility**.
- Some definitions also mention **other kind of activities** related to business aspects, user-centric services, mobility or smart devices and management.

Figure 3 below illustrates the **technological landscape** commonly associated with PED/PEN development, covering renewable energy generation, storage, mobility solutions, interoperability and smart energy management.

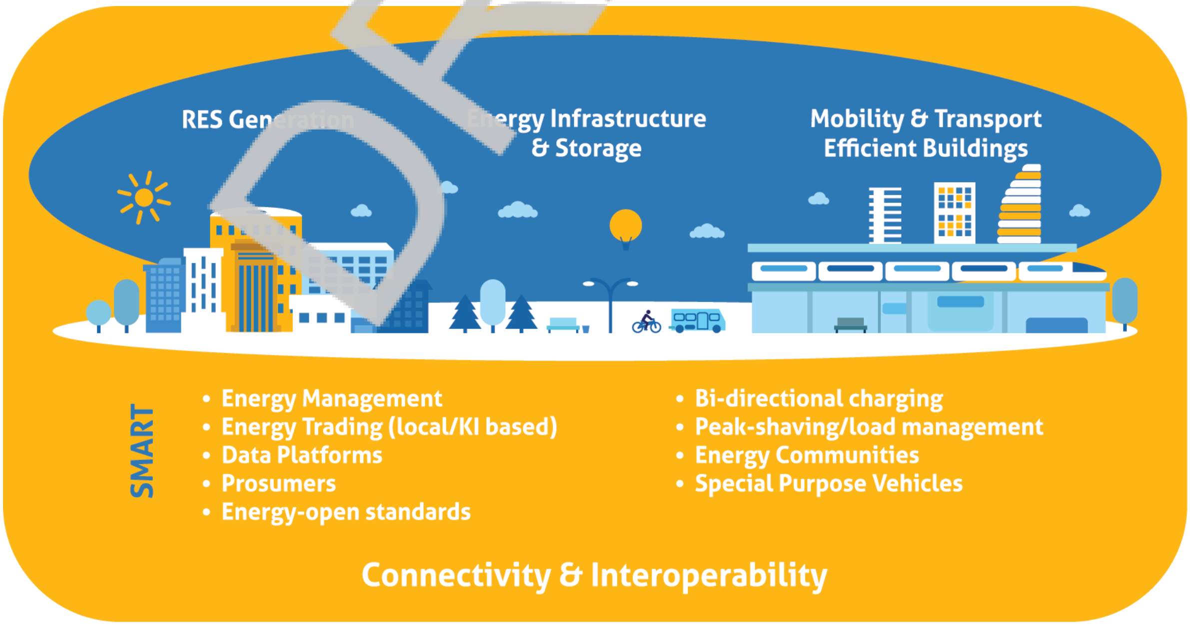

Figure 3: Building blocks of a PED. Source: Wagner-Herold, Geyer-Scholz [12].

[3] For a comprehensive overview of of the European policy landscape, neighbourhood-level renovation frameworks and the development of PED/PEN concepts, see the oPEN Lab *Policy Roadmap* (2024) [1].

However, Figure 3 represents only one part of the broader PED/PEN concept. As highlighted in recent definitions and in the emerging European policy framework, **energy efficiency and demand reduction** remain the starting point for any positive energy approach. Likewise, **social and economic sustainability, user engagement and governance structures** form essential dimensions of a PEN and are increasingly emphasised in research and policy documents.

In the absence of a single harmonised definition, the oPEN Lab team analysed more than **forty existing definitions** to identify common conceptual threads. Building on the existing references and the insights from the oPEN Lab Policy Roadmap [1], oPEN Lab recognises the importance of moving towards a common PEN definition. A shared understanding supports alignment between cities, strengthens comparability and provides a clearer basis for policy design, investment, regulation and local stakeholder engagement.

oPEN Lab defines PENs as follows (Figure 4):

Figure 4: oPEN Lab definition of PEN. Source: Taranu et. al [1]

This definition provides the conceptual foundation for how PENs are understood within this report and across the oPEN Lab project as a whole. However, it is important to note that the case studies presented here **describe PEN ecosystems as they currently stand** - that is, as evolving settings where different elements of the PEN concept are at varying stages of maturity. Cities differ in institutional capacity, regulatory settings, investment cycles and technological readiness. In some cities, the neighbourhood may already display several defining features of a PEN, such as integrated renewable energy sources (RES) or active stakeholder cooperation, while in others, these components are still emerging through early planning, pilot actions or Living Lab activities. The analysis therefore acknowledges that the **examples do not yet constitute a fully operational PEN according to the project's definition**. Instead, they represent different points along a developmental trajectory towards becoming PENs, shaped by local context, institutional capacity and policy conditions.

2.3. PEN ecosystem based on existing literature

As the concepts themselves, literature related to PEDs/PENs is **emerging and taking shape.** The following sections explain the main takeaways and lessons from existing literature.

No cookie-cutter models

JPI Urban Europe [7] stresses that there are **no one-fits-all strategies** regarding implementing the PED/PEN concept. Instead, when developing PEDs/PENs, the "***specific situation of the city*** *should be taken into account, e.g. density, type of buildings, available local RES*". For instance, sufficient room has to be left for the specifics of a neighbourhood to choose the most effective alternative to fossil fuels – all solutions are welcome as long as they are clean and sustainable:

"Implementation of the PEDs requires a deep understanding and consideration of ***cities' contextual conditions, policies, priorities, strategies, resources and solutions****. Knowledge, skills and technologies are needed for planning, designing, implementation and monitoring, as well as replication and mainstreaming of PEDs."* [13]

Also reflecting **differences in local conditions, stakeholder interests and urban development goals** is the fact that definitions of districts and neighbourhoods within the energy transition context vary widely [11]. What constitutes a "district" or "neighbourhood" often depends on each city's specific spatial, social and governance context, ranging from small settlements to larger urban areas or clusters of buildings. This diversity highlights the importance of grounding PEN concepts in the local context and considering contextual factors when analysing or replicating models, as uniform definitions risk overlooking place-based realities and priorities.

Similarly, it has been stressed that the essence of a smart PED/PEN lies in tailoring it to a specific city framework condition, **"local fabric"**, and the needs of diverse stakeholder groups. "*It requires a meticulous process rather than an off-the-shelf solution. It requires collaboration amongst stakeholders, such as citizens and end users, who are pivotal in shaping the district's identity and customer journey*." [12] Which brings us to the next point.

Cooperation with stakeholders, every step of the way

Implementing PEDs/PENs requires cooperation, where those who invest into constructing[4] and supplying for the built environment are the **main problem owners** – citizens, city administration, real estate industry and energy suppliers [7]. Vandevyvere [14] adds that stakeholders include "*municipalities, real estate developers, building owners, tenants, energy*

[4] While some PEDs/PENs are new development, these are PEN renovations in the oPEN Lab project.

providers for electricity and heating, research institutes, mobility providers, energy system providers, information and communication technology (ICT) companies, industry, small and medium-sized enterprises (SMEs), non-profits or non-governmental organisations (NGOs), politicians, citizens and citizen organisations". As the first lesson already revealed, though, this list is not definitive.

As an example, **primary stakeholders** interacting in PEN have been mapped along the value chain of PEN development in the MakingCity Project (see Figure 5):

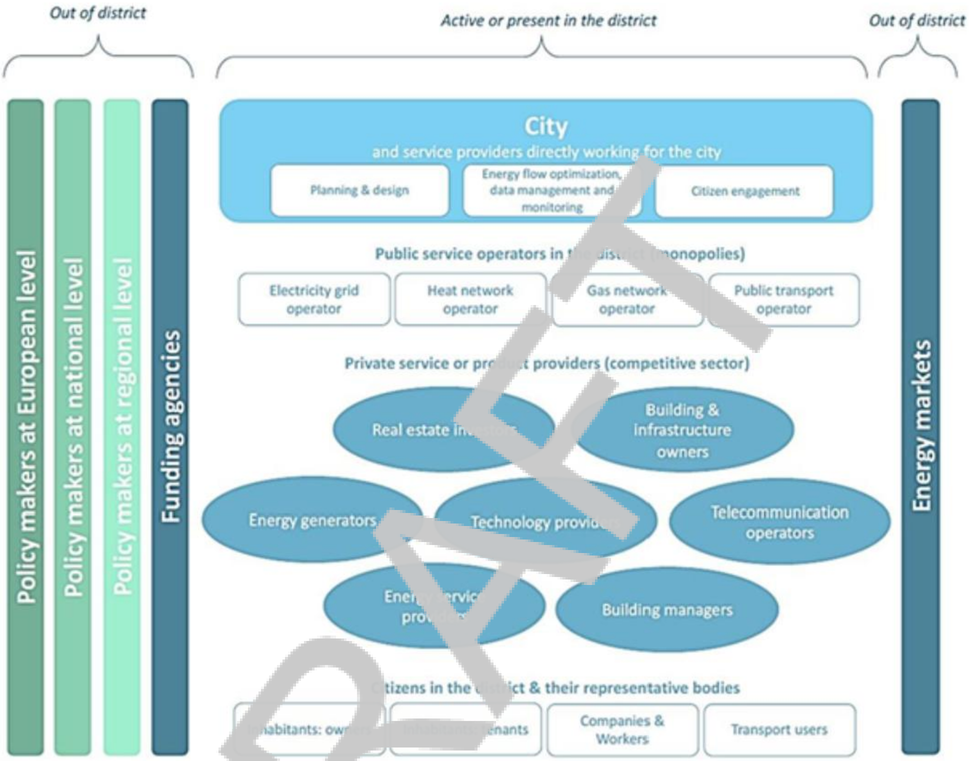

Figure 5: PEN Stakeholder mapping. Source: the MakingCity Project [15] [16].

Not just cooperation, but building trust

Co-creation is needed so that citizens would trust, use and feel **ownership** of the integrated energy and mobility solutions offered in their district. It is not just about individual demonstrators, though – what can be done to increase citizen **motivation, support** and **informed appreciation** of energy transition measures as a whole? In a PED/PEN, citizens might even become **energy prosumers**, so it is important to think about what it means for them, what they need to live and work in a PED/PEN, etc. [14] What is the **shared story** for the future of the neighbourhood [17]? **Social innovation** and **participatory methods/culture** are crucial aspects for realising PEDs/PENs.

Governance makes the difference

According to a publication by the Smart Cities Information System [18], "*proper governance is needed to assure the **legitimacy of the actions** and securing a **long-term engagement** of all different stakeholders*". Similarly, JPI Urban Europe [7] states that one of the most crucial enablers of PENs is **political vision** and governance framework combined with active involvement of problem owners and citizens. The other enablers they highlight are integration of energy and urban planning (see next lesson), ICT and data management.

What needs to be stressed separately is collaborative governance – potential implementation of PEDs/PENs according to the regulations and policies in the cities. This "*goes beyond direct citizen engagement and moves towards the creation of* ***networks or coalitions*** *where discussions and negotiations can take place with a wide range of stakeholders*" [17]. It is stated that "*large energy companies, energy network operators, housing assertions, project developers and big companies are all* ***professional organisations with significant financial capabilities*** *that need to be explicitly included in PED development*" [17].

Integrated and holistic planning

Although traditionally, these have remained separate, **integrated spatial, energy and community planning** are the key to PEDs/PENs [14]. The ongoing implementation of the recast EPBD – including the identification and renovation of the worst-performing buildings [19] – the Energy Efficiency Directive obligations for EU countries to promote local heating and cooling plans in larger municipalities [20] and the Renewable Energy Directive (RED III) requirement for Member States to designate renewables acceleration areas [21] together pose new opportunities for integrated planning at the local level. JPI Urban Europe [7] likewise stresses that in case of PEDs/PENs, a holistic approach is needed – not only solutions for energy production, but also **legal, regulatory and social innovation and their integration into the local ecosystem**.

Being mindful of regulations

Just like different ownership structures across Europe need different approaches for cooperation, different **legal frameworks** require different PED/PEN approaches and strategies. For instance, depending on the national legal and regulatory context, deciding **which stakeholders to involve** varies from country to country [7]. What PEDs/PENs need are **adequate** and **predictable** policy frameworks to encourage ambitious projects. Vandevyvere [14] adds another dimension – traditionally, energy generation and distribution systems, as well as legislation and regulations have assumed a centralised, hierarchical system, which is a great obstacle to energy transition. PEDs/PENs need local and decentralised energy generation, distribution and storage, so **decentralisation efforts** are key to promoting PEDs/PENs. Lack of a harmonised implementation of the collective self-consumption, renewable energy community (Renewable Energy Directive) and a delayed implementation of the citizen energy community (Electricity Market Design) pose barriers towards democratising and decentralising the energy system.

Looking into market conditions

Under market conditions, access to financing opportunities and implementing successful business models in the supply chain is considered. However, "*the market is not an autonomous process, but interlinked with the* ***social and environmental contextual aspects***[5] *of PEDs/PENs* [13]". The importance of developing **financial arrangements** to enable citizens to be a part of PED/PEN development is stressed in the literature. It is stated that "*much depends on national legislation, but local level matters as well – cheap loans, subsidies, facilitating access to financial institutions*" [17].

[5] For more information on financing solutions which internalise social and environmental co-benefits of PENs, see the oPEN Lab report *Enabling finance for neighbourhood renovations* (2025) [24].

2.4. PEN business models[6]

The report *European smart cities business models* [12] highlights the importance of placing a **strong emphasis on business modelling and bankable business cases** to successfully up-scale and roll out piloted solutions and attract private enterprises and private investment for viable long-term operations. While cities tend to focus primarily on public interest, value creation and service delivery rather than on profits and explicit business models, this orientation can create challenges when transitioning from pilots to operational scalability. More specifically, the report introduces the concept of the "piloting trap" as [12, p. 37]:

"…the challenge of broadly deploying a solution that was successfully tested during the pilot phase. Several factors contribute to this difficulty, including the absence of (non-grant-based) financing for rollout, the lack of established operation models and ownership structures, and the deficiency in innovation and procurement processes essential to proceed with the upscaling within the value chain. Consequently, it is crucial to focus on developing upscaling pathways, mechanisms, and processes during the pilot project deployment and to tackle this barrier early in the project lifecycle."

Building on this, the oPEN Lab report *Innovative financing instruments for PEN roll-out* [22] [22] underlines that viable PEN business models must do more than cover costs. They must **align the incentives and values** – economic, social and environmental – **of all relevant stakeholders** within a given regulatory context. From this perspective, PEN value propositions (comfort, reduced energy bills, decarbonisation, health and air quality benefits, local jobs, etc.) only translate into viable business models if there are clear pathways to capture these benefits through revenues, avoided costs, lower risk or cheaper access to finance. As such, PEN business models will need to demonstrate the ability to be cost-covering over the long term; a balanced mix of revenue, co-benefits and risk reduction; and replicability and scalability across different local contexts, thereby helping projects to escape the pilot trap and make the "scaling jump" from demonstration to mainstream deployment.

According to the book *Energy Positive Neighbourhoods and Smart Energy Districts* [23] selecting business models should start from **inspecting the regulation** of the system in which the prospective PEN[7] is situated so to get an understanding of the system to be built up. The guiding question here is "Who can participate"? For example, electricity system operators and market platforms may have technical minimum size requirements or minimum bid thresholds that can prevent a single neighbourhood from participating directly in certain markets. In practice, PENs can often still participate indirectly via aggregators, who pool multiple sites to reach the required thresholds, but this shifts the challenge from technical eligibility to finding suitable intermediary partners and designing appropriate contractual and governance arrangement.

If the regulatory framework is broadly supportive, potential PENs then need to understand the **markets and value streams** in which they hope to partake. For instance, if the market does not offer sufficient reward for flexibility deployment, pure flexibility revenues may not justify a stand-alone business case. At the same time, as highlighted in oPEN Lab reports [24] [22], PEN business models are not limited to selling electricity or flexibility: the value proposition also includes social and environmental co-benefits such as reduced emissions, improved health, comfort and local economic development. It is shown that when such co-benefits are monetised, ambitious PEN renovations can achieve a positive benefit-cost ratio and a

[6] For more information about the barriers and finance solutions that consider the wider co-benefits of PEN renovations, see the oPEN Lab report *Enabling financing for neighbourhood renovations* (2025) [24].

[7] Originally EPN, Energy Positive Neighbourhood.

reasonable return on investment, suggesting that wider societal value can underpin financial viability when appropriately recognised and integrated into the model [24].

Lastly, the book *Energy Positive Neighbourhoods and Smart Energy Districts* [23] advises to **assess the attitudes**, preferences and capabilities of possible/requisite partners. If, for example, a suitably accredited partner is needed to access the necessary markets, is such a partner available? Collaboration between public authorities, private actors and communities does not only influence revenue potential, it can reduce risk and lower the cost of capital, for instance through PPPs, guarantees or blended-finance structures. The question is therefore not only whether revenues can be increased through collaboration, but also whether **better financing conditions** (longer tenors, lower interest rates, risk sharing) can be obtained by structuring the PEN as a multi-actor endeavour.

Due to their complexity, PENs usually require a combination of existing business models for **renovation** (e.g. one stop shops, energy performance contracting), collective **renewable energy investment** and **sharing** (e.g. collective self-consumption, renewable energy communities), mobility (e.g. Mobility as a Service) and **flexibility** (e.g. District Schedule Rate) [25]. These aspects are explored separately in the oPEN Lab project.

Current evidence in oPEN Lab [22] suggests that, under today's conventional market and regulatory conditions, **neighbourhood-scale positive energy solutions seldom represent a straightforward commercial opportunity** purely from the perspective of developers, investors or residents when only direct energy revenues are considered. This is due to a range of political, economic and societal factors that limit market uptake, even though the underlying technologies and their integration are already relatively mature. At the same time, it is shown [24] that when social and environmental externalities - such as health benefits - are taken into account, the benefit-cost balance of ambitious PEN renovations can become positive, indicating that **PENs can be financially viable when co-benefits are properly valued and integrated into the investment logic**.

Finally, it is important to note that PENs are **not an end-product or market commodity in themselves**, but a **means to achieve broader policy goals**, notably the deep decarbonisation of the building stock and the phase-out of fossil fuel-based heating and cooling. Rather than expecting a distinct "PEN market" to emerge, the more realistic trajectory is that **PEN-like configurations and business models gradually diffuse** into mainstream renovation, district heating, flexibility and energy community practices, supported by appropriate regulatory and financing frameworks. Against this backdrop, identifying and mapping PEN stakeholders, their interests and interactions becomes a critical first step. This is where conceptualising PEN organisational models - as done in this report for Genk, Pamplona and Tartu - provides a useful foundation.

2.5. PEDs and PENs in Europe – characteristics and archetypes

As the EU advances towards its ambitious climate and energy goals, the development of PENs and PEDs has become a **crucial strategy in sustainable urban development**. It has been established that these neighbourhoods aim to produce more energy than they consume, integrating sufficiency, energy efficiency measures, renewable energy sources, and smart management systems to minimise carbon footprints and promote climate neutrality.

While the concept of energy-positive urban areas has gained traction, **on-the-ground implementations vary widely** in terms of technological solutions, policy frameworks, community involvement and infrastructure design. Some PEDs/PENs are driven by cutting-edge technologies, while others prioritise community participation, local resource utilisation or policy-driven urban planning.

In 2020, Urban Europe analysed 61 urban projects dealing with the energy transition and sustainability aims out of which 29 declared a PED/PEN ambition – some focusing on small neighbourhoods, while others encompass larger urban districts [26]. These projects, varying in their stages of implementation, offer valuable insights into the **core characteristics** and emerging patterns of PEDs/PENs in Europe that reflect the lessons already described in Chapter 2.3 above.

Adding to this, based on another analysis [27] of 60 existing PED projects in Europe, it is said that Norway and Italy have the most PED projects. Many PED projects declare a 'yearly' time scale[8] instead of a daily/monthly temporal scale or a seasonal one. Also, nearly a third of the projects have less than 0.2 km^2 area in terms of spatial scale. Private investment together with public funding are commonly observed. A mixture of residential, commercial and office/social buildings are found. Finally, the most common renewable energy systems include solar energy, district heating/cooling, wind and geothermal energy. This seems to make up the general profile of what a PED/PEN looks like in Europe.

In the following sections, **two complementary PED/PEN archetype sets** are proposed. The first set focuses on **organisational archetypes**, which describe how PENs are governed and steered, distinguishing between technologically driven, community-centric and policy-driven approaches. The second set addresses **systemic archetypes**, which characterise how neighbourhood energy systems are configured and interact with wider energy networks, differentiating between autonomous, dynamic and virtual PENs. These archetypes are not intended as rigid classifications or end states, but as analytical lenses that capture the main trajectories of complex, evolving neighbourhood energy systems. In the case studies, both archetype sets are applied in parallel to support a structured comparison of the emerging PEN models.

2.5.1. PED/PEN organisational archetypes – technologically driven, community-centric and policy-driven PEDs/PENs

For replicability and comparability, it is important to develop a common understanding of what a PED/PEN entails, which kinds of solutions a "proper" PEN should include and how the deployment should happen. However, as the literature highlights, this shared understanding **cannot translate into a single prescriptive model or methodology**. Sassenau et al. [11] argue that effective district-level concepts must integrate energy, environmental, economic and social dimensions and address both buildings and public spaces, yet the specific mix of solutions varies according to local district characteristics. As challenges and opportunities differ widely between neighbourhoods, there is no single "magic recipe" that can be applied everywhere. Designing a fully bespoke methodology for every district would be impractical and inefficient. This suggests that PENs require adaptable frameworks which are structured enough to guide planning and comparability, yet flexible enough to be tailored to local conditions, needs and limitations.

Indeed, PEDs/PENs across Europe showcase a **variety of approaches** to achieving energy positivity and sustainability. While technological innovation is a common thread, the degree of e.g. community involvement and policy support, together with their holistic integration varies, leading to some loosely interpretable archetypes. Based on the literature review and the core characteristics of existing cases presented above, PENs and PEDs could be broadly categorised into the following archetypes[9]:

[8] Net positive yearly energy balance.
[9] Authors' own based on literature review.

1. **Technologically driven neighbourhoods**

These neighbourhoods prioritise **cutting-edge technologies** to optimise energy generation, distribution and consumption. They often function as urban living labs, testing and implementing state-of-the-art solutions in renewable energy production, smart grids, energy storage and digital monitoring systems. The key characteristics include:

- **High reliance on renewable energy sources -** solar panels, wind turbines, geothermal energy and other renewables are primary energy sources.
- **Energy storage and smart grids -** advanced battery systems, hydrogen storage and decentralised energy management help balance supply and demand.
- **Smart energy systems –** artificial intelligence (AI)-driven automation, Internet of Things enabled energy monitoring and demand-response systems enhance efficiency.
- **High-performance building design** – positive energy buildings, nearly zero-energy buildings and passive house standards with optimised insulation, smart HVAC systems and energy-efficient appliances.
- **Integration with sustainable mobility solutions -** electrification of transport through smart electric vehicle (EV) charging stations, energy-sharing between buildings and vehicles, shared mobility, cycling infrastructure and access to public transport.
- **Strengths compared to other archetypes –** high potential for deep decarbonisation through efficiency, flexibility and high RES penetration; often supported by strong partnerships with research institutions, technology companies and PPPs; generates transferable technical knowledge and demonstrator projects that can inform wider policy and market design.
- **Weaknesses compared to other archetypes –** high investment costs and dependence of advanced infrastructure can restrict scalability; risk of technology-first approaches that underplay social acceptance, behavioural aspects and equity considerations; may require complex governance to manage interoperability, data and cybersecurity issues.

2. **Community-centric neighbourhoods**

These neighbourhoods emphasise **resident participation in planning, decision-making and management of energy systems**, fostering social cohesion and shared sustainability goals. The energy-positive model is integrated with local resource use, collective ownership models and lifestyle changes to ensure sustainability is a communal effort. The key characteristics include:

- **Strong community governance** - residents are actively involved in shaping policies, co-owning renewable energy assets and making decisions about neighbourhood management.
- **Social sustainability focus** - integration of cooperative housing models, eco-villages and collaborative living spaces.
- **Decentralised renewable energy production** - shared energy infrastructure such as cooperatively owned solar panels, community biogas plants or local wind turbines.
- **Education and behaviour change -** awareness campaigns and local workshops to engage residents in energy-saving practices.
- **Emphasis on local resource cycles -** circular economy principles, waste-to-energy initiatives and permaculture-based food production.
- **Strengths compared to other archetypes –** high levels of local ownership and acceptance with “people first, technology second”; bottom-up development can increase resilience as communities are actively involved in defining needs, solutions and governance structures; potential to address social goals (e.g. cohesion, local employment, energy poverty) alongside climate objectives.

- **Weaknesses compared to other archetypes –** scaling beyond the initial community can be challenging due to governance complexity, reliance on key local actors and limited funding capacity; land-use restrictions and planning rules may constrain local generation or cooperative models; technical optimisation may lag if resources and expertise are limited, or if technology is seen as secondary to social processes.

3. Policy-driven neighbourhoods

Policy-driven neighbourhoods are established through **strong municipal leadership and regulatory frameworks**, often aligning with national and EU climate targets. These initiatives scale sustainability efforts at a city or regional level, making them an essential component of urban policy transformation. The key characteristics include:

- **Government-led planning and funding** – municipalities provide policy incentives, regulatory support, investment in infrastructure or initiate the setup of an energy community.
- **District-wide energy solutions** - integrated district heating, waste-to-energy systems and public infrastructure retrofitting.
- **Incentivised private sector participation –** PPPs encourage real estate developers and energy companies to contribute to sustainable urban development.
- **Alignment with long-term sustainability goals -** neighbourhoods are part of city-wide climate strategies (e.g. climate neutrality by 2030 or 2050).
- **Focus on accessibility and inclusivity -** policy-driven PEDs/PENs ensure equitable access to affordable housing and public services while reducing energy poverty.
- **Strengths compared to other archetypes –** ability to steer change at scale through regulation, planning instruments and public investment; potential for long-term stability and continuity when objectives are embedded in formal strategies and legal frameworks; potential to mainstream the PEN concept and integrate it with broader urban development and social policy goals.
- **Weaknesses compared to other archetypes –** top-down planning may be less agile and slower to adapt to local innovations or community preferences; bureaucratic procedures, regulatory constraints and political shifts can delay implementation; risk that formal compliance dominates over co-creation if stakeholder engagement is not well integrated.

The main characteristics of the proposed 3 organisational archetypes are summarised below (Table 1):

Feature	Tech-driven	Community-centric	Policy-driven
Primary driver	Innovation and technology	Social engagement	Government policy
Energy infrastructure	Smart grids, AI, automation	Localised and shared renewable energy	Large-scale district heating, municipal incentives
Governance model	Private sector and research institutions	Community cooperatives and grassroots initiatives	Public sector, municipal planning
Scalability	High cost, dependent on investment	Small-scale, difficult to replicate at city level	Large-scale, but bureaucratically slow

Table 1: Proposed organisational PEN archetypes. Source: authors.

It has to be stressed that while technologically driven, community-centric and policy-driven archetypes all offer somewhat useful conceptual models for analysing the focus of different approaches (and, as such, will be applied as a lens that explores the emerging organisational PEN archetypes in the context of oPEN Lab), in reality, **these categories are not rigidly distinct**. Instead, **most PEDs/PENs projects are hybrid in the sense that they integrate elements from all three archetypes to varying degrees,** depending on local priorities, funding structures and stakeholder involvement. As such, purely technological, social or policy-driven PEDs/PENs do not exist in isolation – it is rather the case that the success of PED/PEN projects lies in the success of blending these approaches to create holistic, adaptive and context-specific solutions. It has been said that "*the ability to integrate technical and non-technical capabilities and engage stakeholders within and outside the city hall, complemented by the capacity to learn, are the key relational components to (PED) success*. [28]" As such, the key is in how to deliver an integrated city vision.

2.5.2. PED/PEN systemic archetypes – autonomous, dynamic and virtual PEDs/PENs

Another useful PED/PEN positioning framework has been proposed by VTT Technical Research Centre of Finland [29], focusing on **autonomous, dynamic and virtual** PEDs/PENs. These three types differ mainly by their system boundaries and allowed interactions with external energy systems. In short: whereas **autonomous** districts are self-sufficient within a fixed geographical boundary, **dynamic** districts retain a geographical boundary while slowing time-shifting imports/exports so long as the annual balance remains positive, and **virtual** districts aggregate non-contiguous assets and may rely on off-site renewable generation and storage contractually tied to the district. More specifically:

- **Autonomous districts** – are designed to **cover all annual energy demand with on-site renewable generation** and may export surplus energy, but do **not** rely on external imports to meet the balance. This implies very high efficiency, substantial local generation (often solar) and storage/flexibility sized to local conditions. It suits **low- to medium-density** areas with ample surface for renewables. The key characteristics include:
    - **Boundary** – fixed geographic area.
    - **Energy exchanges** – export only, annual self-sufficiency.
    - **Implications** – strong emphasis on demand reduction, local photovoltaic (PV)/thermal and storage sizing.
- **Dynamic districts** – also have a **fixed geographic boundary,** but explicitly **import and export** energy over time, targeting a **net positive annual balance** (exports > imports). Flexibility (demand response, thermal/electric storage) and **grid interaction** are integral. This suits **denser** urban contexts where on-site generation is constrained, but temporal balancing with the grid is feasible. The key characteristics include:
    - **Boundary** – fixed geographic area.
    - **Energy exchanges** – bi-directional, positive annual balance required.
    - **Implications** – coordination with grids/markets, controls for temporal matching and flexibility.
- **Virtual districts** – relax the geographical constraint by **aggregating distributed (off-site) renewable generation and storage** that are contractually part of the district's asset base. Local and off-site resources combine to achieve the **annual positive balance**. This model is the most flexible from a siting perspective, but raises **ownership, additionality and accounting** considerations (e.g. power purchase agreements, guarantees of origin). The key characteristics include:
    - **Boundary** – functional/contractual (non-contiguous).
    - **Energy exchanges** – free import/export, balance ensured through owned/contracted renewables (on- or off-site).
    - **Implications** – emphasis on legal/market instruments, traceability and governance of virtual assets.

The main characteristics of the proposed 3 systemic archetypes are summarised below (Table 2):

Feature	Autonomous	Dynamic	Virtual
System boundary	Fixed geographic district	Fixed geographic district	Functional/contractual (assets can be off-site)
Annual balance rule	On-site generation ≥ demand, exports allowed	Exports > imports over a year (on-site generation predominates)	Positive annual balance using on- and off-site assets tied to the district
Energy exchanges	Export only (no imports to meet demand)	Import and export (temporal balancing)	Import and export, off-site generation/storage allowed
Core enablers	Deep efficiency, ample local RES potential, storage sizing	Flexibility, storage, market/grid access, controls	PPAs/energy community frameworks, certification/traceability, regulatory clarity
Typical context	Low-medium density, large roof/land availability	Medium-high density with reliable grid interaction	High-density or constrained sites, strong market/legal instruments
Key challenges	Surface constraints, seasonal mismatch	Operational coordination, ensuring annual surplus	Additionality/accounting, governance of virtual assets

Table 2: Proposed systemic PEN archetypes. Source: Lindholm et al. [29].

For the purpose of this deliverable, these three archetypes provide a **useful lens** to position each oPEN Lab's city's current neighbourhood energy setup - whether it already functions as a full PED/PEN or is **developing first elements** towards one. The framework enables to (i) state the **intended organisational/technical target** (autonomous, dynamic or virtual), (ii) assess **fit with local constraints** (space, regulation, market design), and (iii) identify **governance and business model needs** (e.g. municipal leadership for autonomous build-out, flexibility/market participation for dynamic contractual instruments for virtual). This common language, along with the organisational PEN archetypes proposed before, will be applied in the analysis of the three case studies and then used to **benchmark** them against each other in the comparison chapter (Chapter 7).

3. PEN organisational models: methodology

The literature review revealed that there is **no one-fits-all strategy** when it comes to implementing the PEN concept. There is not one PEN model, but rather **several typologies of PEN strategies**, combining diverse governance models, energy systems and district transformations. As such, when developing PENs, the **specific situation of the city and the neighbourhood** should be taken into account. In order to support neighbourhood development, it is crucial to **understand the specific organisational model for every PEN project**, capturing the complexity of PENs and orchestrating public and private interests in order to support neighbourhood development.

In oPEN Lab, an organisational model for PENs is seen as a framework of various conditions in which the PENs are developing, essentially the key components that outline how **governance, operations and collaboration** will function in practice. As such, the models provide structured frameworks that address the roles of various stakeholders, decision-making processes, financial flows, private and shared assets and operational mechanisms to ensure successful implementation and long-term sustainability. As stated in literature (e.g. [28]), "*PEDs do not originate on their own, but rather, require systematic facilitation geared towards kickstarting local PED ecosystems and developing political constituencies and clusters of expertise*".

This report aims to **describe this emerging organisational model** for the three oPEN Lab pilot neighbourhoods in Genk, Pamplona and Tartu. Building on existing literature – especially the ecosystem components that make up a complex PEN environment (see Chapter 3.1) – **three case studies** were developed, each capturing **a distinct trajectory and its associated challenges**. These trajectories reflect different organisational emphases within the pilots, such as Genk's exploration of a PEN as a service approach, Pamplona's development of an emerging energy community model centred around virtual energy sharing, and Tartu's implementation of a Renovation as a Service (RaaS) model to coordinate multi-owner building retrofits. Input for the case studies was gathered from complementary tasks and materials in the oPEN Lab project, requesting additional information from the local project partners based on the case study structure and guiding questions. Separate online meetings focusing on each of the three case studies were held with respective partners in the oPEN Lab project and pilot cities to discuss any challenges and potential revisions. These resulting case studies serve as three oPEN Lab emerging PEN organisational models, leading to a **comparative analysis** of the main features of the models.

3.1. Case study framework

For framing the 3 case studies, the main **aspects/ecosystem components to analyse** originate from the methodological framework suggested by Delft University of Technology [13]. From the iterative Delphi method, the panel experts identified seven challenging topics, in provisional order of importance, representing what we need to overcome to support the implementation of PEDs/PENs. These are (see also Figure 7):

1. **Governance**: a need for new and innovative forms of collaborative governance;
2. **Incentives**: a need for right (economic, social and environmental) drivers and motivators;
3. **Social**: a need for local community's support and engagement;
4. **Process**: a need for integrated planning and decision-making approaches;
5. **Market**: a need for an appropriate energy market design and business model;
6. **Technology**: a need for reducing energy demand and balancing energy demand and supply systems;
7. **Context**: a need for considering regional and local differences.

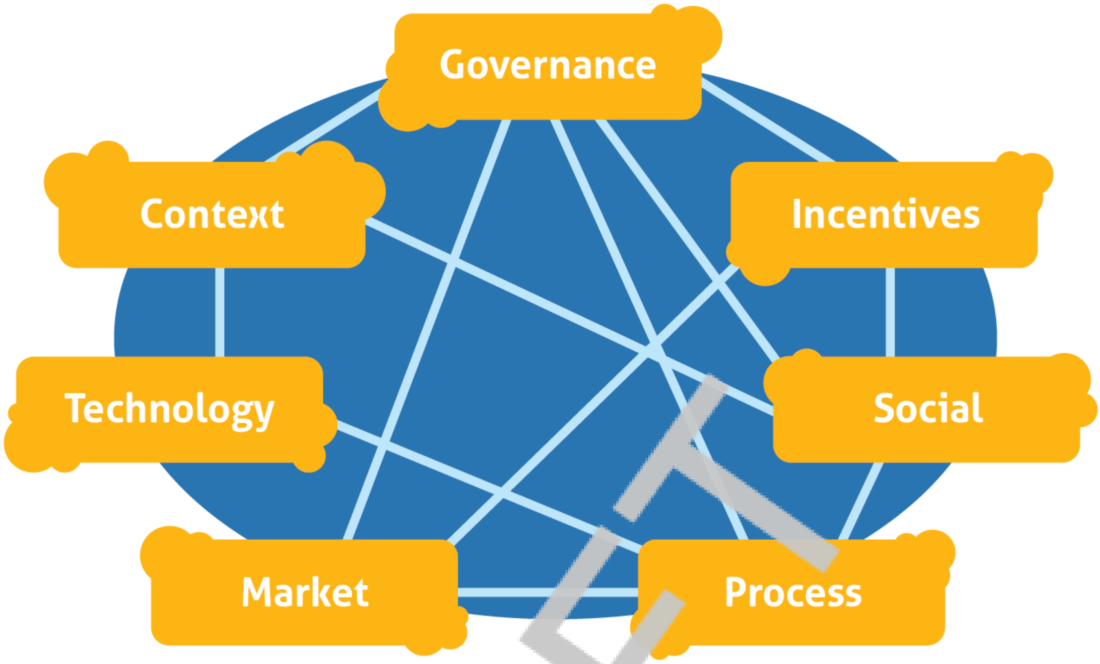

Figure 6: PED ecosystem interdependencies. Source: Krangsas et al. [13].

For the purpose of this report, these ecosystem components were **modified and grouped together** according to the oPEN Lab context. **A 3-step framework for understanding what the PEN ecosystem and organisational model looks like was used** (see Figure 8), exploring what the framework conditions are in which the PENs are developing: (i) context level, (ii) Living Lab level, and (iii) PEN level.

Context level (I)

The first level focuses on describing the "context", which was defined as a **need for considering regional and local differences** in the Delft framework. With regards to the interdependencies with other ecosystem components, here, the focus is on the organisational side of PENs, so interdependencies are mainly drawn with "governance" and "social", but also "incentives" as an important component accounting for the regulatory drivers and motivators on the national/regional level. As such, this report proposes the following aspects under the context level to investigate in each of the PEN settings:

- **Structures** – economic, physical and regulatory settings. Includes a profile of the houses in the neighbourhood (physical), what the market conditions are that hinder/steer PENs (economic), what the incentives/regulations are (regulatory).
- **Cultures** – history, discourses, shared beliefs, values, perspectives and paradigms, habits, practices, behaviours. Includes a social profile of the neighbourhood.
- **Networks** – local actors, groups, coalitions, interconnections, leaders.

Living Lab level (II)

The second level focuses on what the oPEN Lab project does and hopes to achieve within the PEN settings. Here, the focus is on "governance" and "technology". Specific to the oPEN Lab project, governance will explore the organisational side of the project, i.e. how the Living Labs are functioning in the PEN settings. In terms of technology, the aim is to give a brief account of the oPEN Lab interventions planned in each of the cities. In sum, the second, Living Lab level consists of two components:

- **Organisation** – Living Lab approach, organisational side.
- **Solutions** – oPEN Lab interventions, technical side.

PEN level (III)

The third and final level focuses on the emerging **PEN organisational models**. How could governance, operations and collaboration function in practice? What are the emerging roles of various stakeholders, decision-making processes, financial flows and operational mechanisms to ensure successful implementation of the PENs and their long-term sustainability? These are the questions that will be answered through exploring components like “governance” (need for new and innovative forms of collaborative governance), “social” (need for the local community’s support and engagement), “process” (need for integrated planning and decision-making approaches), “market” (need for an appropriate market design and business models) and, to some extent, “technology” (need for balancing energy demand and supply systems). More specifically, the third level will explore the following aspects:

- **PEN vision** - narrative and vision of the PEN, including the timeframe, aims and objectives of the PEN, scope.
- **Governance structure** – who will manage, operate and regulate the PEN? Includes aspects of collaborative governance, roles, community engagement, co-creation, integrated planning and decision-making. Explores **governance models**, including community cooperative governance, PPPs, municipal-led or hybrid models.
- **Operational models** - how could the PEN function on a day-to-day basis? Includes aspects of management, energy systems integration, maintenance and monitoring.
- **Financial models** - how will the PEN be funded and sustained? Includes Genk PEN as a service model, Pamplona energy community model, Tartu RaaS model, investment sources, revenue streams, asset ownership, cost structure, sustainability.
- **Ownership models** – including co-ownership, responsibility sharing. Who owns PEN assets?

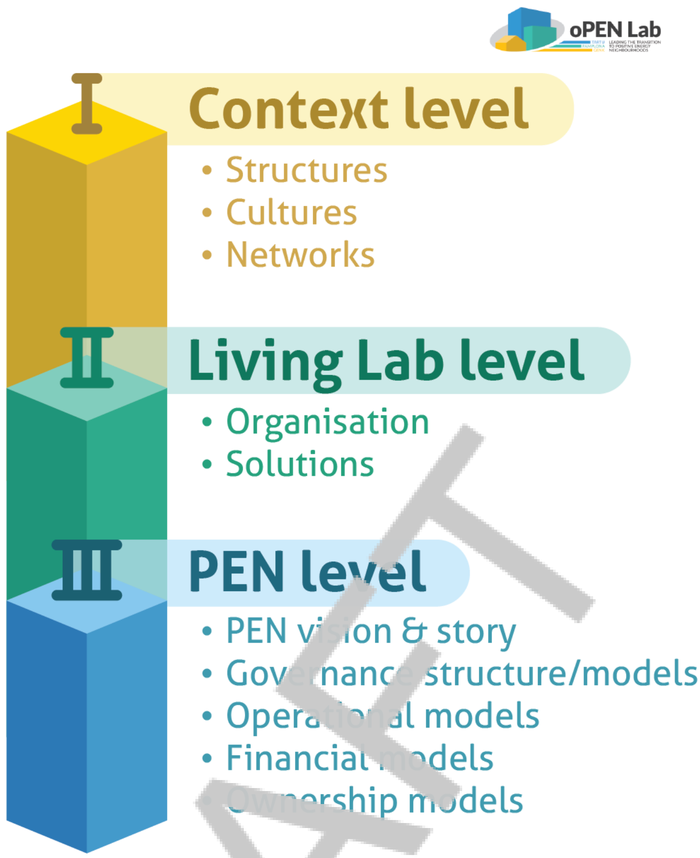

Figure 7: 3 analytical levels used in the case studies. Source: authors.

It is important to note that all of these components (see also Figure 8) will be analysed from the point of view of **organising and coordinating PENs**, highlighting the respective stakeholder relationships, organisational responsibilities as well as risks and challenges. As such, if e.g. looking at technology, the case studies will not present in-depth technological descriptions and analysis[10], but will rather aim to explore how the technological context affects the organisation of the respective PEN.

3.2. Case study scope

As already outlined, the case study analysis focuses on exploring PENs across three interlinked levels: the **context**, **(oPEN) Living Lab** and the specific **PEN level**. Together, these levels provide a structured framework to understand how broader socio-economic, regulatory and physical environments shape the organisational, operational and financial dimensions of each PEN case. By systematically addressing guiding questions under each level, the analysis aims to capture the diversity of local conditions and the varying approaches adopted by the cities involved.

The case study scope (Table 3) involves a **set of guiding questions** for each of the three levels. At the **context level**, the scope covers the economic, regulatory and physical structures that influence the feasibility and organisation of PENs. It also looks at local cultures - values,

[10] These are analysed in detail in the forthcoming oPEN Lab *Report on operational control of PEN environments* (2025) [48], *Building integration in PEN* (2025) [55] and *Report on demonstrated technologies at building and neighbourhood level in three demonstration areas* (2025) [40].

behaviours and social profiles - and at networks of actors and coalitions active in the energy transition. The **Living Lab level** examines how each city's Living Lab approach supports PEN development, focusing on organisational setup, stakeholder roles, citizen participation and technological solutions. Finally, the **PEN level** investigates the neighbourhood as a system, analysing its vision and evolution, governance arrangements, operational and financial models and ownership structures.

Together, these dimensions enable a **more comprehensive understanding of the conditions, drivers and challenges behind each case**. They also establish a coherent analytical basis for comparing different organisational models of PENs, feeding directly into the benchmarking and categorisation presented in the next chapters.

Component	Guiding questions and aspects explored
I Context level	
Structures	*What is the economic setting like? Market conditions hindering/steering PENs, loan interest rates, incentives offered, subsidies, etc. *What is the regulatory setting like? What is the national/regional legal and regulatory context like? How do these conditions affect the organisational set-up of the PEN? Is there a regulatory push? What prerogatives and mechanisms do municipalities have for implementing plans for sustainable neighbourhoods? *What is the physical setting like? Building stock typologies in the neighbourhood, age, building use, heritage protection, etc.
Cultures	*History, discourses, shared beliefs, values, perspectives and paradigms, habits, practices, behaviours. *What are the socio-economic characteristics of the neighbourhood? How does this affect the organisational set-up of the PEN?
Networks	*Local actors, groups, coalitions, interconnections, leaders.
II Living Lab level	
Organisation	*Living Lab approach and set-up, stakeholders, roles, etc. How is the Living Lab organised and set up? *Who are the key actors involved in the governance of the Living Lab (municipalities, citizens, SMEs, academia, etc.)? How are inhabitants involved, what are the end-user engagement and co-creation tools used?
Solutions	*oPEN Lab demonstration activities/interventions, technical side. What are the key technological innovations of the Living Lab? How does the technology context affect the PEN organisation?
III PEN level	
PEN story	*Narrative of the PEN, including the scope, aims/vision, and timeframe of the PEN. *Describe the PEN, how the buildings interact, and what makes them a PEN. What are the challenges of turning into a PEN? *What are the strategies for long-term sustainability? What are the sustainability-related challenges?
Governance structure and models	*Who are the main stakeholders (e.g. 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 organizations) supporting and coordinating the development of the PEN? Please briefly explain the role and responsibility of each stakeholder in the governance model. Who will manage, operate and regulate the PEN? How are the stakeholders involved? How do stakeholders influence the design and operation of the PEN?

	*Are new/innovative forms of governance (e.g. community cooperative governance, PPPs, municipal-led or hybrid models) used in the organisational setup of the PEN? *Are any new forms of social innovation (e.g. energy presumption[11]) used in the PEN? What does the model look like? *Who makes decisions and how? How is planning (spatial, energy, community planning) integrated and decision-making embedded in the PEN setup? *What are the risks (e.g. low community participation, resistance)? How are conflicts between stakeholders resolved?
Operational models	*How will the PEN function on a day-to-day basis? *Management processes - how will energy production, distribution and consumption be managed? Roles of operational partners (e.g. ESCOs, cooperatives or technology providers). *Energy systems integration - how are renewable energy sources, storage and smart grids integrated and controlled? How are energy savings or surpluses distributed? Mechanisms for demand-response and grid flexibility. *Maintenance and monitoring – how are systems maintained and monitored over time? Use of digital tools for smart monitoring and data analysis. *How will systems be maintained and monitored over time? What about troubleshooting technical issues? *What are the risks (e.g. energy system failures, integration challenges)?
Financial models	*What is the combination of business models relevant for your PEN (renovation, renewable energy investment and sharing, mobility, flexibility)? What are the main asset ownership, value streams and operational responsibilities? Focus - Genk PEN as a service model, Pamplona energy community model, Tartu RaaS model. *How will the PEN be financed and sustained? What are the revenue streams and how are costs distributed? Includes investments sources (public funds (EU, national, regional and local grants and subsidies), private investments, cooperative member contributions, etc.), revenue streams (energy and flexibility sales to the grid and aggregators, subscription fees for energy-as-a-service models, energy community membership fees, etc), cost structure (initial capital costs – investments in energy efficiency and HVAC, renewable installations, smart systems, infrastructure; operational costs – maintenance, monitoring), financial sustainability (strategies to ensure long-term viability, e.g. reinvesting profits into neighbourhood upgrades). *Which are the local opportunities for financing PENs (e.g. cheaper green loans, environmental/social/governance finance, grants, subsidies, facilitated access to financial institutions) *Are there innovative financial models used (e.g. crowdfunding, renewable and citizen energy communities, cooperatives)? *What are the risks (e.g. insufficient funding or revenue generation)? How are financial risks shared among stakeholders?
Ownership models	*Who is the owner of the PEN assets? Define the ownership and responsibilities. *Asset ownership – who owns the renewable energy systems, heat and electricity storage and collective HVAC systems? Shared ownership (e.g.

[11] Model where consumers also produce energy, shifting from being purely passive users to active participants in the energy system.

	cooperatives) or 3rd party ownership (e.g. energy providers, energy service company (ESCO), developers)? *Responsibility sharing – who is responsible for upgrades, repairs and operational costs? *What are the risks (e.g. data privacy, grid access)?

Table 3: Case study scope and guiding questions. Source: authors.

3.3. Conceptual boundary between Living Lab and PEN governance

The case study scope highlights the fact that the organisational and governance analysis in this deliverable distinguishes between two interconnected yet conceptually distinct levels: the **Living Lab** and the **PEN**. This distinction is necessary to capture both the **processes** through which PENs are co-created and the **structures** through which they are ultimately organised and operated. In oPEN Lab, PENs are still at an early stage of development and their governance arrangements are emerging from the collaboration frameworks established within the Living Labs. The following discussion clarifies how the two levels are understood and analysed in the context of this report.

The **Living Lab level** represents the **process-oriented dimension** of PEN development. It focuses on how diverse stakeholders - municipalities, research institutions, companies, citizens and community organisations collaborate to test, adapt and validate new technical, social and governance solutions. Living Labs serve as **innovation and coordination arenas** where experimentation takes place, roles are negotiated and trust is built among actors. At this level, governance refers to the mechanisms that enable co-creation and decision-making during the design and demonstration phases, including coordination structures, stakeholder engagement methods and feedback loops between users and developers.

The **PEN level**, in contrast, reflects the **outcome-oriented dimension**, focusing on how the neighbourhood functions once organisational arrangements begin to take shape. Here, governance concerns the **formalisation** of relationships, responsibilities and operational models that will sustain the neighbourhood's positive energy balance over time. It includes questions of ownership, financing, decision-making authority and accountability structures. While many of the same stakeholders remain involved, their roles evolve from collaborative co-creators within the Living Lab to defined actors in governance, management or end-use positions within the PEN.

Recognising the **continuity and transition** between these two levels is essential. The Living Lab provides the social, institutional and technical groundwork for the eventual PEN organisation. Insights from the Living Lab phase - such as cooperation models, engagement tools or partnership formats - often become embedded in the PEN's governance framework once implementation begins. Therefore, the analysis of each case study examines both levels in sequence: first, how the Living Lab facilitates co-creation and experimentation; second, how these processes shift into the emerging governance, operational and financial structures of the PEN. This methodological separation allows for comparative assessment across cases while acknowledging the evolving nature of PEN governance in practice.

3.4. Benchmark and categorisation of PEN organisational models - methodology

In this report, benchmarking refers specifically to a **cross-case comparative analysis** that examines how the three pilot cities - Genk, Pamplona and Tartu - are each developing their organisational PEN trajectories within their respective contexts. The purpose of benchmarking here is therefore **relational, not normative**: it identifies similarities, differences and patterns across the cases, without evaluating them against any single external standard or universal performance benchmark. Instead, the analysis situates each emerging PEN model within its own development pathway and compares it to others to showcase how different configurations evolve, which contextual factors matter and what organisational archetypes they most closely approximate. Benchmarking in this report thus serves as a tool for analytical positioning and learning, not for ranking, scoring or prescribing a single "ideal" organisational model.

As such, while the three case studies make up the core of this report, the ultimate aim is to **benchmark and categorise different organisational models of PENs** emerging from the oPEN Lab project. Whereas each case develops within its own regulatory, social and technical setting, the analysis aims to establish a **common methodological framework** that allows their comparison in a meaningful way. This framework integrates the case study framework (context, Living Lab and PEN levels), the conceptual distinction between the Living Lab and PEN governance, as well as the two complementary archetype typologies resulting from the literature analysis: **the organisational focus archetypes** (technologically driven, community-centric and policy-driven) and **the integration with the energy system-boundary archetypes** (autonomous, dynamic and virtual). The two archetype sets are not competing but **complementary lenses**. The first focuses on **who drives** the neighbourhood and **how governance is structured**, while the second addresses **how the energy system operates** and **how boundaries are defined**.

The **case study framework and scope** presented above (context, Living Lab and PEN levels) is the first element ensuring **comparability across cases**, even when the PENs themselves are at different (emerging) stages of development. By tracing how local context and Living Lab interactions influence emerging PEN organisational setups, the analysis can highlight both shared mechanisms and case-specific differences.

When combining the complementary archetype sets with the three-level analytical structure, they provide a **multidimensional framework** for benchmarking (see Table 4):

Case study level	Organisational archetypes	Energy system archetypes	Main comparative questions
Context level	What political, social and market factors enable or constrain each archetype?	What spatial or infrastructural conditions define system boundaries?	How do local regulations or incentives shape the organisational and technical approach?
Living Lab level	What are Living Lab stakeholder roles and interactions (municipal, community, technology partners, etc.)?	How do oPEN Lab pilots and demonstrations reflect autonomous, dynamic or virtual setups?	How does experimentation/ project activities feed into PEN organisational model formation?
PEN level	What governance, operational, financial and ownership models are emerging?	How are energy exchanges managed and balanced, what is the future outlook like?	How do these configurations support long-term sustainability?

Table 4: Benchmark and categorisation framework for PEN organisational models. Source: Lindholm et al. [29], authors.

Applying this integrated approach allows each case study to be **positioned within both frameworks**, identifying:

- Its **dominant organisational archetype** (e.g. community-centric vs. policy-driven).
- Its energy **system type** (e.g. dynamic vs. virtual).
- The **interplay** between context, Living Lab processes and emerging PEN governance.

The results from each case study are summarised in a comparable format - covering contextual enablers, Living Lab dynamics and PEN organisational characteristics. These archetypes will then be benchmarked across the three Living Labs to identify patterns, synergies and transferable lessons.

Through this method, the deliverable ensures that differences in maturity or local conditions do not hinder comparability, but rather enrich the understanding of how diverse contexts lead to distinct pathways towards PENs. The combined use of **organisational** and **systemic** archetypes provides a coherent analytical framework for categorising PENs and for drawing practical insights to inform replication, scaling and policy alignment in future European renewable energy developments.

4. Genk case study

4.1. Overview of Genk oPEN Living Lab

Figure 8: oPEN Lab Genk neighbourhood. Source: VITO.

Location

Waterschei, Genk, Limburg, Belgium.

Introduction

The **oPEN Living Lab in Genk** is situated in the residential suburb of **Waterschei**, a district that combines two distinct urban fabrics: a former mining neighbourhood built in the 1920s and a social housing area known as Nieuw Texas, constructed in the 1990s. The older part of

Waterschei was developed as a Garden City to house mining families from the nearby coal mine, which shaped much of Genk's early industrial and social identity. Nieuw Texas, located adjacent to the historic district, has a high proportion of social housing (approximately 85%) [4].

The oPEN Lab initiative includes the **deep renovation of 27 social housing units in Nieuw Texas** and **7 privately owned homes in the Garden City neighbourhood**. The goal is to transform these dwellings into energy-positive buildings using both collective and individual solutions. These activities are aligned with the city's broader climate vision under the energy transition roadmap (GEENkool), which outlines a pathway for Genk to achieve climate neutrality by 2050 [30]. As part of the larger oPEN Lab project, the Genk Living Lab serves as a technological testing ground, but also as a model for how PENs can be implemented in economically and historically complex urban settings [31].

Key figures

- Waterschei's total area is approximately 6.9 km^2, with a population of ca. 7,600 residents [32].
- In oPEN Lab, a total of 34 residential dwellings are engaged in the renovation activities, including 27 social housing units and 7 privately owned homes.
- The pitmen in Waterschei once dug over 1000 metres underground into the earth. Coal mining began in 1924. Until the pit was closed in 1987, 72,453,796 tonnes of coal were mined there [33].
- The Waterschei mine was one of the last active coal mines in Belgium and its closure in 1987 marked a turning point in the city's post-industrial transformation. The former mine site is now home to Thor Park, a leading innovation campus dedicated to clean energy and smart technology.
- The Tuinwijk Waterschei (Garden City) is a listed heritage district designed in the 1920s following the garden city principles of Ebenezer Howard. Its winding streets, red-brick semi-detached houses and green communal spaces give the area a distinctive identity and a strong sense of place.
- Waterschei's population reflects its mining legacy, including families with Italian, Turkish, Greek and Eastern European roots who settled in the area during the 20th century. This cultural diversity continues to shape the social fabric of the neighbourhood today.
- The district is located near the National Park Hoge Kempen, offering access to extensive green areas and cycling routes and symbolising the transition from an extractive to a sustainable landscape.
- Waterschei and Nieuw Texas together reflect two phases of Genk's transformation: the former symbolising its mining heritage and the latter representing its post-industrial regeneration.
- Within these districts, a selection of dwellings are part of the Open Thor Living Lab where sustainable renovation and social innovation converge to shape a resilient and inclusive neighbourhood.

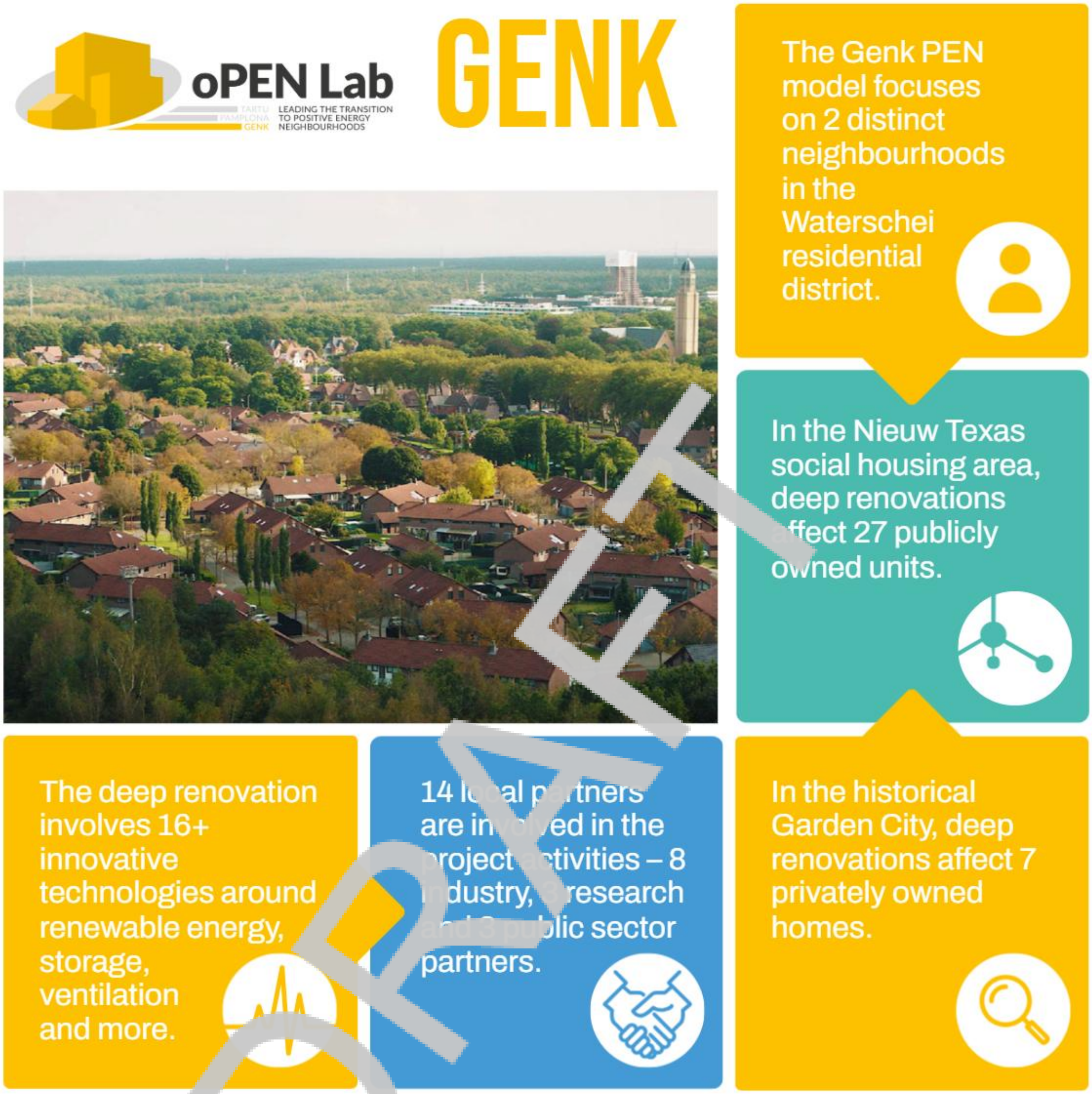

Figure 9: Genk oPEN Living Lab overview. Source: authors.

4.2. Genk oPEN Living Lab context

This section provides contextual insight into Genk's oPEN Lab neighbourhood by examining the underlying **structures**, **cultures** and **networks**. The aim is to lay the groundwork for understanding how local contexts shape the organisational models of PENs.

Figure 10: Chapter 4.2 explores the context level in Genk. Source: authors.

4.2.1. Structures

This sub-section explores the **structural conditions** shaping Genk oPEN Lab neighbourhood, focusing on their **economic settings**, **regulatory frameworks** and **physical characteristics**. Understanding these foundational aspects helps explain the practical opportunities and constraints faced in implementing and scaling PENs.

Economic setting[12]

The market conditions shaping the development of PENs in Genk reflect **both encouraging trends and persistent structural limitations**. On the enabling side, the availability of targeted financial instruments - such as the My Renovation Premium and My Renovation Loan, both co-financed via the NextGenerationEU mechanism in Flanders - demonstrates a clear commitment by the Flemish government to incentivise energy-efficient renovations across a broad spectrum of the housing market [30]. These instruments are notably income-adjusted and have been extended to better serve middle- and low-income households, suggesting a market orientation that aims to promote equitable access to energy efficiency measures.

Additional measures, including property tax reductions tied to energy performance levels and VKF (Flemish Climate Fund) subsidies for social housing companies, further indicate that energy efficiency is financially incentivised in Flanders [30]. The latter, while modest in scope (4,000 euros per measure), still represent a dedicated funding stream for vulnerable housing segments and contribute to the mobilisation of renovation activity in Genk's public housing sector.

However, several market-related constraints continue to hinder the widespread and inclusive rollout of PENs. A key limitation is the **misalignment between financing instruments and the full cost-efficiency potential of innovative renovation methods** - particularly prefabricated elements, which are well-suited to renovations in the social housing context in Genk. These solutions enable tenants to remain in their homes during construction, reducing both social disruption and operational costs for housing companies. Yet, current financial mechanisms fail to recognise these additional social and logistical benefits, and as a result, offer no targeted support for prefabricated approaches [30]. This is a significant missed

[12] For more information about the market conditions and economic instruments relevant to Genk's PEN development, please refer to the oPEN Lab report *Towards a regulatory framework for positive energy neighbourhoods, Flanders (2024)* [30].

opportunity to accelerate renovation timelines while also reducing pressure on social housing waiting lists.

Furthermore, while market incentives exist on paper, **their actual accessibility for economically vulnerable groups remains limited**. Despite income-based adjustments, many lower-income households face practical barriers to participation in energy renovation schemes, such as lack of upfront capital, creditworthiness issues or limited awareness of available programmes. This contributes to a phenomenon commonly referred to as the **Matthew Effect**, whereby those already in a position of economic advantage are more likely to benefit from public subsidies, thereby reinforcing existing inequalities. [30]

Another important market dynamic is the continued **emphasis on individual property-level renovation**, which may dilute the economic and technical advantages offered by integrated, neighbourhood-scale approaches. PENs, by design, seek to leverage economies of scale through the aggregation of demand, shared infrastructure and collective energy management systems. However, current financial mechanisms are generally structured around individual property upgrades, with few incentives specifically designed to support bundled or coordinated investments at the neighbourhood level [30].

In sum, while the financial ecosystem in Genk and the broader Flemish region is relatively well-developed and outwardly supportive of renovation goals, it **falls short in addressing the systemic inefficiencies and social equity gaps** that are central to the PEN approach. A shift towards market incentives (e.g. public procurement, conditional subsidies, etc.) that explicitly value collective renovation, rapid deployment methods and tenant stability - particularly in the social housing sector - would allow for more impactful and rapid action. Addressing these market gaps is essential not only for achieving energy and climate objectives, but also for realising the broader co-benefits that PENs promise in terms of social well-being, affordability and urban resilience.

At the same time, the region must guard against what has been termed the "**pilot trap**": the recurrent cycle of investing substantial public funds into short-term demonstration projects that fail to produce systemic transformation. Too often, valuable insights generated through such initiatives are not institutionalised through policy or regulatory reform, leading to repetition rather than progression. Overcoming this "pilot trap" requires the establishment of robust learning frameworks, improved interdepartmental coordination and a commitment to embedding evidence from pilot experiences into long-term strategic planning and market design.

Regulatory setting[13]

The regulatory landscape shaping the development of PENs in Genk is a **complex interplay** between (1) multi-level governance structures (i.e. responsibilities), (2) evolving climate and energy policy goals, and (3) partial alignment with the core principles of the PEN approach - although there is no explicit legal mandate or dedicated regulatory category for PENs in Flanders or Belgium, several existing frameworks create an enabling environment for elements of the PEN concept, while others continue to present structural barriers.

At the institutional level, the decentralised governance model in Belgium places key PEN-related competencies - such as energy efficiency, building renovation, renewable energy development and local energy planning - under the authority of the **Flemish regional government** and **municipalities** like Genk [30]. This devolved structure provides important

[13] For more information about the regulatory frameworks relevant to Genk's PEN development, please refer to the oPEN Lab report *Towards a regulatory framework for positive energy neighbourhoods, Flanders (2024)* [30].

opportunities for local innovation and experimentation, particularly in the context of initiatives like the **Local Energy and Climate Pact (LEKP)**, which Genk has signed. The LEKP sets tangible targets, including one cooperative renewable energy project per 500 inhabitants and 50 collective renovations per 1,000 housing units by 2030, thus providing a quasi-regulatory framework that encourages neighbourhood-scale sustainable development [30]. However, the current round of LEKP subsidies is set to **expire in 2025**, raising concerns about the continuity of financial support for municipalities to pursue these objectives. Without a renewed funding mechanism or long-term policy commitment, there is a risk that local momentum and institutional learning generated under the LEKP will dissipate before its full potential can be realised.

The **strategic objectives set by regional and national climate and energy plans** also offer high-level alignment with the PEN model. These include the Flemish Energy and Climate Plan (VEKP) 2021–2030, which targets a 40% greenhouse gas (GHG) reduction in the ESR (Effort Sharing Regulation) sectors by 2030, and the Flemish Climate Strategy 2050, which aims for climate neutrality by mid-century. These regional objectives are nested within the national framework established by Belgium's draft updated National Energy and Climate Plan (NECP), which sets a 47% emissions reduction target in the ESR sectors and a 21.7% renewable energy share by 2030. [30]

In addition, the Flemish **Long-Term Renovation Strategy** (LTRS) has now been superseded by the **National Building Renovation Plans** (NBRPs) introduced under the EPBD. The NBRPs set out a comprehensive national roadmap for transforming the building stock by 2050 and, unlike earlier frameworks, explicitly require Member States to report on district- and neighbourhood-level renovation approaches. Annex II of Directive (EU) 2024/1275 [34] lists as a mandatory indicator "*the promotion of district and neighbourhood approaches and integrated renovation programmes at district level*," including energy, mobility, circularity, green infrastructure and broader urban planning considerations. Although the NBRPs do not prescribe PENs as a specific instrument, they establish a policy framework that directly supports the kind of integrated, multi-dimensional renovation efforts that PENs seek to deliver.

Despite this alignment at the strategic level, critical **regulatory barriers remain**, particularly in relation to **energy sharing and system integration**, which are essential to the PEN concept. Under current Flemish law, collective self-consumption is legally restricted to vertical apartment buildings, making it difficult to apply to the mixed and horizontally connected building configurations typical of neighbourhoods like those in Genk. Moreover, shared energy is not remunerated, while energy injected into the grid is, thereby discouraging local balancing strategies. In addition, energy storage systems face double taxation, and tariff structures meant to disincentivise peak demand may inadvertently penalise the electrification of heating, which is a cornerstone of low-carbon neighbourhoods. [30] These factors collectively undermine the economic and operational viability of decentralised, locally managed energy systems.

At the local level, **municipalities like Genk have several legal tools** at their disposal to support PEN-like interventions. These include the ability to adopt long-term renovation strategies, co-develop climate action plans under the LEKP and facilitate Living Labs, district renovation programmes or citizen energy cooperatives. Genk's own climate strategy aims to reduce CO_2 emissions by 40% by 2030, using 2011 as a baseline, reinforcing its commitment to sustainable transformation. [30] However, these instruments operate within cyclical funding programmes rather than systemic regulatory framework, meaning their continuity and scalability are contingent upon political will, temporary funding and administrative capacity.

A further gap in the current regulatory setting concerns the **absence of life-cycle carbon assessment and circularity requirements** in building renovation policies. Although the broader sustainability discourse around neighbourhood decarbonisation includes reducing embodied emissions, promoting prefabrication and encouraging material reuse, there are no mandatory requirements or structured incentives for considering whole-life carbon in the design and implementation of renovations [30]. This omission limits the ability of PENs to contribute fully to long-term decarbonisation goals and restricts innovation in sustainable construction practices. Nevertheless, bottom-up initiatives such as the **Tool to Optimise the Total Environmental impact of Materials** platform, developed by **OVAM** in collaboration with the regional authorities, represent an important step towards addressing this gap [35].

In sum, the regulatory setting for PEN development in Genk can be characterised as **enabling in principle, but fragmented in practice**. Strategic climate and energy goals at the national and regional levels provide a clear rationale for scaling up neighbourhood-level renovations and renewable energy deployment. Municipalities are legally empowered to act and initiatives like the LEKP offer useful frameworks for local coordination and goal-setting. Yet the absence of dedicated legal recognition for PENs, combined with restrictive rules on energy sharing, storage and life-cycle accounting, presents considerable challenges to full implementation.

To move from experimental pilots to mainstream deployment, the PEN model in Genk will require **a more cohesive and targeted regulatory framework**. This includes reforms to energy market rules that enable collective self-consumption beyond apartment buildings, the removal of fiscal disincentives for local storage and electrification and the integration of life-cycle criteria into public renovation funding. Until such adjustments are made, the development of PENs in Genk will remain dependent on local initiative, project-based funding and workarounds that do not yet benefit from a comprehensive legal foundation.

Physical setting[14]

The oPEN Living Lab in Genk is focused on a **suburban neighbourhood** composed of two distinct housing clusters: **the Waterschei garden city**, originally built to house coal miners, and the **Nieuw Texas social housing development**, constructed in the 1990s. Together, these areas offer a representative sample of typical Flemish residential architecture and urban layout, with a total of approximately 1,370 dwellings**,** 1,250 of which are semi-detached homes [3].

The Genk PEN neighbourhood is composed **entirely of residential buildings**. The focus on residential typologies reflects both the original design of the neighbourhood - which was developed to house mine workers and later, social housing tenants - and the strategic objective of upgrading energy performance in the most vulnerable segments of the housing stock [16]. This mono-functional profile enables the project to concentrate its technical and organisational innovations on the specific challenges of retrofitting existing dwellings, particularly in disadvantaged urban areas.

Although the area is functionally uniform, there is diversity in **ownership structure**, with both publicly owned social housing and privately owned homes included [3]. This mix allows the project to explore and compare different renovation governance models, funding arrangements and resident engagement strategies under real-life conditions. The resulting insights are intended to support the scaling of PEN models across other neighbourhoods where mixed ownership and tenure types may present additional implementation complexities [3].

Waterschei Garden City

[14] For more information about the physical frameworks relevant to Genk's PEN development, please refer to the oPEN Lab report *Overview of contracts, guidelines and best practices for value chain integration* (2023) [16].

The Waterschei area has strong historical and architectural significance. Established in the 1920s to house workers of the nearby **Waterschei coal mine**, which closed in 1987, the garden city is composed mainly of semi-detached brick houses, arranged in a characteristic geometry with uniform building materials and thermal properties. The neighbourhood exhibits low-density, green and residential typologies, with winding roads and communal green spaces in line with the garden city planning ideals of the early 20th century [16].

However, the historical value of the garden city presents **constraints on renovation practices**. Since no formal heritage framework had previously been established, the City of Genk adopted a conservative stance on granting renovation permits that might alter the visible character of the district. In response to interest from residents and the momentum generated by the oPEN Lab project, the city commissioned the University of Hasselt to develop a heritage renovation framework specifically for the Waterschei garden city. This new framework stipulates which architectural elements must be preserved and defines the allowable degrees of design freedom in order to balance heritage protection with energy performance improvements. As such, the oPEN Lab project serves as a testing ground for this framework, which on the risk side, may lead to higher renovation costs due to material and design restrictions. [2]

Within Waterschei, 7 of the 34 dwellings renovated under the oPEN Lab initiative are **privately owned homes** located in the garden city. These buildings underwent deep energy renovations within the boundaries of the newly adopted heritage framework [3].

Nieuw Texas social housing

The majority of renovation activity within the oPEN Lab in Genk is concentrated in Nieuw Texas, a **social housing development** built in the 1990s and located adjacent to the garden city. Nieuw Texas is composed of social housing units owned by a public housing corporation and features semi-detached homes, small building blocks and low-rise apartments, all constructed in brickwork and integrated harmoniously with the architectural character of the wider Waterschei district [16].

Nieuw Texas offers a particularly **favourable context for large-scale renovation experiments**. The uniformity in housing typology, materials and layout allows for the standardisation of renovation techniques, which can be tested under near-identical conditions. This supports technical comparisons of various building envelope upgrades, energy systems and renovation logistics. [3] A key feature of the renovation strategy in Nieuw Texas is the use of prefabricated building envelope components, which enables on-site installation with minimal disruption. The retrofitting works were designed for the tenants to remain in their homes during the retrofitting process, a crucial consideration for social housing settings where temporary displacement can cause hardship. [16] However, the intensity of certain renovation phases led to the introduction of flexible arrangements - giving residents the option to temporarily stay in a swap house or with family if preferred. This approach helped reduce renovation-related stress and ensured that social considerations remained central to the technical process. In total, 27 of the 34 homes selected for renovation under the oPEN Lab are located in Nieuw Texas [3].

Figure 11: Genk PEN neighbourhood. Source: Residential Living Lab Genk [36].

4.2.2. Cultures[15]

Waterschei is a **historically significant and socially vulnerable district** in Genk's north-eastern area. Genk itself, situated in the Flemish region of Belgium, has long been characterised by its post-industrial identity and is today considered one of the most economically disadvantaged cities in Flanders. The decline of the coal mining industry, once a major employer in the region, has left lasting socio-economic impacts, particularly in neighbourhoods like Waterschei where much of the housing stock was originally built to accommodate mine workers and their families. [3]

The city's economic challenges were further affected by the closure of the **Ford Genk automobile plant** in 2014, which resulted in the loss of over 4,000 direct jobs and thousands more in the supply chain. This event reinforced Genk's post-industrial profile and increased pressure on the local labour market, particularly affecting households with lower education levels and limited mobility.

Waterschei's population reflects **structural disadvantage**, including high unemployment rates and low-income households**.** These factors contribute to complex and intergenerational social challenges that must be addressed alongside technical energy renovations. [3] The neighbourhood is home to many low-income owner-occupants and social housing tenants, for whom deep renovation remains financially burdensome despite the availability of subsidies and targeted support through oPEN Lab and Flemish regional programmes. [2]

The economic vulnerability of residents directly affects the **organisational set-up of the PEN**. Many households lack the capital or creditworthiness needed to contribute to upfront costs, even when co-financing or support schemes are in place.

The neighbourhood's **linguistic diversity**, with residents speaking Dutch, Italian, Turkish, Arabic and Polish among others, requires an inclusive communication approach. In practice, this means using clear and accessible Dutch in written materials, and when necessary, encouraging residents to bring along a trusted relative, friend or community interpreter to help ensure that information is correctly understood and shared. Such measures strengthen trust and support meaningful participation across language boundaries.

Beyond the economic profile, Waterschei holds a **strong cultural and historical identity** rooted in its mining past and its legacy as a **garden city**. The original design of the

[15] For more information about the cultural aspects relevant to Genk's PEN development, please refer to the oPEN Lab report *Capacity-building handbook and mentoring report* [4].

neighbourhood - featuring winding roads, green spaces and semi-detached houses - continues to shape how residents perceive their environment. There is a shared sense of place and belonging linked to the architectural heritage and to long-standing community networks, many of which were formed in the era of the coal mines. [4]

In recognition of this cultural depth, the City of Genk collaborated with the University of Hasselt and oPEN Lab partners to explore how **renovation strategies can be aligned with local identities and values**. The University carried out a comprehensive study, including a detailed preliminary investigation into garden city characteristics and case studies from other European cities. As part of the research process, they conducted in-depth interviews with residents to assess their views on housing, heritage and the meaning they attach to their homes and neighbourhood. The findings of this research will feed into a **regulatory guidebook** that outlines how to carry out **heritage-sensitive renovations**. [4]

This necessitates a renovation approach that is heavily subsidised, technically supported and logistically non-disruptive - for example, through the use of prefabricated elements that allow tenants to remain in their homes during retrofitting. It also requires tailored engagement strategies that recognise the lived realities of the community, including language barriers, varying levels of digital literacy and differing degrees of trust in institutions.

4.2.3. Networks

A key initiative within Genk's local energy transition ecosystem is **GEENkool** [37], a city-led energy coalition launched in partnership with EnergyVille and EIT InnoEnergy in 2021. The coalition's name ("no coal") reflects its overarching goal: to support the City of Genk in becoming climate neutral by 2050. GEENkool serves as a multi-stakeholder platform, bringing together local companies, research institutions and citizens to co-create a tailored energy roadmap for the city. Its emphasis on broad community engagement and integrated planning makes it a natural complement to the oPEN Lab initiative, which operates at the neighbourhood scale but draws on many of the same principles of co-creation, innovation and system integration.

The organisational ecosystem surrounding the Genk PEN is strongly anchored in **Thor Park** [38], a prominent innovation campus located on the former Waterschei coal mine site. Thor Park hosts a cluster of research, education and business actors working on energy, smart manufacturing and sustainable building technologies, and serves as a physical and symbolic hub for Genk's post-industrial transformation. The park is home to several strategic institutions, including EnergyVille - a collaboration between KU Leuven, VITO, imec and the University of Hasselt - which plays a central role in the oPEN Lab initiative by providing technological expertise, simulation tools and monitoring infrastructure.

Closely linked to Thor Park is **Open Thor Living Lab** [39], a state-of-the-art testing ground for smart energy systems, digital infrastructure and sustainable building solutions. Operated by VITO and EnergyVille, Open Thor enables companies and researchers to experiment with real-life energy technologies in a multi-energy microgrid environment. It is one of the few sites in Europe capable of testing energy innovations at the neighbourhood scale, making it directly relevant for the development and replication of PEN concepts. The experimental and applied knowledge generated at Open Thor supports oPEN Lab activities in Waterschei by offering validated solutions, modelling tools and expertise in integrated system design, user engagement and data-driven decision-making. Through these linkages, the Genk PEN becomes part of a larger, future-oriented innovation ecosystem.

4.3. oPEN Living Lab Genk

This section explores how the Genk PEN has been organised and implemented through a Living Lab approach that brings together public, private and civic actors in a shared governance structure. It also presents the technical solutions demonstrated in the neighbourhood, highlighting the renovation strategies, energy technologies and integrated systems that make up the core of Genk's energy-positive transformation.

Figure 12: Chapter 4.3 explores the Living Lab level in Genk. Source: authors.

4.3.1. Organisation[16]

The oPEN Living Lab Genk is one of the key demonstration sites within the broader oPEN Lab project, showcasing how PENs can be developed in **socially diverse and historically layered urban areas**. Located in the Waterschei district, the Living Lab leverages both physical assets - such as social and heritage housing - and a dense network of public, private, civic and research stakeholders. The overarching aim is to create a sustainable, healthy and inclusive neighbourhood while testing and refining scalable solutions for renovation, energy systems and citizen engagement. [40] The Living Lab integrates technological design with participatory processes, serving as a platform for collaborative innovation.

Stakeholder roles and governance

The Living Lab is geographically rooted in three sub-areas within the Waterschei neighbourhood: Nieuw Texas, the Garden City quarter and the surrounding neighbourhood infrastructure, including public space and local energy systems. Each of these sub-areas has its **own governance structure**, yet all fall under the coordinated oversight of **VITO**, which acts as the Hosting Organisation for the Living Lab [4]. The spatial distinction between the social housing and private segments reflects the need for tailored engagement models, financing schemes and renovation strategies across different user profiles.

The oPEN Living Lab Genk is made up of a **broad coalition of actors**, including public authorities, housing organisations, research institutions, technology providers, NGOs and residents themselves. Among the core organisations involved are [3]:

- **City of Genk** – Local authority responsible for urban planning, heritage regulation and citizen engagement;
- **VITO** – Research institution and Living Lab host, leading technical coordination and innovation governance;
- **EnergyVille** – Providing expertise on energy systems and smart infrastructure;
- **Stebo** – Supporting social innovation, resident engagement and capacity building;

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[16] For more information about the Genk Living Lab setup, please refer to the oPEN Lab report *Capacity-building handbook and mentoring report* (2023) [4].

- **Wonen in Limburg** – Social housing company managing dwellings in Nieuw Texas, actively contributing to social innovation and resident engagement through co-design processes, communication with tenants and tailored renovation approaches;
- **Private companies** – Construction firms, technology providers, ESCO companies and materials manufacturers;
- **NGOs and researchers** – Ensuring the integration of inclusive practices and scientific knowledge.

Each actor brings **distinct objectives** into the Living Lab. For example, technology providers aim to test solutions in real-life settings and explore new market segments; social housing corporations focus on delivering high-performance, low-disruption renovations to vulnerable populations; and researchers seek to generate scientific insights while supporting community-level energy innovation. [3]

Citizen engagement and co-creation

Central to the Living Lab model is the **active involvement of end users**, especially residents of Nieuw Texas and the Garden City area. The project explicitly recognises that deep renovations and energy transitions cannot succeed without the trust, participation and ownership of those directly affected.

A **comprehensive co-design process** was developed for both social and private housing contexts. In Nieuw Texas, co-creation was structured around the **Appreciative Inquiry** method and progressed through a **"Genk Timeline"** of engagement moments. These included workshops, home visits, feedback loops and ideation sessions where residents helped shape renovation priorities and building technologies. [40] A dedicated anchor house served as a neighbourhood contact point throughout the renovation process.

In addition to the Appreciative Inquiry and one-on-one coaching formats, a **broader set of engagement tools** were applied to ensure inclusive participation. These include simple-language communication materials, translated summaries, visual step-by-step guides and information sessions with residents or accompanying family members where needed. Feedback loops are supported by surveys, storytelling workshops and informal neighbourhood meetings. Together, these methods help bridge language, trust and digital literacy barriers while ensuring that residents feel heard and supported throughout the process. A **key lesson** from this approach is that clear, accessible communication and personal follow-up are as critical to the success of energy renovations as the technical innovations themselves.

Waterschei, by contrast, required a **tailored, one-on-one approach** due to the diversity of ownership profiles and housing conditions. STEBO offered personalised renovation coaching covering technical, financial and legal advice. A visual "postcard campaign" and in-home demonstration sessions were used to raise awareness and trigger renovation interest during key life events (e.g., home purchase or family expansion) [40].

The co-design process helped **align technological solutions** - such as energy boxes, PV systems and thermal storage - with user needs and building typologies. Feedback from residents was directly integrated into technical specifications and procurement documentation, ensuring real-world relevance.

Even though the renovation works are close to complete, the **community engagement activities are still ongoing** in Nieuw Texas and Waterschei. The main goals for these activities are to educate the people on how to live in an energy-efficient building (tips for occupant behaviour) as well as retrieving feedback on the usability and comfort of the new techniques.

The effort to **find common ground** between the different experimentation zones - Nieuw Texas and the Garden City - also illustrates the need for **a shared narrative**. Discussions are ongoing about implementing collective infrastructure (e.g. shared energy systems or public amenities) as a way to build unity and make the PEN concept more tangible and cohesive across the diverse sub-areas. [2]

4.3.2. Technological solutions[17]

The technological backbone of the Genk PEN is based on a twofold strategy: combining **highly energy-efficient building renovations** with the **optimal control of innovative building systems** at both individual household and neighbourhood scale [4]. These innovations are deployed through a **collective renovation concept**, applicable to both social rental and private homes. Importantly, the approach accommodates differentiated ownership structures and seeks to balance standardisation with flexibility, enabling customisation within a scalable model.

The objectives of the Genk PEN demonstration are [4] [16]:

- To renovate **34 houses** (27 social housing units in Nieuw Texas and 7 private homes in the Waterschei Garden City area) up to energy-positive buildings;
- To **test, monitor and compare** various renovation packages and renewable energy technologies;
- To provide a **testbed for future innovations**, using the neighbourhood as a Living Lab;
- To inform the creation of **general guidelines** for the design and scaling of PENs across similar contexts.

The renovation works are grouped into two main categories [4] [16]. Together, these components form **solution packages** that are deployed across different homes in the lab. Each house, while identical in envelope design, receives a unique combination of building systems. This experimental diversity enables precise comparative performance analysis under standardised conditions [4].

- **Building envelope**:
  - Renovation of walls, roofs, windows and doors.
  - Use of **prefabricated insulated shells** for consistent and efficient retrofitting.
  - These shells standardise the building's thermal envelope while minimising disruption, allowing tenants to remain in their homes during the renovation.
- **Building technologies**:
  - Integration of key energy technologies in one prefabricated energy box, including:
    - Heat pumps (air-sourced and ground-sourced);
    - Renewable energy systems such as Building Attached PV, Building Integrated Photovoltaics (BIPV), PV Thermal panels and solar thermal collectors;
    - Thermal and electrical storage units;
    - Ventilation systems;
    - Heat emission systems like underfloor heating, radiators, fan coils and infrared panels;
    - Control systems and sensors for monitoring and optimisation.

[17] For more information about the prefabrication processes, please refer to the oPEN Lab report *Optimization of the prefabrication process through digitalization* (2023) [89].

    - Each energy box has a unique combination of technologies, where two main types can be distinguished:
        - Individual energy boxes, serving one household;
        - Collective energy boxes, serving two to four households.
- **District technologies:**
    - District PV, with artistic print;
    - District infrastructure with district battery, district PV, EV charging points, pick-nick banks, etc.

Figure 13: Renovation process in Genk. Source: VITO.

One of the most innovative aspects of the Genk PEN is the use of **plug-and-play "energy boxes"**. These compact, external units house the integrated set of technologies - heat pump, inverter, battery and ventilation system - and serve multiple semi-detached homes simultaneously. By concentrating infrastructure in an external module, this solution reduces the need for invasive in-home retrofitting and simplifies ongoing maintenance. It also increases flexibility, allowing system components to be upgraded or replaced without major disruption. These energy boxes, in conjunction with smart meters and control platforms, form the basis for automated energy management at both building and district level. [1]

All technological interventions are embedded within a **neighbourhood-wide energy management system** that enables real-time data exchange, demand-side flexibility and predictive energy optimisation. The system integrates weather forecasts, dynamic energy tariffs (e.g. day-ahead electricity prices), occupancy and comfort parameters and energy usage data from individual dwellings. This data-driven infrastructure supports bidirectional communication between individual buildings and the energy management platform, enabling automated control of heating, cooling, storage and consumption. The system can shift energy loads to times when electricity is cheapest, while still ensuring comfort for each household. Different homes can follow distinct schedules, thereby distributing the energy load across the district efficiently. [1]

Notably, the oPEN Living Lab in Genk **does not aim to change active user behaviour**. Instead, automation is leveraged to optimise energy performance while keeping the user experience passive, thus lowering the barrier to adoption and reducing reliance on behavioural change. [1]

In **Nieuw Texas**, 27 social housing units were renovated while residents remained on site. Each unit received a standardised envelope retrofit with a distinct internal configuration. Communication with tenants was essential to minimise disruption and build trust in this vulnerable community. [16] In **Waterschei**, private homes participate voluntarily. Homeowners must first invest in envelope renovations to prepare the dwelling for heat pumps. The project partners then invest in energy systems such as PV, ventilation and control systems. [2] This model highlights the challenges of working in mixed-ownership neighbourhoods, calling for tailored financing and personalised engagement.

The renovation works were informed by detailed **technical planning and tendering processes** [40]. A concept note and technology matrix guided the selection and combination of systems for each home, with a focus on modularity and future readiness (e.g. EV charging and district cooling networks). The design made by the architects also incorporated input from citizens collected in co-creation sessions. Coordination challenges between separately tendered envelope and technology works were addressed by requiring time and budget for joint planning in the tender specifications.

At **district level**, the project explores shared infrastructure such as BIPV systems, collective storage, smart control systems and an energy community for surplus sharing. Design decisions are shaped by citizen engagement and technical feasibility studies. Integration of smart canopies and mobility options (e.g. EV sharing) supports broader community objectives.

Shared investments

Wonen in Limburg (WiL), the social housing corporation, is responsible for the **building envelope renovations**, ensuring improvements to insulation, roofing, doors and windows. These renovation activities follow public procurement rules as required by the Flemish Association of Social Housing (Wonen in Vlaanderen), ensuring transparency and compliance with state aid frameworks. [16]

Meanwhile, **VITO** as a key technical and research partner within EnergyVille, oversees the **integration, provision and operation of the building technologies**. These include photovoltaic systems, heat pumps (individual and collective), home batteries, thermal storage and building energy management systems. These technologies are housed in **external prefabricated energy boxes**, which enable plug-and-play installation and reduce disruptions during retrofitting. [16]

For the privately owned homes in the adjacent Waterschei Garden City, homeowners themselves are responsible for funding and implementing envelope renovations. VITO will still provide and manage the energy technologies, but the project partners are not involved in direct decision-making, meaning progress depends on each household's willingness and financial capacity. Therefore, this sub-project is treated separately in the operational structure. [16]

4.4. Moving towards an organisational PEN model in Genk

This chapter explores the **potential organisational models** for a future Genk PEN, drawing on lessons learned from the living lab in Genk. While a fully developed PEN is not yet in place in the pilot area, the discussion outlines possible approaches to governance, operations, financing and ownership that could support long-term sustainability. Based on insights from local experiences and stakeholder interactions, the proposed framework represents an informed, assumption-based projection of how a PEN in Genk might be structured to manage energy renovation and innovation at neighbourhood scale.

Figure 14: Chapter 4.4 explores the PEN level in Genk. Source: authors.

4.4.1. PEN vision

The Genk PEN is not just a technical experiment, it is the story of two neighbourhoods in Waterschei as they move from a legacy of coal mining towards a future shaped by energy innovation, social inclusion and community resilience. **Nieuw Texas** is a dense cluster of social housing, whereas the **Garden City area** is a neighbourhood of privately owned, semi-detached homes built for coal miners and their families. Despite their differences in ownership and age, these two areas are bound together by a common purpose: to demonstrate that **a neighbourhood can become energy positive** - not only reducing its energy demand and carbon footprint but producing more renewable energy than it consumes yearly.

At the heart of the Genk PEN are **innovative technical solutions** and new forms of neighbourhood collaboration. The insights of the oPEN Living Lab will be used to formulate recommendations on which renovation measures should take place in both social rental or private homes. A follow-up trajectory is being set up to explore collective renovation strategies and refine the heritage framework of the Garden City dwellings. Currently the question remains whether all dwellings in the district need deep renovation such as the living lab houses, including the installation of prefabricated insulated envelopes, heat pumps, ventilation, solar panels, batteries and smart systems. The renovations should be tailored to each home. However, all houses of the PEN should be linked through a **neighbourhood energy management system** that connects individual buildings into a virtual microgrid. This means that homes in both Nieuw Texas and Waterschei Garden City can share locally produced energy, balance supply and demand, and respond to real-time price signals or weather forecasts. The neighbourhood as a whole becomes more than the sum of its parts: it is a living, adaptive system where **residents, buildings and technologies interact** to create a net positive energy outcome for the community.

The transformation into a PEN began with the first wave of deep renovations in Nieuw Texas and private homes in the Garden City, with most renovation works already completed (30 out of 34 renovations). The oPEN Lab project aims to achieve **energy positivity** for these 34 houses through a combination of energy-efficient renovation and on-site renewable production. But the vision goes further: by 2050, under the GEENkool roadmap, Genk aspires to be a **climate neutral city**, using the experience and lessons learned in Waterschei as a blueprint for the rest of the city and beyond. Moreover, other projects that go beyond energy transition are currently also ongoing in Waterschei. One example is **Waterrijk Waterschei** [41]**,** a project that focuses on reducing stormwater overflows, replenishing the groundwater reserves, increasing green space and biodiversity and improving the overall living environment in Waterschei. Its key goals are to implement nature-based solutions for rainwater infiltration and reuse, preventing both drought and water-overload impacts, and engaging residents in water-wise behaviour and neighbourhood adaptation. All initiatives to support the climate transition in Waterschei are coupled in the framework of **“Missie Waterschei”** [42]**.**

An important pillar of the Genk PEN is to create a **sense of community trust and agency**. Through open dialogue, co-creation sessions, home visits and testimonials, residents are brought into the centre of the process, helping to shape the solutions that affect their daily lives. The shared story that is emerging is one of **collective progress**: from a past defined by fossil energy and social division, to a future where homes, technologies and people work together to achieve energy self-sufficiency and comfort. As such, the narrative of the Genk PEN is about **turning a legacy of coal into a future powered by community-driven innovation**. The **"Genk Groeit" programme** [43] is a running project which illustrates very well the importance of community engagement for the city of Genk. This project aims to spark curiosity and learning around technology and energy in the neighbourhoods of Nieuw Texas and Waterschei by creating a low-threshold learning ecosystem that connects local residents with the core themes of energy and engineering.

4.4.2. Governance structure and models

The governance model of the Genk PEN should reflect a multi-level, collaborative approach embedded in the city's long-term sustainability and climate-neutrality agenda. A starting point to shape this governance is the **oPEN Living Lab Genk**, which functions as a vehicle for aligning and coordinating stakeholders across public, private, academic and civic sectors in the implementation of integrated energy transition strategies at the neighbourhood level. Beyond coordinating building renovations and the deployment of smart technologies, the governance system of the PEN should also facilitate co-creation, innovation testing and citizen engagement to advance a fair and future-proof built environment.

Roles and responsibilities

Local government. The **City of Genk** plays a central role in shaping the policy and regulatory environment for the PEN. It is involved in visioning, planning and legislative alignment activities and ensures that PEN initiatives remain consistent with the broader climate targets set in the city's 2030 strategy and the GEENkool roadmap towards climate neutrality by 2050. [3] [1] The municipality also coordinates with stakeholders through bilateral discussions and co-creation sessions to identify renovation locations, remove legal obstacles and ensure the integration of social goals such as energy affordability and housing preservation. However, many of the key energy and building regulations that shape these actions fall under regional-level competence, which limits the extent of municipal decision-making.

Citizens and building owners. Residents, including private owner-occupants and social housing tenants in Nieuw Texas and Waterschei, are active participants in the governance model. While private owners make renovation decisions independently, tenants are engaged through structured co-creation formats such as home visits, interviews and ideation sessions, helping shift the model towards more inclusive governance and participation. [3] Recent co-design activities in Nieuw Texas have also enabled residents to contribute to shaping shared infrastructure, including district batteries, PV systems, EV charging stations and community spaces, ensuring that new installations meet both technical and social expectations. [40]

Civil services, like (1) SAAMO [44], which focuses on community development for vulnerable citizens, (2) Stebo [45], which empowers socially vulnerable individuals (especially migrants and low-income groups) by supporting their access to housing, work, learning and entrepreneurship opportunities, and (3) energy houses, who give renovation advice, are also key stakeholders in the PEN governance model.

Private sector and energy providers. Private sector actors include **technology providers**, **construction companies** and **energy solution providers**. Their role is to implement state-of-the-art technologies and support residents in adopting and using these solutions. In the oPEN Living Lab Genk, renovation technologies – such as prefabricated building envelopes, PV panels and demand-side energy management systems – are tested in real-life conditions, enabling industrial partners to refine their products and approaches. The insights gained from this process can also inform PEN development in other contexts.

Research and academia. Institutions such as **VITO**, **EnergyVille** and **the University of Hasselt** are crucial governance actors responsible for coordinating the Living Lab structure, data analysis and innovation management. VITO acts as the **host organisation** of the residential Living Lab and is developing tools for the technical coordination of a PEN (District Energy Management System, Wijkrenovatietool [46], SmarThor data platform [47] etc.). Academic partners also feed scientific knowledge and field data into policy recommendations and contribute to the replication of the model beyond Genk.

Decision-making processes

The decision-making in Genk's PEN still needs to be developed, but the governance structure of the Living Lab shows that it should be **shared across multiple stakeholder groups**, depending on the domain. The current decision-making process in the oPEN Living Lab Genk is the following [3]:

- **VITO** leads technological decisions and coordinates smart energy systems and innovation strategies.
- **The City of Genk, Stebo** and social housing company **Wonen in Limburg** lead the social and community engagement side of governance.
- **Private and social housing owners** hold the authority to approve and implement building renovations.
- **Technical partners** determine the feasibility of integrating micro-grid technologies and other energy systems.

Although the governance structure is still evolving, efforts are being made to create a **balanced decision-making process** through bilateral city-partner meetings, bi-yearly governance board meetings and co-creation activities with all stakeholders. As such, the governance style can be described as a **hybrid model** that blends hierarchical and participatory elements - leveraging public leadership with stakeholder engagement and multi-actor collaboration.

Collaborative governance and networks

Genk's PEN governance will incorporate **various forms of collaborative governance**, including emerging coalitions. The governance model includes amongst others:

- The **oPEN Living Lab** itself acts as a platform for aligning housing, energy, technology and community stakeholders in a unified operational structure.
- **Flux50's Learning Network**, coordinated with support from VITO, WiL and the City of Genk, connects municipalities, energy companies, technology providers and cooperatives to explore governance, data ownership and legal barriers to energy communities. These networks deepen knowledge exchange and support long-term capacity-building. [40]
- While synergies between the **oPEN Lab** and **Open Thor Living Lab** are still being defined, their co-existence underlines a broader ambition to institutionalise multi-stakeholder collaboration in Genk [3].

Social innovation

The Genk PEN will support various forms of **social innovation**, particularly through citizen participation and the idea of **PEN as a service**. This model proposes energy systems that are collectively owned and managed, with services offered to residents without the need for individual up-front investment. It leverages real-life testing to design inclusive business models, encouraging a fair energy transition. [4]

Although **energy sharing** is not yet fully realised due to legal and market barriers, there is an ambition to test **collective self-consumption models**, especially for social housing, in the future. Such innovations can be seen as steps towards a more participatory and decentralised energy governance system.

Integrated planning

The governance model in Genk will embed elements of **integrated planning** by aligning spatial, energy and community development strategies. This is evident in the Waterschei neighbourhood, where energy retrofits are combined with heritage preservation, social housing upgrades and public infrastructure improvements [2]. The City's 2030 climate strategy and long-term renovation roadmap serve as guiding frameworks for these spatial-energy-community linkages. Furthermore, the coordination between local development plans and the GEENkool roadmap reinforces a unified approach to spatial and environmental planning at city scale. [1]

Integrated decision-making

Decision-making in the PEN will build on **cross-sector coordination** among residents, social housing associations, technology partners, researchers and municipal authorities. The governance model should facilitate iterative decision-making through participatory design processes, feedback loops and adaptive planning. While key technical and legal decisions remain within the domain of formal stakeholders (e.g., VITO, Genk City Council), social processes - such as co-design workshops and citizen testimonials - are increasingly shaping the direction of the project. [3] A balance is sought between top-down project delivery and bottom-up input, particularly in social housing contexts where tenants are often excluded from traditional decision-making.

Strategic development and future orientation

Plans are in place to transition the Genk Living Lab into a **more formalised structure** beyond the oPEN Lab project's lifetime. A future governance setup may involve shareholders from institutions such as VITO, EnergyVille NV, Wonen in Limburg and Thor Park. An **Innovation Committee** is under consideration to guide future project selection and maintain a balance between technological performance and social inclusion. [3]

At the same time, challenges persist in aligning the Genk Living Lab with the broader **Open Thor Living Lab**, as their stakeholder bases and objectives differ. These divergences may affect how governance is scaled or replicated in future initiatives. However, the Genk Living Lab remains deeply anchored in the city's strategic goals, such as the GEENkool roadmap, and serves as a local testbed for regulatory innovation, energy citizenship and multi-level collaboration.

4.4.3. Operational models

The operational model of the Genk PEN is designed to demonstrate how local energy production, distribution and consumption can be managed at the neighbourhood scale. It seeks to combine technical innovation with real-life functionality in both public and private housing contexts, underpinned by collaborative partnerships in the wider PEN ecosystem.

Management processes

In Genk, the energy system is managed through a distributed, yet highly coordinated operational setup. Energy production is based on on-site renewable sources, particularly solar PV, installed on social housing units in the Nieuw Texas neighbourhood. The excess electricity generated is envisioned to be shared through the establishment of a Renewable Energy Community (REC), allowing redistribution either to public infrastructure or neighbouring households that are not part of the oPEN Living Lab itself.

Energy systems integration

A key operational innovation in Genk is the smart integration of renewable energy production, storage and demand-side management through a connected infrastructure designed to enable **multi-vector energy integration**. The strategy operates both at the building and neighbourhood levels. At the individual building scale, houses are disconnected from the gas network, with energy needs reduced through improved insulation, efficient heating and ventilation systems. Locally installed PV systems and heat pumps provide the renewable energy backbone for each home, supported by thermal storage and batteries, in some cases integrated into modular “energy boxes”. [48]

At the neighbourhood level, a collective infrastructure with district PV, district battery and EV sharing stations can be controlled to improve the energy flexibility of the neighbourhood and decrease high peaks of energy demand or solar energy production. These individual and collective systems will be connected to a central data platform and the **neighbourhood energy management system**, which facilitates system-wide energy flow coordination. [48] The energy flow begins with electricity sourced from rooftop PV or the grid, which is converted into heat or cooling and distributed to the homes, with energy buffered in local storage systems.

Each dwelling may operate with a slightly different schedule based on occupancy and daily routines, but the integrated control system balances these variations to achieve optimal performance at the district scale. Nevertheless, current regulatory and infrastructural barriers remain a limitation for expanding collective self-consumption models within the neighbourhood. [48]

Maintenance and monitoring

In Genk, all installed technologies of the oPEN Living Lab houses are continuously monitored through a **digital infrastructure** operated by VITO and partners. Data from each dwelling - covering energy use, indoor climate and system performance - are transmitted via local HVAC controllers and gateways to central platforms (Cast4All SIMPL and EnergyVille’s SmarThor), where they are processed and analysed. This ensures proactive system optimisation, fault detection and a continuous feedback loop between residents, researchers and technology providers. [40]

However, it is not feasible to install over 200 sensors (similar to the oPEN Living Lab Genk houses) in all dwellings of the Waterschei district: the investment costs for these sensors and the maintenance costs of the data platform would be too high, while the added value would be limited. Therefore, follow-up research is required to **identify which key parameters are crucial** to monitor and control to feed into tools such as district energy management system or a predictive maintenance system for the PEN.

Renewable Energy Community (REC) model

The Genk PEN also aims to evolve into a REC, where surplus energy generated in the Living Lab (especially in Nieuw Texas) can be shared with non-participating neighbours and potentially with the wider community infrastructure. **Wonen in Limburg** seeks to extend this surplus electricity access to other tenants who are not currently involved in the Living Lab.

However, despite the technical feasibility, there are significant **regulatory and administrative hurdles** to implementing this model in Flanders. As identified by **Flux50's Learning Network** on energy communities and energy sharing, setting up an REC in Flanders entails:

- High administrative fees (up to 150 euros per customer per year) from energy suppliers, threatening the financial viability of small RECs;
- Limited financial incentives (e.g. Flanders does not offer the distribution cost reductions that are available in Wallonia and Brussels);
- Legal uncertainty regarding value added tax and asset ownership;
- Lack of clarity around the transposition of EU energy-sharing regulations;
- Regulatory requirements that prohibit offering energy at reduced or free prices, in contrast to the EU Decree.

Despite these obstacles, the Genk case is actively contributing to broader **policy learning**. Real-time data from Genk is being shared within the **Flux50 Learning Network**, influencing discussions with policymakers (e.g. VEKA, Flemish Energy Agency) and contributing to the design of fair, grid-friendly and socially inclusive energy systems. Moreover, Technical Assistance Hubs have been set up by the Flemish government to support cities like Genk in navigating these complex regulatory landscapes and rolling out RECs.

As such, the Genk PEN's operational model is characterised by a hybrid system of public, private and research-led actors working together to deploy and manage innovative building and energy technologies. Its ambition to become a fully integrated REC is constrained by the current legal and economic framework in Flanders, but nonetheless, it operates as a **real-life testbed** for future energy systems.

4.4.4. Financial models

In the current model of the oPEN Living Lab Genk, **VITO** financed the acquisition and operation of energy technologies, monitoring systems and control infrastructure, while **Wonen in Limburg** (the social housing association) covered the costs of building envelope renovations. For the private homeowners in **Garden City Waterschei**, the same principle is maintained: VITO invested in the energy technologies and related assets, while the homeowners covered the costs of the building envelope renovations. These investments are complemented by support from the **European Commission and oPEN Lab consortium partners**, which funds both research and selected assets under the oPEN Lab framework, enabling innovation testing and scalability. [4]

With the financial model of the Living Lab as example, the financial model of the Genk PEN should be built as well on a **multi-source funding structure** that combines public, private and research-based contributions.

Genk PEN as a service model

The **Genk PEN as a service** model aims to represent a key approach designed to facilitate collective energy renovation and empower multiple stakeholders through shared value creation and risk mitigation [4].

A major challenge in the Genk context is the **lack of available funding and accessible financial products** for deep energy renovation, particularly for low-income households and social housing tenants. At the same time, the renovation sector faces a lack of real-life testing environments for near-to-market innovations, as well as a gap in resident trust and awareness regarding the benefits of renovation. The PEN as a service model could address these issues by leveraging the collective scale of neighbourhood renovation, sharing costs and benefits across partners and generating new revenue streams from innovation, data and services.

At the heart of the PEN as a service model is the role of a **trustworthy, independent party** who acts as a **facilitator, aggregator and quality assurer**. This party coordinates collaboration among residents, housing associations, industrial partners and public authorities.

The financial model recognises a diversity of users and customers, each with different needs and potential revenue streams. **Housing associations** receive advice on renovation portfolios, methods, feasibility and can participate in collective procurement and service contracts. **Industrial partners** gain access to real-life testing and demonstration, improve offerings and develop scalable solutions through product and service monitoring. **Data Users -** industrial partners, policy makers and researchers - benefit from granular performance and behavioural data, enabling further R&D and policy innovation. **Energy Users -** tenants and private homeowners - benefit from improved comfort, reduced bills and participation in energy communities without the need for upfront investment or individual project management.

Potential core stakeholders in the Genk PEN as a Service model include **VITO** (Living Lab host, technical integrator), **Wonen in Limburg Social Housing Association** and its residents, **private housing residents**, **Stebo** (energy agency supporting engagement and outreach), **City of Genk** (urban planning, policy support), **Industrial partners** (product and solution providers) and **EU, local, regional, and national policymakers** (enabling regulatory and funding environment).

To deliver on its value proposition, the PEN as a service operator undertakes:

- **Integration of existing infrastructure with new energy devices** into tailored solution packages for buildings and neighbourhoods.
- **Advice and consultancy** for housing associations and residents, including financial models, feasibility studies and project management.
- **Research and development** in smart controls, Internet of Things applications, building energy management systems and new prototypes.
- **Product and service testing**, monitoring and validation for industrial partners and market readiness.
- **Data analysis and processing** to create feedback loops for innovation, policy and performance improvement.

The business model can be sustained through a combination of **membership fees** (charged to participating organisations, industrial partners or energy communities for access to the Living Lab platform and services), **asset acquisition** (investment in energy devices, prefabricated renovation elements and other infrastructure), **data platform fees** (covering the costs of maintaining and operating the digital backbone of the Living Lab, **building and lab use fees** (rental or usage charges for test environments and demonstration projects) and **consultancy fees** (income from advisory services, project management and technical support).

By aggregating demand and supply, the Genk PEN as a service model could improve the **viability and financial attractiveness** of renovation projects. The service model can reduce transaction costs, enable **collective procurement** and de-risk investment for both housing providers and technology suppliers. For industrial partners, participation accelerates **product development and market acceptance**. The continuous testing and validation cycle ensures that innovations can be refined and scaled up, with lessons learned feeding directly into policy and wider market development. Finally, as data and experience accumulate, the PEN as a

Service model can be replicated across new neighbourhoods, helping to mainstream positive energy solutions and unlock further investment for the energy transition. [4]

4.4.5. Ownership models

The Genk PEN needs to adopt a **hybrid ownership model** that reflects the different types of stakeholders involved. In this setup, the building owners - both Wonen in Limburg and private homeowners - retain ownership and responsibility for their buildings and physical renovations. The **technical systems** – such as PV panels, batteries, heat pumps, ventilation and monitoring infrastructure – can be funded by an **"energy as a service" model**, whereby energy technologies are offered to housing owners without requiring upfront investment from them. [3] This approach allows both social and private housing residents to benefit from improved comfort and lower energy bills, while retaining accessibility. The model also enables shared responsibility and ensures that both technological and operational decisions are aligned with user needs, market flows and research goals. [49]

4.5. Summary of the emerging Genk organisational PEN model

Genk presents a compelling case for analysing PEN development in a post-industrial city transitioning towards a low-carbon and knowledge-based economy. The city's historical dependence on heavy industry has shaped both its physical fabric and institutional mindset, resulting in a strong municipal leadership role and an evolving ecosystem of collaboration with universities, housing associations and private actors. The Genk case is analytically interesting as it illustrates how a **policy-driven innovation approach** can foster systemic transformation in a context marked by socioeconomic challenges and legacy infrastructure.

4.5.1. Context level

Genk offers a **strong, but fragmented foundation** for PEN development. Ambitious policies, capable institutions and dedicated funding support renovation, but frameworks remain focused on individual buildings rather than neighbourhood-scale solutions. The city's **post-industrial and multicultural character** demands inclusive, socially aware approaches that build on residents' strong sense of place and community. A robust **innovation network**, centred on Thor Park and EnergyVille, drives technical progress, but greater citizen and SME involvement is needed. Overall, Genk's context is **policy-driven and institutionally strong**, though scaling PENs will require better financial alignment, regulatory reform and social inclusion.

Structures

Genk's structural environment combines strong policy ambition with practical constraints that limit the full rollout of PENs. The **economic setting** features well-developed renovation incentives and social housing subsidies, but these remain geared towards individual buildings rather than collective, neighbourhood-scale solutions. Prefabricated renovation approaches - well-suited to Genk's social housing stock - are not yet adequately supported, and lower-income households still face barriers to accessing financial schemes.

The **regulatory framework** provides high-level alignment with PEN goals through the Flemish and national climate plans and the Local Energy and Climate Pact. However, lack of energy sharing legal frameworks, storage double grid taxation and lack of life-cycle carbon minimum requirements remain key bottlenecks. Existing tools enable local action but lack long-term stability and coherence.

The **physical context** - the Waterschei garden city and Nieuw Texas housing estate - offers an ideal testing ground for integrated renovation, combining heritage-sensitive private homes with standardised social housing typologies.

Overall, Genk benefits from a **supportive, but fragmented enabling framework** - strong municipal leadership and policy direction exist, but systemic progress depends on bridging financial, regulatory and institutional gaps to scale neighbourhood-level renovation and energy management.

Cultures

Genk's cultural setting is shaped by its **post-industrial legacy**, marked by the decline of mining and manufacturing and the resulting socioeconomic vulnerability of neighbourhoods like Waterschei. The area faces limited financial capacity for renovation, making energy transition efforts inseparable from broader social concerns. Its **multilingual and multicultural composition** requires inclusive, trust-based communication tailored to different literacy and language levels. At the same time, Waterschei's **strong sense of place and heritage**, rooted in its mining history and garden city layout, **fosters attachment and community cohesion that can support collective action**.

As such, the cultural context in Genk is characterised by **socially responsive renovation**: success depends on combining technical innovation with trust-building, inclusion and sensitivity to historical and cultural meaning.

Networks

Genk's energy transition is driven by a **strong institutional network** linking the municipality, research actors and industry. The city-led GREENkool coalition, created with EnergyVille and EIT InnoEnergy, coordinates stakeholders towards climate neutrality by 2050 and complements oPEN Lab's neighbourhood-scale work.

At the core of this ecosystem is **Thor Park**, the former mining site transformed into a hub for clean-tech innovation. It hosts EnergyVille and the Open Thor Living Lab, which provide advanced research, testing and simulation capacities directly supporting PEN development.

Genk's well-established partnerships and shared infrastructure are **major enablers** for the PEN. However, broadening engagement beyond institutional actors - especially to residents and local SMEs - remains crucial for long-term inclusiveness and replication.

4.5.2. oPEN Living Lab level

The oPEN Living Lab in Genk functions as an **intermediary structure** linking citywide climate ambitions with practical experimentation at the neighbourhood scale. It provides a platform where policy, technology and citizen engagement intersect, allowing the city and its partners to test and refine approaches that can later inform the broader rollout of PENs. The Lab's strength lies in combining institutional coordination with real-life implementation in socially diverse environments such as Waterschei and Nieuw Texas.

Organisational setup

The oPEN Lab in Genk is led by the **City of Genk** in partnership with **EnergyVille, Thor Park and the local social housing company**. The municipality provides strategic direction and coordinates local actors, while EnergyVille contributes research, modelling and monitoring capacity. The Lab operates within an existing ecosystem of innovation centred around Thor Park, ensuring close alignment between policy goals and technical expertise.

The Lab's structure reflects a **policy-driven coordination model**, leveraging research partnerships for implementation, but still evolving towards stronger integration with community-level actors and social housing operators.

Citizen engagement and co-creation

Resident participation in Genk's oPEN Lab is tailored to a **socially and linguistically diverse population**, using accessible communication tools, in-person meetings and collaboration with local intermediaries. Engagement focuses on building trust, clarifying renovation processes and ensuring minimal disruption to residents' daily lives. Co-creation is supported through surveys, interviews and heritage-focused dialogues that connect technical renovation goals with community identity.

Engagement efforts in Genk show that **inclusiveness and trust-building** are crucial for successful energy renovation in vulnerable areas, though sustained participation beyond the project phase remains a challenge.

Technological solutions

The oPEN Lab introduces **prefabricated renovation methods**, energy monitoring tools and building-integrated renewable energy and energy efficiency upgrades adapted to the local housing stock. Pilot activities in **Nieuw Texas and Waterschei** test scalable retrofitting techniques compatible with social housing needs and heritage requirements. Close links with the **Open Thor Living Lab** allow real-life validation and optimisation of these solutions.

As such, Genk's approach shows how **technical innovation can serve social goals**, providing replicable models for low-disruption, high-impact renovation in mixed-tenure neighbourhoods.

4.5.3. PEN level

At present, the PEN in Genk remains **in an early, formative stage**, with only the first organisational and technical elements beginning to take shape. Rather than representing a fully operational PEN, the Genk case reflects an **emerging ecosystem** where lessons from the oPEN Lab and broader city strategies are gradually informing how such a neighbourhood might function in practice. The focus is therefore on identifying the **building blocks** - institutional, social, financial and technical - that could evolve into a coherent PEN model in the coming years.

PEN vision

The emerging PEN vision in Genk is guided by the city's broader **climate neutrality target for 2050** and by the ambition to **transform Waterschei and Nieuw Texas into demonstration areas** for socially inclusive, energy-efficient renovation. The approach prioritises deep retrofitting of existing housing, low-disruption construction methods and local community engagement rather than immediate energy positivity. The PEN vision in Genk is **evolutionary**, focusing on building long-term capacity and frameworks that can later support full neighbourhood-scale energy management.

Governance structure and model

Governance is currently **municipality-led**, with coordination anchored in the City of Genk and supported by EnergyVille and the social housing company. Decision-making remains project-based and tied to the oPEN Lab framework rather than a dedicated PEN governance entity.

As such, the Genk PEN represents a **transitional governance model** - policy-driven and institutionally strong but still lacking a permanent structure for neighbourhood-level management and ownership.

Operational model

Operationally, the focus is on **deep energy renovation** of buildings, testing prefabricated envelope systems and integrating monitoring tools to track energy performance. While these interventions create the foundation for future energy sharing and management, no autonomous or collective energy system is yet in place. As such, the Genk PEN is currently **technically preparatory**, establishing the efficiency and data infrastructure necessary for future energy-positive operation.

Financial model

Funding is largely **project-based**, combining EU public funding with municipal and regional renovation subsidies. Investments are fragmented across demonstration sites, with no consolidated business model for long-term financial sustainability or revenue generation at the neighbourhood level. As such, the financial model is **grant-dependent**, highlighting the need for future mechanisms that can aggregate investments and sustain neighbourhood-scale operations beyond pilot funding.

Ownership model

Ownership structures reflect the **mixed-tenure composition** of the area - social housing is publicly owned and managed, while private dwellings remain individually owned. No shared asset ownership or cooperative arrangements currently exist, though the concept of collective renovation governance is under discussion. As such, the ownership model is **diverse but unintegrated**, posing both challenges and opportunities for developing collective management structures aligned with future PEN principles.

4.5.4. Emerging Genk organisational PEN model

The Genk case study concludes that Genk is an example of a **municipal-led integrated innovation model**. The Genk model illustrates how **municipal leadership and research-driven collaboration** can advance systemic innovation in a socially and economically constrained context. It demonstrates that even without a dedicated legal framework or mature energy-sharing mechanisms, cities can lay the groundwork for PEN development by combining pilot experimentation, inclusive engagement and institutional alignment. Genk's approach bridges social policy, heritage preservation and technological renewal, making it a valuable reference for other **post-industrial, mid-sized cities** aiming to pair social resilience with energy transition.

In comparative terms, Genk aligns most closely with the **policy-driven organisational archetype** and the **dynamic systemic archetype**. This positions it between top-down and adaptive PEN models, providing a useful reference for cities that combine strong institutional leadership with evolving market and community engagement. The **key characteristics** of this emerging organisational PEN model include:

- **Policy-driven coordination** - The City of Genk plays a central role, steering the transition through strategic alignment with regional climate goals and partnerships with innovation and research actors.

- **Strong institutional ecosystem** - The PEN evolves within a robust local network built around **Thor Park**, **EnergyVille** and the **GEENkool coalition**, linking research, governance and implementation.
- **Social inclusion as a guiding principle** - The model prioritises engagement with vulnerable and multicultural communities, focusing on accessible communication, trust-building and low-disruption renovation methods.
- **Technology as an enabler, not a driver** - Prefabricated retrofits and data-based monitoring are applied to improve living conditions and efficiency rather than to achieve full autonomy or market-driven outcomes.
- **Incremental evolution** - The PEN remains in an **emergent stage**, progressing from demonstration-led activities towards an integrated, neighbourhood-scale governance and operational structure.

Steering factors

The development of the Genk PEN is strongly supported by **municipal leadership and long-term political commitment** to achieving climate neutrality. The city has effectively mobilised its institutional capacity, aligning local action with broader Flemish and EU frameworks such as LEKP and regional renovation strategies. Collaboration with **research and innovation partners**, particularly EnergyVille and Thor Park, provides a solid technical and knowledge base that supports evidence-based decision-making and experimentation. At the same time, Genk's focus on **social inclusion and heritage-sensitive renovation** ensures that technological progress is grounded in community needs and local identity, creating a socially responsive model that integrates energy transition with quality of life improvements.

Hindering factors

Despite these strengths, several challenges continue to constrain the full emergence of a PEN in Genk. The absence of **dedicated governance and financing mechanisms** limits the ability to manage and sustain activities beyond the project phase, while **regulatory barriers** - particularly around energy sharing, storage and taxation - hinder the creation of integrated local energy systems. Current investments remain **fragmented and grant-dependent**, preventing the establishment of long-term, self-sustaining financial models. Additionally, engagement beyond the institutional network remains limited; **private actors and SMEs** are not yet fully integrated and citizen participation, though growing, lacks continuity and formal structures. These factors collectively underscore the need for **systemic reform and capacity building** to transition from pilot-driven innovation to a stable, scalable PEN governance model.

For a **summary** of the emerging organisational PEN model in Genk, see Figure 16 below.

Figure 15: Emerging organisational PEN model in Genk. Source: authors.

5. Pamplona case study

5.1. Overview of Pamplona oPEN Living Lab

Figure 16: oPEN Lab Pamplona neighbourhood: San Pedro Neighbourhood (left), La Compasión Escolapios School (right). Source: Living Lab Pamplona [50].

Figure 17: IWER complex (currently inactive in the project). Source: oPEN Lab Pamplona [51].

Location

Rochapea district, Pamplona, Spain.

Introduction

The oPEN Lab activities in Pamplona, Northern Spain are carried out in the **Rochapea district** with around 26,000 residents. The Rochapea district is known for being a **working-class area from the 1940s** – industrial elements can be found in the neighbourhood's architecture. Specifically, Living Lab tackles challenges connected to the **Renovation Wave**, by developing innovative approaches to building renovations and energy solutions, which will contribute to decarbonisation efforts. Additionally, reducing energy poverty (poverty rate is around 11.3% in Rochapea) through oPEN Lab solutions will contribute to increased **social cohesion** in the area. [4] [52]

More precisely, the Living Lab in Pamplona is comprised of **two pilot sites**: it will exploit the potential of renewable energy production, enhance the attainment of environmental objectives and increase energy autonomy by targeting renovations in the energy domain within the **La Compasión Escolapios school** (self-ownership) as well as in two housing blocks in the **San Pedro social housing complex** (owned by Pamplona City Council), creating virtual energy linkages between them. [50] In addition, the project initially included a third pilot site of the former industrial complex **IWER** in the project proposal, which has also been used throughout the project for various valuable activities; unfortunately, for various reasons, the complex ultimately had to be left out of the project as a demonstration site. All three sites, especially the school, have **high visibility**, which is valuable for demonstrating them as examples for raising awareness, while engaging and activating the community as part of the process.

Key facts and figures [52] [50]

- The population of Pamplona is around 211,000 inhabitants, while Rochapea district, where the oPEN Living Lab is located, has a population of about 26,000 residents.
- Pamplona is the capital of the Autonomous Community of Navarre [53].
- Rochapea is one of the most **densely populated** districts of Pamplona as well as one of the more vulnerable sites in the Navarre region, as the poverty rate is around 11.3%
- The Pamplona Living Lab has carried out project activities in three pilot sites: two social housing blocks in San Pedro site and a building of La Compasión Escolapios School complex
    - **San Pedro** site with a total of 42 buildings with 235 apartments (60 m^2 each), which have been last retrofitted in 1985.
    - **La Compasión Escolapios School** dates originally to the mid-20th century, with the selected building being added to the complex in 2011. The school has around 900 students.
    - The **IWER** building is considered to be a district landmark. The former industrial complex comprises numerous buildings with a total surface area of 33,999 m^2 and currently hosts a diverse mix of businesses, office spaces and conference rooms, among others.
- The Pamplona Living Lab renovations aim to contribute around **1,880 m^2 to nearly Zero Energy Building (NZEB) standards**, directly benefiting over 1,000 users in the pilot buildings.

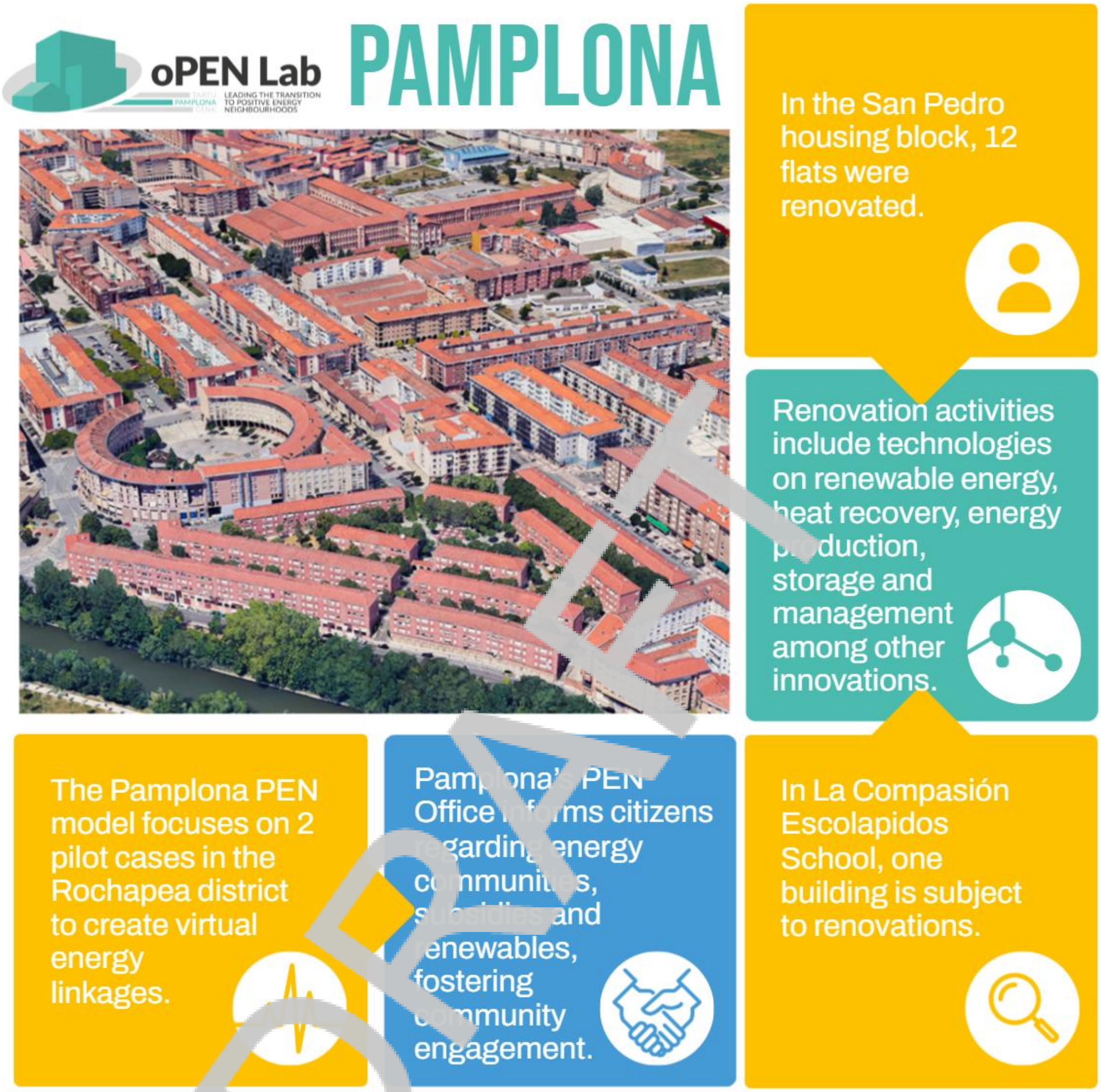

Figure 18: Pamplona oPEN Lab overview. Source: authors.

5.2. Pamplona oPEN Living Lab context

This chapter provides contextual insight into Pamplona's oPEN Lab neighbourhood by examining the underlying **structures**, **cultures**, and **networks**. The aim is to lay the groundwork for understanding how local contexts shape the organisational models of PENs.

Figure 19: Chapter 5.2 explores the context level in Pamplona. Source: authors.

5.2.1. Structures

This sub-chapter explores the **structural conditions** shaping each oPEN Lab neighbourhood, focusing on their **economic settings**, **regulatory frameworks** and **physical characteristics**. Understanding these foundational aspects helps explain the practical opportunities and constraints faced in implementing and scaling PENs.

Economic setting[18]

Stemming from the European EPBD, for non-residential buildings it is required to submit a **National Building Renovation Plan** (NBRP) to adhere to the minimum energy performance standards, while for residential buildings, the 2024 EPBD recast dictates the need to set a national trajectory to reach a 16% reduction of primary energy consumption by 2030 and up to 22% by 2035. [10]

In Pamplona, NZEB standards are in place for new buildings and major renovations, setting requirements for energy performance [52]. However, there is a **missing framework of public incentives to go beyond these minimum requirements and reach energy-positive levels**. This is to be considered a hindering market condition to PEN rollout in the Pamplona context.

That is why the interventions of the Pamplona Living Lab regarding support for renovations show a clear step from business as usual, reflecting a positive impact. Specifically, efforts to reach **NZEB standards** have been made by the national government, by creating the framework for multiple incentive programmes co-financed by **NextGenerationEU** through the ***Plan for Housing Renovation and Urban Regeneration.*** Therefore, renovations are supported by subsidies, aligning with Spain's Long-Term Renovation Strategy (LTRS) and the national energy and climate plan (Plan Nacional Integrado de Energia y Clima). Under this framework, an influential incentive programme is the **Programa de Rehabilitacion Energetica de Edificios**, which has a budget of 300 million euros: under this programme, action by individuals and communities as well those with Citizen Energy Committees, Renewable Energy Committees (RECs) or those impacted by energy poverty are supported through encouraging energy renovations (at least 40,000 buildings), increasing energy efficiency by improving the building envelope. This programme is related to the **Royal Decree Law 15/2018,** determining the fiscal measures around energy efficiency and the integration of renewables. [52]

Regarding financial barriers and energy poverty, the EPBD obliged Member States by detailing public policy measures on ways to reduce the impact of renovations and upfront costs for vulnerable households. More specifically, to **support social fairness** in this case, the EPBD

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[18] For more information about the market conditions and economic instruments relevant to Pamplona's PEN development, please refer to the oPEN Lab report *Towards a regulatory framework for positive energy neighbourhoods, Spain (2024).* [52]

dictates **proactive support mechanisms for a more affordable transition towards improving energy performance.** These measures include highlighting the importance of focusing renovation policies on the worst-performing buildings to mitigate the impacts of energy poverty, stating that financial support should also be first and foremost offered to those in a situation of energy poverty and taking the vulnerability of certain households into account when implementing penalties for non-compliance. [54] While it is positive that addressing vulnerability and reducing energy poverty are the focal points of renovation regulations, it is nevertheless clear that mitigating financial barriers remains the task for individual Member States through a national policy framework, which makes **vulnerable households dependent on such frameworks**. [52]

Regulatory setting[19]

On the national level, under Spain's **España 2050 framework,** there is a commitment to 2050 carbon neutrality goals, detailed in the chapter *Sustainability and Climate Change*, and under **Law 7/2021**, this goal was ingrained into the Spanish legal framework, making the target legally binding. Regarding the importance for the **development of PENs**, this law should be considered a central element, given that it details the use of building materials with a low carbon footprint, stresses the importance of accessibility as well as the use of renewables in renovations, among other relevant aspects, such as zero-emission heating/cooling systems and EV parking space policies. In addition, **The Long-Term Renovation Strategy** (ELP 2050) highlights the importance of consumer and demand-side management, which is essential for the development of PENs: flexibility regarding demand allows for the maximisation of self-consumption on the level of the neighbourhood and providing flexibility regarding the consumption, production and storage of energy. Crucially, to further **support the creation of energy communities**, Spain attempted to ratify the Royal Decree-law 7/2025 in June 2025, which would have increased the range of self-consumption from two km to five km and allowing increased sharing of energy. However, this decree was non-validated and thus the **range for self-consumption remains two km in Spain.** ELP 2050 also details the use of thermal renewables, reduction of demand and the electrification of heat. [52]

Further, and importantly for the development of PENs, **the National Integrated Energy and Climate Plan 2021–2030** increases solar energy targets to exceed 76 GW (previously, the target was 37 GW) and sets the national share of renewable energy at 48%, while reducing final energy demand by 44% (compared to the demand levels in 1990). Additionally, promoting the Energy Storage Strategy and demand flexibility are also important measures in PNIEC regarding PENs, as the focus on the neighbourhood level is highlighted in the policy. **The 2021 Road Map for Self-Consumption to Improve Self-Consumption and Citizen Participation** central ideas were also restated within the National Integrated Energy and Climate Plan. [52]

On the regional level, regional governments are the policymakers regarding the areas of housing and urban planning, as well as making available national public funds to users, per the **Spanish Constitution** – therefore, these competencies are also in the domain of the Navarre region. Navarre has prepared the **Energy Plan of Navarre,** which sets objectives regarding energy transition and the creation of a regional energy agency – for energy-related goals, the plan includes financial instruments to work on the Navarre energy sector. Specifically, the focus is on increasing wind and solar energy capacity, with the overall renewable energy being planned to increase from its current share of 25% to 50% by 2030. The plan also includes efforts to reduce energy consumption and increase the share of renewable electricity to 100% by 2030. However, as a crucial element, around 88% of these

[19] For more information about the regulatory frameworks relevant to Pamplona's PEN development, please refer to the oPEN Lab report *Towards a regulatory framework for positive energy neighbourhoods, Spain (2024).* [52]

funds is expected to be sourced from private funding, including consumers and companies. Navarre region's **Foral Law on Climate Change and Energy Transition** sets the goal of reducing greenhouse gas emissions by 23% (compared to 1990 levels) by 2030. [52]

On the local level, Pamplona municipality is regulated by its own **2030 Energy Transition and Climate Change Strategy for Pamplona (SECAP),** which sets ambitious goals. At the centre of this framework is the focus on the rehabilitation of roofs and facades of 60% of buildings built before 1979 (30,274 dwellings) – these are buildings built before the framework on energy regulation came into existence. In general, SECAP's objectives are to mitigate the impact of climate change, eradicate energy poverty and guide a just energy transition. Pamplona has also set the objective of increasing the production of renewable energy by 37%, increasing energy efficiency by 39%, reducing the emissions of CO_2 by 64% (by the year 2030, compared to the levels of 1990) – it is possible that regarding these goals, PENs can have a positive impact in supporting their attainment in Pamplona. [52]

Physical setting

Two distinct pilot sites have been chosen in the Rochapea district, Pamplona for implementing the PEN solutions of oPEN Lab project.

The first of the pilot sites is within the **San Pedro Group buildings** (owned by Pamplona City Council), which comprise 42 buildings with a total of 235 social housing apartments, each with an area of around 60 m^2 (pre-renovation). For oPEN Lab activities in San Pedro, **two buildings with 12 apartments are subject to renovations**, impacting the living spaces of 24 residents. These buildings were built in 1948 and most recently (pre-oPEN Lab interventions) retrofitted in 1985. Thus, minimum energy requirements are not met on site and energy is bought from suppliers. More precisely, the **energy performance of the housing blocks was deficient** (250–350 kWh/m^2), [3] [52] and according to the Energy Performance Certificate (EPC), the building falls under **category E**. [40] One of the challenges regarding renovations was taking into consideration the facade aesthetic preservation of the neighbourhood as well as interior surface requirements.

The second selected site is a building of **La Compasión Escolapios School** complex, specifically one of its more recent buildings from 2011, which includes a sports hall, classrooms and teachers' offices, currently offering both primary and secondary education to around 900 students. The building has a thermal envelope with adequate insulation, but **lacks sufficient technological building management systems**, such as a double flux ventilation with heat recovery, making the global energy performance unsatisfactory. Added to this, the heating is gas dependent. To gradually eliminate these shortcomings and decrease the negative environmental impacts as well as reach climate neutrality by 2050, the school has prepared a medium-term plan. [50]

5.2.2. Cultures

Social profiles

The Rochapea neighbourhood has over 26,000 residents. Regarding more specific social profiles, most residents in the social housing dwellings of San Pedro complex are **refugees, immigrants or low-income elderly residents, disabled citizens along with their caregivers, who are at risk of social exclusion.** This is to be placed in the wider context that the poverty rate in the Rochapea neighbourhood is around 11.3% – regarding this, one of the objectives of the Living Lab in Pamplona is to attract different social profiles to reside in the area. [3] [55]

On the other hand, La Compasión Escolapios School is an educational space for students and a professional environment for teachers from the various parts of Pamplona, while most students come from the Rochapea district [50]. Therefore, while the most direct stakeholders include the students and the employees, impact of oPEN Lab initiatives in Pamplona are also carried more broadly to the students' families, for instance.

Regarding these demographics of Pamplona, some of the broader community-related objectives of the Living Lab are to **boost local economic activity by introducing employment and business opportunities related to renewable energy and energy renovation** in the area. This would improve the overall living conditions in Pamplona, while also increasing the **welfare and energy autonomy** of the Rochapea neighbourhood. Another aspect of the Living Lab in Pamplona is the creation of the **PEN office** (one-stop shop), which carries out dissemination activities as well as encourages and assists the implementation of local projects and initiatives. Several other citizen engagement approaches offer additional empowerment and engagement opportunities to local stakeholders. [3]

Collective citizen engagement

More precisely, stakeholder and local resident empowerment and inclusion are important parts of the Living Lab model in Rochapea. A **bottom-up strategy** is being pursued, in which local agents play an active role in the district's transition. To this end, a **district council** has been created, made up of local collectives, where projects can be presented and redefined to best suit the district's needs. This council serves as a link between the ecosystem of neighbourhood agents and the core group of the living lab. At the same time, there are a number of **"ambassador" agents** who promote ideas for new projects, act as trusted local players and serve as a link between citizens and other local stakeholders.

The district council, the inclusion of the ambassadors as well as the PEN office have been positive initiatives, offering influential results: with the support of ambassadors, different **working groups** with a specific **steering group** emerged. For example, one of such groups worked towards the creation of Rochapea's first renewable **energy community**, offering also insight into creating similar communities in Pamplona more widely. [2] Another one has been defined to promote **digital tools** that enable the sharing of district perception, needs detected as well as urban behaviour patterns (such as local mobility). This is data which helps to get a better understanding of the district and provides the basis or collaborative proposals for new projects to be carried out in the district. A further working group has been created to assess the **neighbourhood's bird population**, look for solutions to restore it as well as create guidelines to assist policy and decision makers. On the other hand, there are also **macro-level challenges** regarding the Living Lab in Pamplona and the associated citizen activities, especially related to long-term continuity and economic sustainability without having to fully depend on national or European-level subsidised projects.

Further, **La Compasión Escolapios School** strives to have multilevel impact with its Living Lab activities, in addition to the strategic energy efficiency modifications. The school aims to support community creation, promote sustainable mobility and behaviour as well as create a wider learning programme, which would include topics such as sustainability and climate change, collective planning, gender equality, collaborative and multi-level work and sense of belonging among other valuable subjects. This should also act as a basis for replication activities of the project, through encouragement for other similar establishments. Furthermore, as a trusted agent, the school has access to a large part of the population (students, school staff and families), serving as a highly significant channel of dissemination and engagement. Therefore, the school is an active player and promoter of ideas for projects to be implemented in the district that will contribute to its transition towards a positive energy neighbourhood, playing a dynamic role in the steering and working groups.

Community activation and involvement, as well as co-creation and education have thus guided the project’s activities in Pamplona, fostering a community-centric approach, shaping the details around the envisioned project solutions and thereby ensuring that the outcomes clearly reflect the local needs and interests, while also ensuring a citizen-based continuity of the PEN development after the oPEN Lab project.

5.2.3. Networks

Environmental and sustainability efforts as well as energy efficiency initiatives can be observed through local collaborative practices across the Navarre region – reflecting that such initiatives are **not limited to just the oPEN Lab project**, but dynamic approaches can also be seen among local actors, companies, coalitions and community groups more broadly.

The industry and public authority network and collaboration can be seen through several initiatives. Firstly, **Capital Energy** has implemented a Territories project, focusing on renewable energy and infrastructure development in several Navarre municipalities. Specifically, the development of the Joluga wind farm is an example of Capital Energy’s activities in local communities, to invest in green initiatives [56]. Another strategic partnership between the government and industry is the **Red Eléctrica (electricity system company) and the Government of Navarre Partnership** has been created to promote Navarre region’s ecological transformation, where the central role is on renewable energy. Specifically, Red Eléctrica has committed to investing in the region’s energy transition, which will contribute to the supply of electricity and the development of the electricity grid, but also have a wider positive impact on the economic and social development of the Navarre region through more employment opportunities and an increase in the economic competitiveness of Navarre. [57] **CENER's** board of trustees is made up of the Government of Navarra, the Central Government, through the Ministries of Economy and Competitiveness, and of Industry, Energy and Tourism, and the Centre for Energy, Environmental and Technological Research. Specialised in applied research and the development and promotion of renewable energy, it is active worldwide in six areas of work: wind, solar thermal and solar photovoltaic, biomass, building energy and renewable energy grid integration.

There are also multiple initiatives focusing on research, education and innovation at the Public University of Navarre. For instance, the Arrosadia campus of the **Public University of Navarre (UPNA)** has been transformed into the UPNA Green Smart & Sustainable Campus, through funding from EU NextGeneration funds. Specifically, the objective is to make the campus more sustainable, by reducing its energy consumption from non-renewables by 30%. This goal is achieved by introducing EV charging points and PV panels, with energy storage systems coming to use as well. [58] Connected to this project is also the **NAIR Center,** which provides AI solutions to the PV energy system and energy storage system, to predict energy production. [59] Finally, the **Institute of Smart Cities (ISC) at the Public University of Navarra (UPNA)** focuses on the research, design and implementation of smart environments. Importantly, the institute is a collaboration between 7 departments at UPNA, ensuring a comprehensive and innovative view and analysis of projects. Specific areas of research include energy, resource management, sensors and communication management in urban areas, which impact the social, strategic as well as the technological levels. Such activities play an important role in the development of low-energy districts and sustainable urban environments. [60]

Industry and academia collaborative networks can also be seen in the University of Navarra, as it collaborates with the **Repsol foundation** to explore and research the impact of green hydrogen in the energy transition. Public awareness and education on this matter is achieved through public events, publicising developments, as well as educational programmes focusing on hydrogen technologies. This collaborative initiative was created to highlight the impact and role of the companies in decarbonisation. [61]

NASUVINSA is a public company of the Government of Navarre whose main purpose is the promotion of land and public housing. It also collaborates with local, regional, national and international organisations and networks to develop and coordinate, among other activities, transformation projects such as Low-carbon Districts and New European Bauhaus [62].

Finally, an important network is between different companies themselves. The non-profit **Enercluster –** Navarra Renewable Energy Cluster gathers around 85 companies working in the renewable energy sector of Navarre, to induce collaboration, innovation and growth of the renewables sector. For more concrete approaches, Enercluster uses working groups, which focus on specific issues to derive solutions, initiatives and policies. [63]

Therefore, there are several networks (non-exhaustive list within this overview section) working actively in the energy transformation and green transition domain around Pamplona, specifically on the level of the Navarre region, confirming the continuous commitment to environmental goals and the general interest in developing this area of action further. The oPEN Living Lab with its engagement of local citizens fits into the existing networks by offering further insight and points of view on the local level.

5.3. oPEN Living Lab Pamplona

This chapter explores how the Pamplona PEN has been organised and implemented through a **Living Lab approach** that brings together public, private and civic actors in a shared governance structure. It also presents the technical solutions demonstrated in the neighbourhood, highlighting the renovation strategies, energy technologies and integrated systems that make up the core of Pamplona's energy-positive transformation.

Figure 20: Chapter 5.3 explores the Living Lab level in Pamplona. Source: authors.

5.3.1. Organisation

The Living Lab in Pamplona, which is focused on the Rochapea district, aims to implement **one of the first PENs in Spain**. The overarching goal of the oPEN Living Lab in Pamplona is the development of a novel urban energy model, with opportunities for replication and scalability. Additionally, the Living Lab in Pamplona serves several objectives to encourage economic development and opportunities in the Rochapea district through supporting the creation of additional employment and business opportunities in the domain of (renewable) energy and deep energy renovations. Therefore, the activities of the Pamplona Living Lab support the increased welfare as well as the living and economic conditions in the Rochapea district. [3]

Regarding the partners working on the successful development and implementation of the Pamplona Living Lab, the main partners are the following:

- **Pamplona City Council** and the **University of the Basque Country** (UPV/EHU) form the core group of the Living Lab and, therefore, of the PEN development. The city council manages the project at a global level and the UPV/EHU is responsible for social innovation and monitoring issues [64].
- **AH Asociados** (architectural firm)**, CENER** (national energy research centre), **OBENASA** (constructor originally associated with IWER) and **la Compasion Escolapios school** are or have been part of the group of experts who support the core group in strategic and operation decision-making and managing the daily activities of the project (design, construction, operation, replication, evaluation of the PEN in Pamplona). [51]
- **La Compasión Escolapios School and the City Council** act as the owners of the two pilot sites of the Pamplona Living Lab, making them important decisionmakers for developing and implementing oPEN Lab solutions in them.

Other key agents that have been defined during the project are:

- **Neighbourhood council**: as the forum where the neighbourhood's ecosystem of agents is represented and as part of the group of experts that support operational and strategic decision-making for the neighbourhood.
- A number of **local agents** who act as intermediaries (or so-called local ambassadors) between the neighbourhood and the organisations that coordinate each project in the neighbourhood. At the time of the study, these were mainly: **trade associations** (dissemination, advice and participation), the four **schools** (project creation, dissemination, awareness-raising, training and participation), renewable **energy communities as Arrotxa-E** (participation and advice), **cooperatives as Landare** (dissemination, advice and participation) and **some citizens** (project proposals, dissemination, advice and participation).

There are **additional actors and roles, divided into specific actionable categories** to (1) ensure the full integration of technological solutions, which would be adaptable to end-user needs while also being able to impact user behaviour, (2) ensure maximum alignment of the expected oPEN Lab solutions and stakeholder needs, (3) provide affordable energy to the related stakeholders, (4) explore new revenue streams and client bases [1], and (5) create an active and engaged community capable of pursuing further initiatives to transform the district into a PED:

Policymaking

- Municipal Energy Agency officials of Pamplona City Council
- Social housing administration of San Pedro housing complex
- Legal department (Strategic Office)
- Citizen engagement groups (district council)

Economy

- Energy suppliers
- Distribution system operators (DSO): Iberdrola
- ED engineering (design)

Societal capacity

- Residents of the San Pedro housing complex
- UPV/EHU has the role of supporting co-creation and social activities with local stakeholders, along with providing technological solutions (such as the digital twin, building information model, activities related to thermal energy) [51] [3]
- Merchants' association
- Schools
- Landare (a non-profit focused on the responsible consumption of organic goods)
- District Council
- Renewable energy community ArrotxaE
- KarKarKar (non-profit consumer cooperative focused on mobility services and products to accelerate the transition towards sustainable mobility)

Technology

- BCARE: [65] technology solution provider
- CENER: [66] technology Energy Management System supplier, photovoltaic solar technology supplier
- National Reference Centre for Renewable Energy and Energy Efficiency

Furthermore, Pamplona local government, public and private financiers as well as subcontractors support the local activities of oPEN Lab.

Stakeholder engagement

Stakeholder engagement in Pamplona includes different objectives, such as gaining a deeper understanding of the local context, awareness-raising, creating and activating the local community, enhancing the sense of belonging as well as specific co-design activities, for maximum input on social and technical aspects [40] and to last over time. The community and local stakeholders of Pamplona have been mapped based on the idea of a **quadruple-helix community**, which includes academia, industry, civil society and the government. More specific stakeholders under each category are detailed in chapter 5.4.2 Governance structures and models.

From the initial stages of the project, **stakeholder engagement offered valuable insight** for the project. An action plan was formulated to ensure the most extensive and wide-ranging engagement activities, which included a stakeholder's mapping canvas, and a strategic roadmap of actions to be implemented. Further, a **co-design strategy** related to six thematic areas carried out within the Rochapea district ensured that feedback and input was gathered regarding the renovation and building technology aspects for PEN [40]. Within this strategy, specific actions have been conducted to engage the local actors:

1. **Co-creation activities regarding San Pedro and IWER Square**. Regarding San Pedro, a workshop was conducted with people with the same profile as the expected future residents of the **San Pedro** pilot building (elderly people living in social housing) regarding their expectations for renovations, with input for design (colours, materials, for instance) gathered through a VR (virtual reality) solution. The **collaboration and input of elderly residents** was important for designing an inclusive and adapted indoor space, even if currently, the residents in newly renovated buildings are not elderly people. As part of future activities in IWER a new public square will be built, and the conception for it was opened to codesign activities with citizens. This has served as a starting point for building closer ties with local stakeholders and was a first step

towards **creating an active local community** that will support actions aimed at moving the district towards becoming a PEN.

2. **Participatory actions in the district through art: la Compasión Escolapios School** along with three other neighbourhood schools (Rochapea, Cardenal Ilundain and Patxi Larrainzar), local stakeholders, the business association and members of the community have actively participated in co-creation activities such as collaborative neighbourhood murals and the associated participatory painting to create and activate the community, get to know the neighbourhood, reflect on it (what it has been, what it is and what we want it to be), strengthen the sense of belonging, raise awareness on the need for change towards a more sustainable and self-sufficient district, and provide training on possible solutions through artistic expression. [67]
3. **Training and raising awareness actions**. The Environmental Education Museum has organised various activities with schools and citizens to analyse energy consumption and the solutions that could be implemented. Both in terms of technology and behaviour, in an attempt to define a realistic roadmap of small changes to be adopted. There are also training sessions planned for future residents to ensure a comprehensive understanding of the technical aspects. Tenant companies added additional insight.
4. **Implementation of Geographic Information System tools** to know the situation of the neighbourhood through an interactive map application where local stakeholders can provide input based on their perception (mobility behaviour, energy consumption, comfort level, mobility district needs, etc.). In addition, a **3D viewer** has also been developed with the aim to disseminate all the energy related activities that have been or are being implemented in the district.
5. **Promotion of new projects in the district** such as Txio Txio (recovery of the neighbourhood's bird population), my green place (promotion of the interactive maps and collaborative murals) and PERSIST (to gain a deeper understanding of how socio-economic, socio-cultural, and socio-political factors influence the development of PENs and their interconnections with technological, regulatory, and investment aspects in different geographical, cultural and economic contexts).
6. **Supporting the creation of energy communities** conducting various training and support workshops for the REC steering group, both during its creation (definition of the statutes) and in its subsequent development.

Further, the oPEN Living Lab in Pamplona reflects the importance and value of **engaging with local stakeholders** both **during and beyond the project's duration,** as well as within other energy-efficiency and energy production related projects. For this, **a local PEN office** (an energy management office) has been created for increasing the local understanding of the need to reduce energy consumption – which can be done through deep renovations –, while explaining the benefits of producing energy on a local scale. The PEN office increases the communication with local stakeholders, promoting and assisting with carrying out local energy-related projects, while ensuring collaboration in future aspects of the Pamplona Living Lab. More specifically, the PEN office supports Rochapea residents in understanding the subsidies in place for energy retrofitting as well as their contracts – the energy management office has had a positive impact on the overall uptake of the project in Rochapea. [2]

In addition, the **district council** is expected to play a key role in the district both as a consultant (local expert) and as a catalyst and promoter of new projects/ideas to be developed in the district [3]. **Working groups** and a **steering group** as well as local ambassadors also create links between insights from the community and project activities. It is also considered that the **local energy community** could play an important role in the district, not only as a prosumer (production and consumption of local sustainable energy), but also as a promoter of new projects (shared mobility, collective building renovation, etc.).

While the city of Pamplona aims to manage Living Lab initiatives beyond the duration and framework of the oPEN Lab project, there are some challenges identified related to long-term continuity, the long-term engagement of local stakeholders, the involvement of industry stakeholders in living lab activities, and sustainable business model.

While it can be complex to effectively include the needs of citizens in developed solutions, stakeholder engagement is invaluable in oPEN Living Lab Pamplona. Thus overall, the impact and organisation of stakeholder engagement is positive in Pamplona, due to the proficiency of the partners (UPV/EHU, AH Asociados, OBENASA, CENER, Pamplona City Council) as well as innovative techniques used during co-creation processes (such as VR solutions, interactive maps, etc). The inclusion of local citizens increases citizen empowerment as well as the broader acceptance of the project, given that they have an impact as co-owners in the project. Further, co-creation ensures the value of developed solutions for the end users, given that they have been adapted considering local needs and have a positive impact on the energy consumption locally, which is the basis of an energy efficient community. [3]

5.3.2. Technological solutions[20] [21]

The PEN solution of oPEN Lab in Pamplona is among the first of its kind in Spain. Specific for the PEN solution in Pamplona are its **two currently active pilot sites** – San Pedro and La Compasión Escolapios School – **which are to be combined** to create a PEN and monitored by a single virtual system. More precisely, while the two pilot sites will still be operating independently (as the ‘day ahead matching strategy’ is used for the virtual energy market), a **virtual energy balance** will be shared between the sites. [1] The creation of a combined PEN follows the regulatory framework, as the sites of the energy community members are less than two km away from one another (adhering to regulations of 2022, setting the limit to two km). Here, the main energy coordination between buildings that applies is regulated by the **self-consumption** regulatory framework with compensation mechanisms (RD 244/2019) and energy opportunity schemes for **virtual power flows.**

In the two pilot sites (San Pedro buildings and La Compasión Escolapios school), the **scope of the technical interventions** targets renewable energy production and storage while simultaneously incorporating energy efficiency measures.

Regarding the **San Pedro building**, the Pamplona City Council has undertaken a **comprehensive renovation** of two buildings (in total 12 apartments), applying the highest architectural and technical standards with the aim of transforming them into **positive-energy buildings**. Among the solutions implemented, it is worth highlighting the lightweight roof renovation solution, comprising thermal insulation and integrated photovoltaics (BIPVs), which are capable of generating 73 MWh of clean energy annually. Furthermore, an innovative high-performance industrialised façade renovation solution, which includes vacuum insulation panels was successfully demonstrated, and it is the first case of the panels used for this purpose in Spain, as for the use and scale. Finally, an advanced Energy Management System

[20] For more information about the technological solutions, please refer to the oPEN Lab *Report on demonstrated technologies at building and neighbourhood level in three demonstration areas* (2025) [40].

[21] For more information about the data collection, design and prefabrication processes, please refer to the oPEN Lab report *Optimization of the prefabrication process through digitalization* (2023) [89].

(EMS) will optimise and coordinate operation of all energy assets and interoperate with the Building Management System and two Human Machine Interfaces (HMI), one per apartment building.

In the case of **La Compasión Escolapios School** demo building, **technical interventions will** comprise the installation of up-to-date available technologies and managing them with advanced controls and innovative algorithms to **optimise the use of local renewable energy, increasing energy self-sufficiency and an annual positive energy balance** with regard to energy boundaries of the incipient PEN. Among the solutions to be implemented, it is worth highlighting the installation of PV panels with integration of heat harvesting BIPV, the installation of a double flux ventilation system with heat recovery from BIPV panels to lower heating and cooling demand, the installation of two 49 kW low global warming potential (GWP) heat pumps in substitution to gas boilers, the implementation of an EMS/HMI and virtual interoperation with the San Pedro building in a joint PEN operation, laser scanning for fast development of a building information model (BIM) for the renovation process and operational phase, and a digital twin for EMS/HMI.

Within the scope of oPEN Living Lab in Pamplona, several **broader key innovative approaches** are planned:

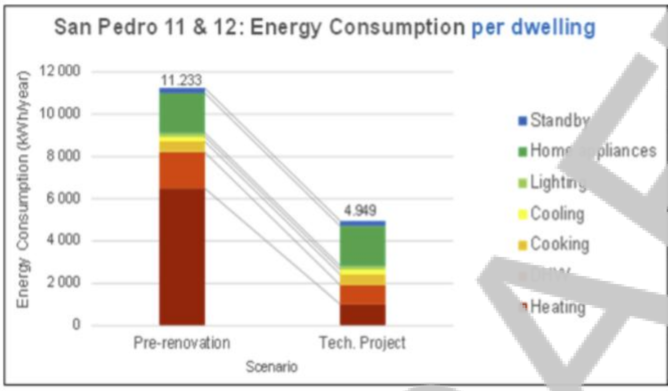
- Maximising end-user engagement in the implementation of oPEN Lab solutions.
- Encouraging new business and economic opportunities, specifically in the deep renovation and energy-related domains.
- Alignment with climate goals is envisioned, which includes life cycle assessments from the beginning of the project to reach a 50% reduction in embedded energy, a 70% GHG emissions reduction by end of the project, aiming for zero emissions by 2030.
- Using advanced digital methods, regarding design, industrial manufacturing and renovation/construction – this is done also to optimise time, environmental impact and costs.
- Creation of at least one renewable energy community.
- 100 kW photovoltaic installation at the local Patxi Larrainzar school, with 80% of the energy being managed by a renewable energy community – both initiatives have been supported by the oPEN Lab project.
- Other technical solutions include the creation of digital twins, operational strategies of energy management as well as investing in BIPV. [4]

A variety of **digital and technical resources** were used to support oPEN Living Lab development and activities in Pamplona:

- **BIM** was used for technical design, and for its successful use, the municipality changed its system to REVIT for cohesion.
- **3D and drone scanning** supported gathering the data necessary for constructing BIMs.
- **Prefabrication and optimised digital renovation workflow** were partly used for the San Pedro building, specifically walls including vacuum insulation panels.
- **VR** (virtual reality) solutions were used for co-creation of interior design activities.
- **Development of digital tools** (interactive maps and 3D viewer) for district data collection, dissemination and engagement purposes. [16]

The renovations of the San Pedro social flats were finished at the end of 2024 [40] and first residents have moved in.

Figure 21: Renovated San Pedro Building. Source: Maria Azkarate [68].



(kWh/household)	Prior	Project	Save
Heating	6.490	1.006	-84%
DHW	1.713	914	-47%
Cooking	506	506	0%
Cooling	225	225	0%
Lighting	176	176	0%
Home appliances	1.885	1.885	0%
Stand-by	238	238	0%
TOTAL	11.233	4.949	-56%

Figure 22: Comparison of expected annual energy consumption per dwelling measured pre-renovation and expected demand after renovation in San Pedro. Source: Kalms et al. [40].

5.4. Moving towards an organisational PEN model in Pamplona

This chapter explores the potential **organisational models** for a future Pamplona PEN, drawing on lessons learned from the oPEN Living Lab in Pamplona. While a PEN is not yet established in the city, the discussion outlines possible approaches to governance, operations, financing and ownership that could support long-term sustainability. Based on insights from local experiences and stakeholder interactions, the proposed framework represents an informed, assumption-based projection of how a PEN in Pamplona might be structured to manage energy renovation and innovation at neighbourhood scale.

Figure 23: Chapter 5.4 explores the PEN level in Pamplona. Source: authors.

5.4.1. PEN vision

In Pamplona, the objective of the oPEN Lab initiative is to **demonstrate the positive potential impact a PEN could have**, through the various energy-related and social interventions and initiatives. Instead of only meeting the minimum energy performance standards, the oPEN Lab initiative goes further: the Living Lab directly **targets the background difficulties to induce renovations and increase energy efficiency past the minimum requirements**, by renovating buildings, boosting renewable energy production and adding smarter storage and monitoring systems. The **envisioned result in the Rochapea district is that the neighbourhood does not just use energy more wisely but will produce more than it needs,** creating a **positive energy model**, giving back to the wider system and setting an example to motivate the reproduction and scaling up of these solutions defined through a living lab methodological approach. This will also provide an opportunity to ease the access of vulnerable residents to affordable renewable energy. In addition to the technological and renovation aspects of the project, what really makes the Pamplona Living Lab stand out is the role of the community, local activists, contributors as well as stakeholders. As a result of oPEN Lab activities in Rochapea, the impacted residents have become **"energy active"**, taking part in workshops, promoting new projects in the district, sharing knowledge, and getting involved in how energy is produced and used, while understanding the importance of renewable energy in a wider movement towards climate neutrality in Europe. These lessons have also been the results of the several activities being undertaken, both at a technical and social level, which have been successful in increasing the understanding and uptake of PED/PEN solutions in the pilot sites.

In Pamplona, a **series of initiatives take place in parallel,** demonstrating that the establishment of a positive energy district can emerge through a set of independent initiatives on the neighbourhood level. In the future, depending on the extent of integration allowed by the regulative framework, these activities could be linked together to produce further energy links – there is thus potential for inter-initiative cooperation in Pamplona. These activities include a virtual energy connection between the school and San Pedro buildings. Another important aspect of oPEN Lab interventions in Pamplona is the use of the living lab methodology, which supports close collaboration between stakeholders and technical solutions to ensure alignment with needs while more broadly increasing citizen engagement and awareness. This network is crucial to the sustainability of long-term success of energy-related change.

oPEN Lab initiatives in Rochapea importantly follow the **virtual energy community model,** with a virtual monitoring of energy linkages set up between two pilot sites (San Pedro and the School), reflecting models of learning and improvement from system to system.

The PEN story in Pamplona is still ongoing, with the first residents having moved into the apartments of the newly-renovated energy-positive San Pedro apartment complex, the School La Compasión is starting the renovation project and the community is working in different urban level projects. Importantly, the San Pedro complex has connected the creation of an energy positive building with the aspirations to provide **accessible housing** [68]. Different aspects of renovation, such as optimising industrial renovation workflows, use of innovative materials, energy management and heat harvesting, have been seen to have potential for replication and usefulness in supporting the establishment of a PED/PEN. A model that is highly replicable and is proving to be of interest both nationally and internationally is the model of renewable energy community creation and development conducted by the city Council in Rochapea.

5.4.2. Governance structure and models

To define the governance model of the PEN and of the associated Living Lab, a t**heoretical process** was conducted. During the process, it was observed that it was not possible to define the model at the beginning of the project due to a lack of knowledge and the need of including other actors in the process. Thus, it was decided to change the strategy and define it later, once the project was further implemented, so the definition of the governance structure and models will be established in an organic way, through the different projects and activities ongoing in the PEN.

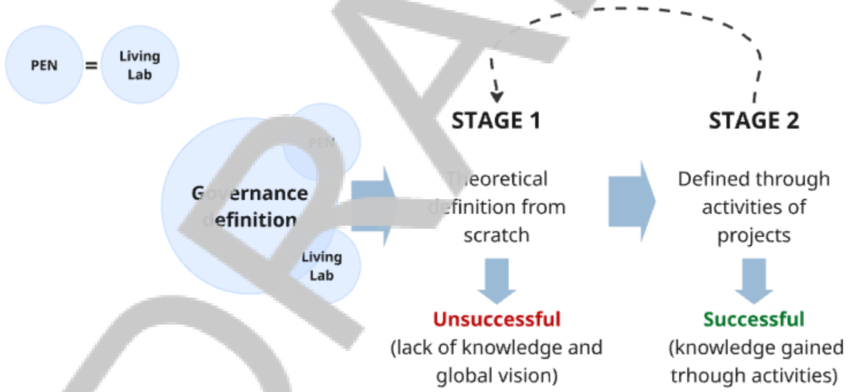


Figure 24: Explanation of the process definition of the governance structure and model of the PEN and Living Lab. Source: UPV/EHU.

Currently, different **levels of governance** can be distinguished. On the one hand, at the district level **(macro level)**, we find the core group and the expert group that make operational and strategic decisions. They are in contact with the stakeholders' ecosystems through key **local actors** (ambassadors) and the district council. When a new project is created, a steering group and one or more working groups are established at the **local level (meso level)**. Within each project, at the **micro level**, different activities are carried out, each of which has its own management system.

More formally, important actors included in the governance of the two pilot sites are the **Pamplona City Council** (owner of the San Pedro complex), as well as the **La Compasión Escolapios School**, who itself is the direct owner of the school complex.

Regarding the **stakeholders who engage with Pamplona Living Lab solutions daily,** the social groups are different. In the San Pedro housing complex, residents include people with disabilities, while La Compasión Escolapios School directly engages mainly its students, teachers and other staff in the building – indirectly, the impact is broadened to people living in the community with ties to the school (such as students' families) as well as possibly other educational institutions in the Rochapea region, for whom the La Compasión Escolapios School can set a positive example and learning opportunity for similar future initiatives. The activities of Escolapios have had a **domino effect,** and currently the four schools in the district are involved, creating synergies between them and collaborating on joint projects, something that is unprecedented in the district. The community and local stakeholders of Pamplona have been mapped based on the idea of a quadruple helix community, which includes academia, industry, civil society and the government (Figure 26 below). More specifically, the stakeholders derived from the quadruple helix are mapped as follows:

- **Civil society:** residents of the San Pedro area, including current social housing residents and potential future (post-renovation) residents. The La Compasión Escolapios School stands as a central social actor within the area, offering not only an essential space for student learning but also a broader hub of education for the community. Drawing students from across Rochapea, the school holds significant potential to serve as an active agent throughout the district by supporting community education while fostering the adoption, expansion, and replication of project initiatives. The local community is also involved in co-creation, testing and knowledge exchange, also facilitating dissemination.
- **Government:** a main stakeholder (regarding interest as well as influence) in this domain is the City Council of Pamplona along with several of its departments, such as Nasuvinsa (the public housing and urban development agency), but also energy, environmental education and communication, among others. This administration is involved broadly in all main community building and engagement as well as dissemination activities.
- **Industry/private sector**: technology and service providers, construction, utility, and energy companies, social housing companies, distribution system operators and small business associations. These actors are mainly included in renovation activities (OBENASA, Ibañez, ED engineering, ID domotica, etc.), the creation of ideas and products, testing, energy trading along with supply and management (DSO, other energy suppliers).
- **Academia**: includes oPEN Lab partner university (UPV/EHU), other research centres, CENER IRE, CENER Solar and CENIFER. Throughout this project, a focus on publications, training materials, collaboration are the centre of interest and value for this stakeholder group. [3] Their role is coordinating and managing the Living Lab and the PED (UPV/EHU), supporting community building, trainings, raising awareness and involving various agents, creating new concepts or improving them through co-creation processes. Academia also participates in different working groups.

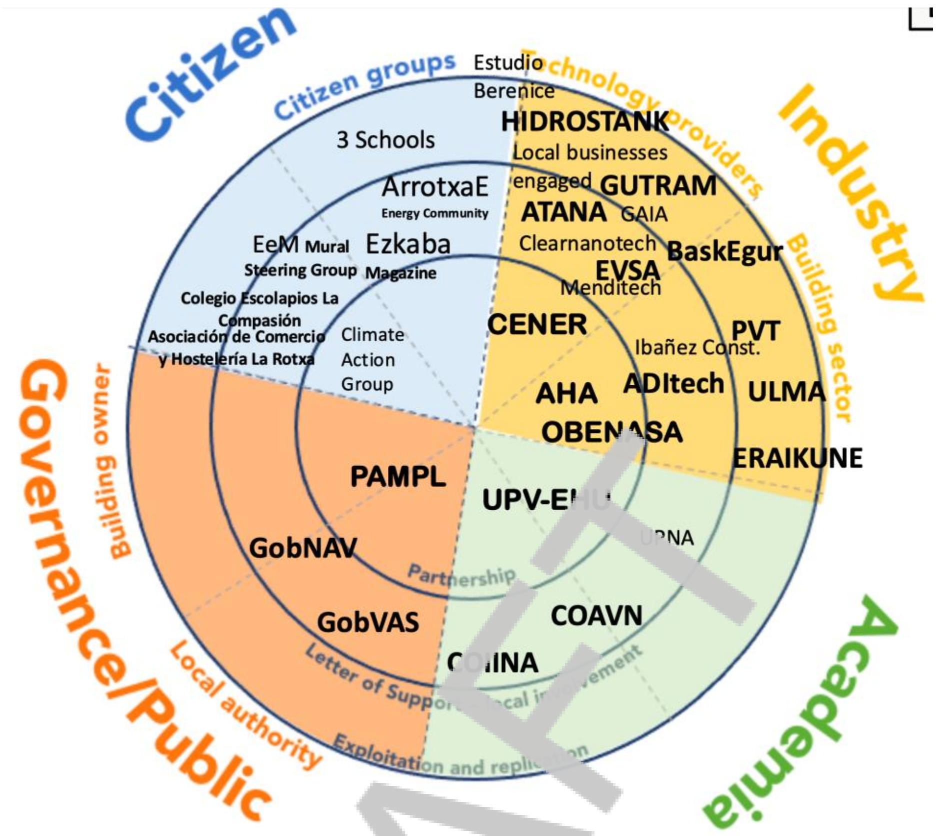


Figure 25: Updated version of quadruple helix outlook in Pamplona Living Lab. Source: UPV/EHU.

The Pamplona Living Lab has also offered important insight from the activities of the PEN office as well as the citizens working and steering groups, which were governance models set up to foster direct stakeholder dialogue and engagement, providing answers and explanations to any Living Lab operations and activities, to ensure a community-centred approach as well as guarantee the maximum efficacy and uptake of the solutions in Pamplona. Therefore, stakeholder engagement activities across the Pamplona pilot sites have been successful, combining co-creation and creative output (for instance in the form of community murals and the Txio Txio project), to foster commitment to the solutions and ensure that the design and solutions remain relevant for the community.

5.4.3. Operational models

Operational roles

On the meso-level in the oPEN Lab project, it is possible to distinguish different operational roles and management system layers:

1. **AH Asociados** is the coordinator at local level, taking charge of ensuring that the different pilots carry out the established actions and achieve the established objectives.
2. **Owners of the pilot buildings**: The City Council in the San Pedro building, and La Compasión Escolapios in the school. They make the final decisions on the solutions to be integrated into the renovation.

3. **Technical experts** in the different areas of building renovation, who support the owners in the design and decision-making process. Among the partners of oPEN Lab is CENER, which specialises in sustainable energy production, energy management (BMS/HMI), energy twin and heat harvesting; AH Asociados, who provides support in BIM modelling, installations and architectural solutions, and assists owners in managing renovations. UPV/EHU provides support for the co-creation actions that have been established as part of the renovations, the monitoring of buildings before, during, and after the works, energy storage studies in collaboration with CENER and AR/VR solutions.

   Other technical experts who are not part of the project consortium also play an important role in the renovation process and subsequent operational phase. These include builders, engineering firms, sensor manufacturers, energy providers, DSOs, material suppliers, photovoltaic installers, etc.

4. **The UPV/EHU leads social innovation actions** at the urban level. Together with the **City Council**, they are responsible for raising awareness, engaging and involving local agents, as well as disseminating the activities carried out in the district at the community level and carrying out co-creation processes for both project activities and new ones that arise.

5. **The City Council** through the PEN office, with the collaboration of other departments, promotes the implementation of diverse initiatives that support the district's energy transition (building renovations, PV installation, nature-based solutions, etc.).

Although they are not partners in the oPEN Lab project, there are intermediaries or ambassadors who actively support the co-creation and dissemination processes. Among them, it is worth highlighting the four schools in the neighbourhood, the traders' association, the Landare association, the neighbourhood council and residents. This group is becoming increasingly consolidated, becoming not only disseminators and active agents in the project's actions, but also promoters of new ideas.

Management of energy production, distribution and consumption

Regarding the **San Pedro building**, the City Council is responsible for managing the building as its owner. However, the residents of the flats and their needs are managed by the **CERMIN** association. For energy management, CENER has implemented a BMS (Building Management System) and energy digital twin, and the subcontractor ID domotica has implemented the HMI (Human-Machine Interfaces) and all the sensors necessary for the BMS and HMI. A percentage of the energy produced is **transferred** to the REC and the rest is **consumed** by the building itself and/or stored in its batteries for use during periods without energy **production**.

PV energy self-consumption in San Pedro buildings:

Initially, the building's design planned **two supply points** (CUPS), one for Portal 11 and one for Portal 12. The PV installation was physically divided between both portals, with a **collective self-consumption** setup proposed for each. The allocation percentages were going to be crossed between them; for instance, the production from San Pedro 11 shared with Portal 12, and vice versa.

This planning allowed for **real, joint management of self-consumption** through the BMS , extending beyond the scope limits of the inverters. The HMIs for each building and their connection with the EMS (Energy Management System) add a layer of prediction to correct and improve the BMS's decision-making.

Sharing the PV production between the two buildings is permissible under current legislation. However, due to the internal management restrictions of the DSO company, a single CUPS is not allowed to participate in more than one collective self-consumption scheme. Given this issue, the way forward was involving two other municipally owned buildings in the **two collective self-consumption systems**.

Given these premises, the design of the self-consumption systems is as follows:

San Pedro 11:

- **PV Production:** 80% for the building needs.
- **PV Production:** 20% for the neighbourhood senior citizen's club needs.
- **BMS Management:** Shared with SP12.
- **HMI:** SP11's own.
- **Inverter and Batteries:** SP11's own.
- This supply point services the public EV charging post.

San Pedro 12:

- **PV Production:** 70% for the building needs.
- **PV Production:** 30% for the Environmental Education Museum needs.
- **BMS Management:** Shared with SP11.
- **HMI:** SP12's own.
- **Inverter and Batteries:** SP12's own.

Regarding the **La Compasión Escolapios school** building, the La Compasión Escolapios group is responsible for managing the building as its owner. For energy management, CENER will implement a BMS and energy digital twin, and the subcontractor Inbiot will be in charge of supplying all the sensors necessary for the BMS and HMI. The energy produced is consumed by the building itself and/or stored in its batteries for use during periods without energy production.

CENER will manage the virtual exchange of energy between the two buildings.

Energy systems integration

In the **San Pedro** site, energy management systems, including control signals and data, are managed by a specific **Building Management System (BMS) along with EMS** [40], which is centralised at the building level. Additionally, each flat (dwelling) has access to an interactive home automation system control, which guides new residents through an interface and therefore encourages the residents to take on the role of an active residents. [55]

At **La Compasión Escolapios School**, the heat gathered from the roof will be used by the classrooms, while the roof will also be the location of several other planned installations, namely heat pumps, thermal storage, EMS/HMI and batteries. The double-flux heat recovery systems will be placed in the offices, classrooms as well as the gym, while e-meters and sensors will be placed throughout the entire building for effective monitoring. [50]

Further, in both buildings, more detailed energy monitoring measures are planned to include the following:

- **3D and photogrammetry scan** before, during and after works (photogrammetry assisted by drone and terrestrial laser scan).
- **Installation of sensors** for Indoor Air Quality, energy consumption, energy production, energy management.

- **Optical sensors** to characterise heat flow through the thermal envelope and support building digital twins
- **Quality of envelope analysis**: U-value, thermography, air tightness test, fluxometry, (Heat Loss Coefficient).
- Advanced **weather station** (temperature, relative humidity, wind speed and direction, precipitation, sky irradiance, etc.).
- **Pyranometer** for accurate measurement of global solar irradiance.

5.4.4. Financial models

The Living Lab activities are financed through grants (public funds) as well as self-funding. The business model of the Pamplona Living Lab is based on the "**Urban centre model**": a public-private economic model driving groups carrying out the activities of the Living Lab (e.g., AH Asociados and OBENASA in collaboration with Pamplona City Council and the Universities). [3] [69] Work is currently underway to define a more financially sustainable model that does not depend on public funding.

5.4.5. Ownership models

For the San Pedro pilot site, **Pamplona City Council** is the owner and thus responsible for overseeing the renovation process. For La Compasión Escolapios School, the **school itself** owns the school complex, giving the school's management team control over renovation procedures and making decision-making quick as it is an internal process. [50]

Regarding the pilot site in the former industrial complex of IWER, which had initially been included in the plans as a counterpart to the two apartment buildings in San Pedro, renovation could not be initiated by May 2024, due to legal complexities, which fostered delays and ultimately led to the exclusion of this pilot site from the oPEN Lab project activities to decrease uncertainties. Due to these circumstances, it became necessary to formally cancel this pilot site. Nevertheless, the knowledge, experience and technical insights acquired through the activities undertaken – together with the specifications and requirements developed during the drafting of the technical project – will, in due course, be incorporated into the future redevelopment of the IWER complex. It appears highly unlikely that such a significant asset will continue to remain underutilised for an extended period.

5.5. Summary of the emerging Pamplona organisational PEN model

Pamplona represents a **socially inclusive and digitally enabled** approach to neighbourhood-scale energy transition. The Rochapea district pilots - the San Pedro housing complex and La Compasión Escolapios school - demonstrate how energy-positive ambitions can emerge through coordinated public governance, citizen participation and virtual energy sharing between buildings. At the centre of the model is thus a community-based virtual approach. The model is still evolving, but it provides valuable lessons on how community engagement, flexible regulation, and technical innovation can drive early-stage PEN development within a supportive local ecosystem.

5.5.1. Context level

Pamplona offers a **solid institutional and policy foundation** for PEN development, but faces financial and regulatory constraints that limit large-scale rollout.

Structures

Spain's and Navarre's **energy frameworks strongly support** renewable energy deployment and sharing, as well as energy efficiency, while local policy (SECAP 2030) sets ambitious decarbonisation targets. However, most financing depends on private funding and there is no specific incentive structure for going beyond minimum efficiency towards positive energy balance. Social protection and renovation support schemes exist, but remain dependent on national capacity and therefore inconsistent. Overall, Pamplona's structure supports renovation and renewable energy integration, but lacks coherent long-term financial mechanisms for neighbourhood-level scaling.

Cultures

Rochapea's social profile reflects **moderate economic vulnerability** (11.3% poverty risk) and a **diverse population**, including elderly residents and migrants. The oPEN Lab approach emphasises empowerment and local ownership through education, co-creation and visualisation tools (e.g. AR/VR). This has fostered strong community activation and a growing "energy-active" culture. Pamplona's experience highlights how inclusive, participatory processes can align social and environmental goals and provide a basis for future sustainability of efficiency initiatives.

Networks

Beyond the initiatives of oPEN Lab, there are **several networks and cooperation projects** between academia, the industry and government in Pamplona, confirming the continuous commitment to environmental goals and the general interest in developing this area of action further. The Living Lab with its engagement of local citizens fits into the existing networks by offering further insight and points of view on the local level. Strong local partnerships facilitate trust, coordination and innovation. However, long-term replication depends on maintaining citizen engagement and ensuring financial sustainability.

5.5.2. oPEN Lab level

The Pamplona oPEN Lab serves as a **bridge between municipal strategies and neighbourhood implementation**, combining technological pilots with social experimentation.

Organisational setup

The Living Lab is co-led by the Pamplona City Council and UPV/EHU, supported by CENER, AH Asociados, OBENASA and La Compasión Escolapios. Cooperation and engagement involve citizen-based core and expert groups, a district council as well as local "ambassadors," ensuring coordination between institutional and community levels. Decision-making is inclusive and iterative, enabling technical and social alignment throughout implementation.

Citizen engagement and co-creation

Engagement is highly structured through a six-step participatory strategy involving workshops, AR/VR visualisation, artistic co-creation, training and energy community development. The approach empowers residents - particularly socially vulnerable groups - to influence design, renovation and awareness activities to ensure maximum alignment between needs and solutions. The result is a citizen-centric process where residents become active participants in the transition, ensuring social legitimacy and behavioural impact.

Technological solutions

Pamplona is working towards a **virtual energy sharing model** connecting the San Pedro housing complex and La Compasión Escolapios school. Both sites integrate advanced PV systems, building envelope upgrades, heat pumps and EMS/HMI. This digital linkage enables real-time energy balancing and optimises renewable use. Despite the IWER site's current exclusion as a pilot site, its preparatory work contributes learning on industrial-scale PV. Technology choices directly shape the governance and financial model by linking public assets via a shared virtual energy framework.

5.5.3. PEN level

Pamplona's PEN is still at a **formative stage**, functioning as a set of interconnected pilots rather than a single integrated system. Its most innovative feature is the **virtual energy exchange** - a scalable foundation for future neighbourhood energy communities.

PEN vision

The city envisions Rochapea as a **socially inclusive, energy-positive neighbourhood**. The current pilots lay the groundwork for future scaling by demonstrating how public buildings and housing can become renewable energy hubs while empowering citizens. The long-term goal is a self-sufficient, digitally connected district that produces more energy than it consumes.

Governance structure and model

In Pamplona, there are actors involved in governance on the macro, meso and micro level. Regarding specific stakeholders, the city operates a well-integrated quadruple-helix collaboration model, linking government, academia, civil society and industry. Governance follows a **multi-level approach**: the City Council and UPV/EHU lead strategy, supported by expert groups, local councils and ambassadors connecting to the community. Decision-making remains project-based, reflecting a municipal-led coordination model with active citizen co-governance. Over time, this may evolve into an institutionalised renewable energy community model.

Operational model

On the meso level, operations are coordinated by AH Asociados, technical experts, owners of pilot sites, UPV/EHU and CENER, managing technical execution, monitoring and virtual energy exchange between sites. Each pilot owner (City Council, School) manages its own building, but within a **shared EMS framework**. Data-driven systems allow both local optimisation and integration across the two sites - a key step towards real PEN interoperability.

Financial model

The financial setup is primarily **project-funded**, combining EU, municipal and private resources. The underlying business model - the Urban Centre Model - promotes public-private collaboration, but remains dependent on grants. Developing a post-project financial framework is crucial to ensure sustainability and expandability.

Ownership model

Ownership mirrors the **institutional diversity** of the pilots: San Pedro is publicly owned by the City Council, while La Compasión Escolapios is partly privately owned. There are no collective ownership mechanisms yet, but future energy community structures could introduce shared governance and benefit-sharing models across the district.

5.5.4. Emerging Pamplona organisational PEN model

In the centre of the organisational design of the San Pedro housing complex and La Compasión Escolapios School is a **virtual energy sharing system**. In this model, energy linkages are created through a virtual power flow that are shared between the two sites. This creates an integrated system, increasing self-sufficiency and energy resilience, while reflecting the central role of renewable energy in the pilot sites. The **monitoring** approach to this system is also done virtually, with the help of sensors placed in each of the pilot sites, among other necessary technical interventions. This real-time data is integral to accurately monitor and predict consumption patterns as well as balance the energy flows between the two buildings.

Pamplona's organisational PEN model has the following **core characteristics**:

- Virtual interconnection between buildings for energy exchange.
- Strong municipal leadership with participatory governance structures.
- Deep citizen engagement through co-creation and education.
- Integration of digital tools (EMS, HMI, digital twin) enabling real-time optimisation.
- Policy alignment with renewable energy deployment and sharing goals.

Pamplona's developing model demonstrates how cities can prototype energy-positive systems without full physical interconnection. By leveraging virtual energy sharing, citizen co-creation and community-based coordination, it shows a pathway to inclusively scale neighbourhood energy systems even under fragmented ownership and regulatory constraints.

Steering factors

Pamplona benefits from a **progressive regulatory environment** supporting energy communities, strong municipal coordination and a high degree of citizen participation. Education and visualisation tools strengthen energy literacy and ownership, while technological innovation (virtual energy exchange, EMS) enables local optimisation. Together, these drivers position Pamplona as a frontrunner in socially integrated PEN development.

This virtual PEN model in Pamplona is developing and implemented in Spain's **regulatory framework**, which **supports** a collective self-consumption and energy community approach. On the one side, the NZEB requirements and various objectives to increase the production and reliance of renewable energy create the necessary supply for the virtual model and contribute to sustainability standards, given that the use of renewable energy and producing a surplus of it is at the heart of the model. On the other hand, regulatory frameworks support consumer side flexibility, which is a major enabling factor for supporting collective self-consumption of energy in Pamplona.

The insights and value from activities in IWER also act as steering factors, given the activation of the community through stakeholder engagement as well as the complex's potential for future redevelopment and subsequent contributions to energy efficiency in Rochapea.

Hindering factors

While there is an enabling regulatory framework in Pamplona, there are nevertheless also some **hindering factors**, such as the distance-based limitations on building energy communities. The general sustainability of PEN renovations relies heavily on community engagement and citizen education and activity, which is why public collaboration activities have also been central to oPEN Lab projects – this supports continuity and replicability of sustainability initiatives in Pamplona. For this, finding the necessary financial support - not reliant on public funding, for instance - is also crucial. Mapping the challenges and actively working towards resolving them is a crucial part of oPEN Lab in Pamplona. To this end, the project is still actively evolving in the Rochapea district, offering opportunities to explore and test different solutions. Replication will require a more stable funding base, clear incentives for energy positivity and continuous community activation.

For a **summary** of the emerging organisational PEN model in Pamplona, see Figure 27 below.

PAMPLONA – emerging community-centric virtual energy sharing PEN model

A socially inclusive, digitally enabled and participatory pathway linking buildings through virtual energy exchange

Snapshot

- **Pilot sites:** San Pedro housing complex (public housing) and La Compasión Escolapios School.
- **Key actors:** City Council, UPV/EHU, CENER, AH Asociados, citizen groups.
- **Technical focus:** Virtual energy exchange, PV, EMS/HMI, envelope upgrades, heat pumps.
- **Social context:** Diverse district including elderly and migrant residents; moderate vulnerability.

Context overview

- **Structures –** supportive regulation for energy communities; strong renewable policies; financing inconsistent; no dedicated incentives for achieving positive energy.
- **Cultures -** social vulnerability but strong willingness to engage through education and co-creation; AR/VR tools and artistic workshops build local ownership.
- **Networks -** strong quadruple-helix partnerships; Living Lab fits into larger sustainability networks; future replication depends on sustained engagement and funding.

Living Lab highlights

- **Organisational setup -** co-led by municipality and academia; inclusive multi-actor coordination.
- **Citizen engagement –** six-step participatory process; ambassadors, district councils, co-creation.
- **Technological solutions -** virtual energy sharing between two buildings, advanced PV, EMS, real-time optimisation tools.

Emerging PEN features

- **PEN vision -** a digitally connected, socially inclusive energy-positive district.
- **Governance -** municipal-led + community co-governance; future expansion of energy community likely.
- **Operational model -** virtual power flow; real-time balancing via shared EMS.
- **Financial model -** EU + municipal + private co-financing; grant dependency persists.
- **Ownership model -** mixed public/private asset ownership; no collective ownership yet.

Steering factors

- Enabling regulation for collective self-consumption.
- Deep citizen involvement and strong educational processes.
- Digital tools supporting optimisation and transparency.
- Multi-level governance structure.
- Future energy potential of IWER building.

Hindering factors

- Distance limits on energy communities.
- High grant dependency; unclear long-term financing.
- Needs sustained engagement to maintain momentum.
- Limited incentives for positive-energy performance.

Key takeaway

Pamplona demonstrates a **community-centric virtual PEN model**, leveraging citizen participation, municipal coordination and real-time digital tools to prototype neighbourhood-scale energy exchange. It offers a socially grounded pathway toward future PEN deployment.

oPEN Lab

Figure 26: Emerging organisational PEN model in Pamplona. Source: authors.

6. Tartu case study

6.1. Overview of Tartu oPEN Living Lab

Figure 27: Annelinn district in Tartu. Source: Ragnar Vutt.

Location

Annelinn district, Tartu, Estonia

Introduction

The **oPEN Living Lab in Tartu** is situated in **Annelinn**. Annelinn is the largest district of the city, covering 5.4 km² and housing around 24,000 people, making it the district with the highest population density in Tartu. Planned in the late 1960s by Mart Port and Malle Meelak, it was conceived as four “microdistricts,” though only two were completed before the Soviet collapse. Built mainly in the 1970s and 1980s, Annelinn is dominated by five- and nine-storey prefabricated panel apartment blocks, set out in an amphitheatre-like layout rising from the

Emajõgi floodplain. Today, the area remains a classic late-Soviet large housing estate, which suffers many issues as a result of poor planning.

The **district is the largest in Tartu**, stretching along the left-side bank of the river Emajõgi. It boasts two high schools and four basic schools, a nursing home and an elderly day centre, various sports centres and a library in addition to various service hubs for food and shopping.

Socio-economically, Annelinn is **diverse but carries a distinct profile** within Tartu. Statistically, the majority of Tartu's Russian-speaking residents are concentrated there, making the district culturally and linguistically diverse. The district is known for being a densely populated, mixed community where the key challenges are aging infrastructure, parking problems, energy efficiency and social cohesion.

Current policy emphasis is on preventing decline by fostering renovation, improving services and integrating the district more fully into Tartu's development trajectory. The oPEN Lab initiative includes the **deep renovation of two apartment buildings in Annelinn** and additional PEN solutions in the fields of energy storage and renewable energy production.

While the original deep renovation ambition of the project, which was aimed at a district of nine-story apartment buildings of which three were targeted for renovation, remained unfulfilled, it entailed several important tasks that helped shape and understand the emerging PEN in Tartu. One of the key actions was the development and validation of a high-fidelity **digital twin** for a representative high-rise residential neighbourhood. The digital twin covers a minimum of 22 buildings, clustered based on their location and typology, and fully integrated with the district heating grid. This neighbourhood-level digital representation serves as the baseline for estimation, comparison and optimisation of future energy scenarios, supporting the transition towards PEN.

Additional **surveys** of the district and tight cooperation with local housing associations have further informed the creation of a PEN in the city.

Some facts and figures

- Annelinn's total population is 24,551 [70] and the district covers an area of 5.4 km^2.
- Population density is the highest in the city: ca 5,100 per km^2.
- Built during the Soviet occupation era, the district is dominated by five- and nine-storey prefabricated panel apartment blocks with poor building quality.
- The district was left unfinished – only two of the four planned neighbourhoods were ever built.
- It is home to a multicultural and multilingual community – while a proportion of the inhabitants have been living there since its conception, it is also a home for temporary workers and students.
- Due to changing needs, the district faces many challenges as a result of poor planning, construction quality and cramped space.

Figure 28: Tartu oPEN Lab overview. Source: authors, Ragnar Vutt (photo credit).

6.2. Tartu oPEN Living Lab context

This chapter provides contextual insight into Tartu's oPEN Lab neighbourhood by examining the underlying **structures**, **cultures** and **networks**. The aim is to lay the groundwork for understanding how local contexts shape the organisational models of PENs.

Figure 29: Chapter 6.2 explores the context level in Tartu. Source: authors.

6.2.1. Structures

This sub-chapter explores the **structural conditions** shaping each oPEN Lab neighbourhood, focusing on their **economic settings**, **regulatory frameworks** and **physical characteristics**. Understanding these foundational aspects helps explain the practical opportunities and constraints faced in implementing and scaling PENs.

Economic setting[22]

As of 2025, Estonia is marked by one of the **highest annual inflation rates in Europe** [71]. This surge in inflation has elevated the cost of construction materials, labour, and financing, increasing the expenses associated with zero energy renovations[23]. Combined with the volatile geopolitical landscape and the energy crisis catalysed by Russia's invasion of Ukraine, which prompted the country's near total ban on Russian energy sources and a disconnect from the Russian electricity grid, the small nation has experienced **unprecedentedly turbulent conditions** both economically and in the energy market.

In Estonia, 96% of apartments are privately owned [72], which are organised into apartment housing associations and housing co-operatives. The proportion of state-owned social housing is relatively low in Estonia (1.1%), which is significantly below the EU average of 8% [73]. As such, **apartment building renovations depend heavily on the private homeowners' decision** to renovate, which can be hindered by several factors. Firstly, while there is a national renovation grant available and additional Renovation as a Service (RaaS) support (in Tartu), the upfront cost can be too high for housing associations, despite the promise of long-term savings. Additionally, renovation prices in Estonia have increased by 100% between 2010 and 2018, with latest market prices continuing to show growth [74]. Secondly, in multi-apartment buildings, achieving consensus among residents for renovation projects can be challenging and is considered a major barrier to renovations.

As in the rest of the country, the local market conditions in Tartu for PEN rollout are mostly characterised by **energy efficiency initiatives**. This includes the Estonia's long-term renovation strategy [75] which sets specific renovation goals by 2050 (see more in next chapter); the public subsidies to support renovation, such as EIS (former KredEx) financing [76]; and the municipal services to encourage renovation, **such as RaaS** [77] **in Tartu**, which provides financial support for technical consultation and renovation.

[22] For more information about the market conditions and economic instruments relevant to Tartu's PEN development, please refer to the oPEN Lab report *Towards a regulatory framework for positive energy neighbourhoods, Tartu (2024)* [91].
[23] For more information on the issue of high interest rates in Estonia, see the report *Positive Energy Neighbourhoods – Overcoming financial and market barriers* (2023) [90].

Past successful renovation initiatives such as the SmartEnCity project [78] also serve as proof of concept, encouraging further near-zero energy renovations and moving towards a PEN.

Regulatory setting[24]

While the creation of PENs is not specifically incentivised by the Estonian government, there are several factors and regulations that encourage their development which are described in the following passages.

Dynamic tariffs and demand-side flexibility. Estonia has implemented mechanisms to encourage demand-side flexibility, a crucial component for PENs. For instance, the government offers payments of up to 5,000 euros per megawatt-hour (MWh) to consumers who adjust their electricity usage during peak demand periods. This approach not only helps balance the grid but also incentivises the adoption of smart energy management systems within communities.

Energy efficiency standards for buildings. To promote energy-efficient construction, Estonia has established minimum energy performance requirements for buildings. As of 2020, new buildings are required to meet Class A standards, effectively making them Nearly Zero Energy Class buildings. For major renovations, including renovations supported by the national funding scheme, buildings must achieve at least Class C. These standards encourage the integration of energy-efficient designs and technologies, such as prefabricated components, which support the development of PENs as they are quicker to install, making scale-up easier (e.g., neighbourhood level renovations), compared to 'traditional' renovation methods.

Long-term renovation strategy. Estonia's Long-Term Renovation Strategy (LTRS) aims to improve the energy performance of buildings nationwide: its main goal is to completely renovate the building stock to energy performance class C by 2050, making it necessary to renovate 100,000 private houses, 14,000 apartment buildings and 27,000 non-residential buildings in the coming years. The strategy includes measures to support the renovation of both residential and non-residential buildings, with the objective of making the nation's building stock energy efficient and reducing CO_2 emissions.

Renewable energy subsidies and reverse auctions. To promote the use of renewable energy sources, Estonia has established a system of subsidies and reverse auctions. Through these auctions, renewable energy producers can receive a sliding premium on top of the market price for electricity, providing financial incentives for the generation of renewable energy. This system supports the integration of renewable energy into communities, a key aspect of PENs.

Additionally, according to the Energy Policy Development Plan (ENMAK) 2030 [79], by 2030, 80% of heat produced in Estonia must be from renewable energy sources, and the energy efficiency of buildings must increase to at least class C which is another regulatory incentive guiding PEN development.

Reducing GHG emissions. The National Energy and Climate Plan (REKK 2030) [80] from 2019 sets out various targets: for example, ambition has risen in the governance agreement for 2021-2023 which envisions climate neutrality by 2050. This goes beyond the 80% GHG

[24] For more information about the regulatory frameworks relevant to Tartu's PEN development, please refer to the oPEN Lab report *Towards a regulatory framework for positive energy neighbourhoods, Tartu (2024)* [91].

emission reduction by 2050 which had been set out in the General principles of climate policy document from 2017 (KPP 2050).

However, **several regulatory barriers or gaps** still exist that hinder the emergence of PENs in Estonia:

- **Low renovation ambition**: the minimum requirement for major renovations is an Energy Performance Certificate (EPC) class C, which is insufficient for deep decarbonisation at the PEN scale; there are few incentives to exceed the minimum, with A-energy class renovations being much more costly than lower class ones.
- **Constraints on energy sharing**:
    - Energy sharing within or between apartment building blocks in Estonia remains largely unregulated and technically challenging. The transition from individual apartment-based electricity purchasing to a joint purchase agreement is legally constrained: **Estonian law requires unanimous consent from all apartment owners within a building**, i.e. 100% of votes must be in favour. If even one apartment owner opposes the switch, the building cannot adopt a joint electricity procurement model. This rigid requirement significantly limits flexibility and adoption. A more practical and inclusive model would allow residents to opt-in or opt-out individually, enabling partial participation without blocking collective progress.
    - On the technical side, **energy sharing within apartment buildings or between neighbouring buildings is currently hindered by infrastructure limitations**. To enable electricity sharing without incurring standard network usage fees, extensive physical rewiring is required. This includes installing new cabling and metering systems that bypass the public grid, which is both costly and disruptive. As a result, virtual energy sharing models, such as peer-to-peer trading or community solar, are not yet feasible under current regulations and grid architecture.
- **Uncertain, fragmented support:** stop-start grant availability and unclear long-term financing reduce renovation momentum.
- **Implementation capacity:** creating PENs requires coordinated technical, legal and social processes at neighbourhood scale; current frameworks and capabilities are still evolving.

Physical setting

Annelinn is Tartu's largest, late-Soviet large housing estate planned in 1969–1973 and built mainly in 1970–1990, composed overwhelmingly of five- and nine-storey prefabricated slab-block apartments laid out as micro-districts (two of the four planned were completed).

Figure 30: Unrenovated apartment buildings in Annelinn. Source: Tiina Pitk.

Functionally, Annelinn is **mostly residential** with **local service nodes** (schools, shops, health and social services) and a few newer small commercial/office buildings. The area is oftentimes characterised as monofunctional, consisting of high-rise, high-density, residential apartment buildings.

A technical report on Kaunase 80 [81], a typical nine-storey panel apartment building in Annelinn, provides an overview of the quality of this mass-built block: prefabricated envelope with aging joints and limited insulation, and energy class D prior to renovation.

6.2.2. Cultures

As mentioned in the previous chapter, Annelinn is the densest and largest district in Tartu. While there is no distinct socio-demographic data available on the residents, surveys show that the district hosts not only most of the city's Russian-speaking minority, but also a wealth of other minorities, making it a very culturally diverse area. In terms of how this may affect PEN development, while **it provides a rich cultural base to draw on, it also presents potential problems in terms of aligning differing cultural expectations regarding urban developments**.

In the 2023 survey "Tartu and Tartu people" commissioned by the Tartu city government [82], the residents of Annelinn appreciate the homely feel of the district and the proximity of services. However, they also expressed the most negative opinions about their surroundings, citing **lack of cleanliness, beauty and greenery as issues**. Additionally, noise, parking problems, and safety were also mentioned as concerns. The local residents were also more likely to bring up social problems such as drunk and loud people.

The questionnaires conducted during the oPEN Lab project [83] showed that while the residents consider the public space in their neighbourhood important, only a third would be willing to participate in improving it. Surveys also showed that currently, there is **little cooperation between the housing associations and residents**, even though more than half of the respondents consider it to be important. Regarding climate resilience, most respondents feel that heat waves are "bearable" for them with only a quarter supporting the installation of a cooling system in the apartment building.

Social acceptance of renovation remains uneven. While some residents see renovation as an opportunity to improve comfort and property value, others perceive it as costly and disruptive. Housing associations act as collective decision-making bodies, but achieving consensus across residents is a challenge.

The district has its own **representative body** (Annelinna Selts – Annelinna Association [84]), a grassroots non-profit organisation founded in 2016 with the goal of uniting the various communities of the district and to represent their interests. The association has several online media channels and organises annual Community Days for the neighbourhood.

6.2.3. Networks

The transformation of the Annelinn district should be viewed in the larger Tartu context. In the city, there are several key local stakeholders supporting and coordinating the creation of smart, inclusive, and energy-efficient neighbourhoods, the most important of which is **the Tartu City government**. The local government is the catalyst and initiator of the oPEN Lab initiative and a key source of financial support to test the innovative prefabricated panel renovations. They are responsible for issuing permits and ensuring the district develops sustainably.

The key partner to the city government are the local residents and the **housing association of the Uus 1 apartment building**, who is responsible for the renovation decision. Tight cooperation between the city government, the residents and their representative body, and the other local supporting actors is vital to ensuring the success of the innovation project and launching of the PEN in the district.

A key technology partner is GREN that offers renewable energy-based district heating – a crucial component in the emerging Tartu PEN.

Other important local actors are the Tartu Regional Energy Agency (TREA), the University of Tartu, Tallinn University of Technology (TalTech), the Institute of Baltic Studies (IBS) and many more (see more about the Tartu Living Lab set-up in chapter 6.3.1.).

6.3. oPEN Living Lab Tartu

This chapter explores how the Tartu PEN has been organised and implemented through a Living Lab approach that brings together public, private and civic actors in a shared governance structure. It also presents the technical solutions demonstrated in the neighbourhood, highlighting the renovation strategies, energy technologies and integrated systems that make up the core of Tartu's energy-positive transformation.

Figure 31: Chapter 6.3 explores the Living Lab level in Tartu. Source: authors.

6.3.1. Organisation

The Tartu PEN is located in the Annelinn district – a dense, culturally diverse space that suffers from poor urban planning. The aim of the PEN in the region is to contribute not only to the positive-energy development of the neighbourhood, but to build a community that is inclusive and forward-thinking.

Stakeholder roles and governance

In the development of the Tartu Living Lab, the leading partner and initiator is **the Tartu City government** (most notably, the Spatial Planning Department but also working horizontally with other departments - such as the Department of Public Relations and the Department of Municipal Property - where needed), supported by a Strategic Steering Group (including IBS, TREA, TalTech, the University of Tartu, and other local stakeholders). The local government is the catalyst and initiator of the initiative and a key source of financial support to test the innovative prefabricated panel renovations. They are responsible for issuing permits and ensuring the district develops sustainably. Decisions are taken at two levels: strategic decisions via the city council and steering group, and operational decisions in weekly working group meetings (technology and engagement). This distribution of roles reflects a hybrid governance model where municipal leadership is complemented by research partners and consultants.

The key partner to the city government are the local residents and the **housing association of the Uus 1 apartment building**, who is responsible for the renovation decision. Tight cooperation between the city government, the residents and their representative body, and the other local supporting actors is vital to ensuring the success of the innovation project and launching of the PEN in the district.

Another key actor is the **Tartu Regional Energy Agency (TREA)**, which offers technical consultancy and support to housing associations both in the district and in the city at large.

The University of Tartu and the **Tallinn University of Technology (TalTech)** support the development of the PEN in Tartu with research and technical consultancy, while playing an important role in citizen engagement as well. The university's experts have provided renovation calculations for the targeted houses and developed a renovation calculation tool to facilitate these discussions [85]. They are also responsible for creating renovation solutions.

The Institute of Baltic Studies (IBS) provides additional research support and coordinates the citizen engagement activities together with the other project partners. IBS is also responsible for the home automation tender, which is a crucial element in deep renovations.

Citizen engagement and co-creation

Building on **decades of good participatory practices**, the Tartu city government has been actively involving the local residents in PEN creation. Even though the Tartu Living Lab has been subject to three pivots during the project, citizen engagement and co-creation have been central in planning.

Regular **information events** to introduce deep renovation technologies, goals and ambitions, along with "**dreaming workshops**" for co-creation have been held with all apartment buildings who have expressed a wish to join the project [86]. Additional **study visits** to inspire and facilitate experience exchange have been organised throughout the project.

In the case of the Ravila 49 apartment building, which ultimately declined the renovation offer, several home automation workshops were also held to discuss smart home solutions and their benefits, and a renovation working group was created to make decisions on behalf of the residents and prepare the technical tender of their apartment building.

As of September 2025, similar plans are also in place for the new building, Uus 1, where a preliminary resident survey has already been held. This will be complemented by home automation workshops (including informational materials, user trainings, etc.), co-creating an artwork, and co-creationally improving the immediate surroundings of the building.

In case an active community of owners emerges in the neighbourhood who wishes to apply for additional funding for public space solutions, the city government also boasts annual **participatory budgeting**, which empowers citizens to propose, vote on, and implement the ideas of their choice.

Value proposition

The Living Lab organisation brings value to several stakeholder groups:

- **For the residents and citizens:** support in preparing for large scale renovations; additional financing; support in the implementation phase; bringing the best and innovative technical solutions to the area; engaging the community, increasing their awareness of energy-efficiency and offering support in determining the actual condition of their apartment building; and rejuvenating the neighbourhood co-creationally.
- **For the public sector:** complying with and delivering strategic climate goals, implementing relevant mitigation measures; boosting innovating; bringing the best external and foreign expertise to the city.
- **For the private sector:** testbed for innovative solutions and services.

6.3.2. Technological solutions

The **Tartu PEN centres around the renovation of two apartment buildings**, one privately owned (Uus 1) and one a city-owned social house (Mõisavahe 67). Both are five-story buildings and in dire need of renovation. EV chargers near the houses and in the neighbourhood, an innovative thermal storage solution, and other renewable energy production and storage solutions complement the emerging PEN.

The **objective of the Tartu PEN demonstration** is to:

- **Fully renovate** two apartment buildings using prefabricated panels to demonstrate their efficiency and feasibility in high-rise renovations.
- **Implement, test and monitor various technological innovations** such as
  - **thermal storage** that links to the Tartu Living Lab district heating area and integrates multiple sources of heat, collecting industrial residuals, surplus from air conditioning and renewables, and converting excess PV electricity to heat; connected through a community heat network it acts as a buffer that balances generation and consumption, with effectiveness increasing as the network grows and diversifies;
  - **BIPV** that has never been implemented in apartment building renovation in Estonia but is increasingly important in achieving PEN-level energy-efficiency;
  - **PV panel battery with inverter** for crisis situations.
- **Create a digital twin for a representative high-rise residential neighbourhood** which provides a validated neighbourhood-scale baseline that quantifies hourly heating and electricity demand, compares and optimises renovation and energy transition scenarios, identifies required envelope and system upgrades, evaluates the technical and operational potential of building-integrated PV under real urban constraints to maximise local self-consumption, and supplies actionable evidence for

stakeholders to plan short-term renovations and long-term pathways to climate neutrality.

- **Involve the residents** of Annelinn in the abovementioned innovations through engagement and co-creation.

In short, the following **technological interventions** are planned in the Tartu PEN:

- **Uus 1 apartment building renovation**
    - Deep renovation with prefabricated panels, including installation of ventilation with heat recovery
    - PV on the roof and façade (BIPV) of the building with a battery storage solution
    - Joint purchase of electricity (renewable energy community)
    - Home automation with smart metering
    - EV chargers
- **Mõisavahe 67 social housing apartment building renovation**
    - Deep renovation with prefabricated panels
    - Installation of ventilation with heat recovery and a noise attenuator
    - Testing the nine-storey prefabricated panel renovation solution on one end wall: testing a mid-belt connection detail to distribute the load of the prefabricated panels onto the building's wall structure, resulting in the panels on the four lower storeys being supported by the foundation, while the panel on the upper storey is supported by the mid-belt
    - PV on the roof and façade (BIPV) of the building with a battery storage solution
    - Joint purchase of electricity (renewable energy community)
    - EV chargers
- **Thermal storage**
- **Other**
    - EV charging in the district

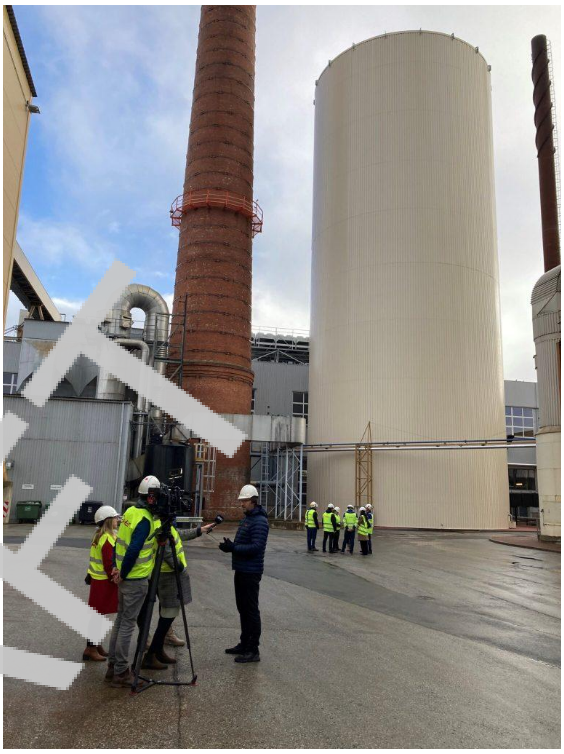


Figure 32: Thermal storage by GREN. Source: GREN.

Complimentary to the oPEN Lab project, the nearby Raatuse school will also receive PV on the roof and façade of the schoolhouse with a battery storage solution, including an inverter for use in crisis situations. A PV-panel-covered roof for one bike sharing dock will also be tested and installed.

Figure 33: Mõisavahe 67 renovation in progress (September 2025). Source: Annika Urbas.

Renovation as a Service

RaaS is a **free renovation support service** [87] for apartment buildings to help housing associations plan renovations and secure extra funding from the national grant scheme. The goal is to raise the housing association boards' and residents' understanding of renovation options, funding sources and conditions. The programme is co-funded by the European Investment Bank together with the City of Tartu and runs from May 2023 to June 2026. Work is organised through regular meetings with each housing association and its board. The service guides buildings through three stages:

1) **Preparation for up to 150 associations**: mapping renovation needs, producing a written technical overview, issuing energy labels from consumption data, drafting design briefs and preliminary budgets aligned with funding institution's rules, estimating owners' payments before/after renovation, seeking initial loan terms from banks, and providing template contracts (technical consultant, design, construction, supervision).

2) **Decision-making for 50 associations**: training days for boards, solar PV simulations (including shading and payback), and refined financials based on construction bids.

3) **Contracting for 25 associations**: final financing after tenders, hands-on support to reach signed construction contracts, plus guidance and trainings on construction quality control.

6.4. Moving towards an organisational PEN model in Tartu

This chapter outlines the organisational models of the Tartu PEN, examining how governance, operations, financing and ownership are structured to support long-term sustainability. Grounded in local conditions and stakeholder dynamics, the model reflects a context-specific approach to managing energy renovation and innovation at neighbourhood scale.

Figure 34: Chapter 6.4 explores the PEN level in Tartu. Source: authors.

6.4.1. PEN vision

The Tartu PEN is situated in the Annelinn district, a **large post-socialist housing estate** with a population of around 24,500 and a building stock consisting mainly of prefabricated apartment blocks from the Soviet occupation period. The neighbourhood is experiencing a deteriorating building stock, poor energy efficiency, visual decline, and social issues, all of which highlight a pressing need for revitalisation.

The Tartu PEN focal points are the **two apartment buildings** at Uus 1 and Mõisavahe 67, and the Raatuse school, which are the main sites of the deployment of the technological innovations.

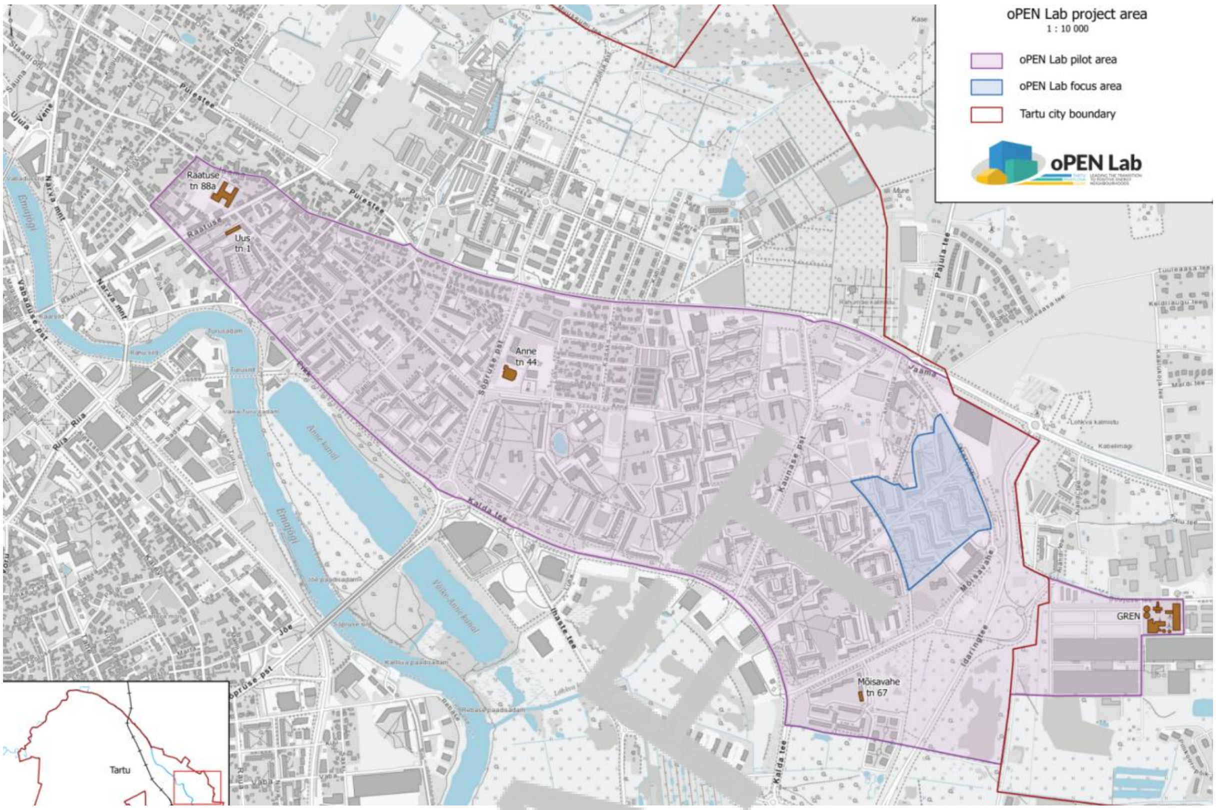


Figure 35: Tartu PEN area on a map. Source: Tartu City Government.

The **vision of the Tartu PEN is to demonstrate a model, in which housing associations and residents are supported through prefabricated deep energy renovation, renewable energy integration and neighbourhood-scale energy solutions**. The PEN seeks to deliver not only lower energy use and emissions but also a better living environment, improved comfort, increased property values and community empowerment. Therefore, PEN is not merely a technical demonstration but also a social innovation process, fostering trust, municipal leadership and co-creation with residents.

The jointly created Tartu PEN motto is: *Let's renovate Tartu dwellings and improve the living environment together with the community!*

The aims of Tartu PEN are:

- **Test a technically innovative renovation solution** that combines prefabricated panel renovations on (high-rise) apartment buildings, energy production and storage solutions and energy savings.
- **Pilot BIPV** which is a new technology in not only the Tartu PEN but also the country as a whole – the approach is very important for high-rise buildings where roof surface for PVs is limited.
- **Overcome renovation barriers** by providing solid precedents of innovation along with guidance materials and good practices.
- Provide **feedback and lessons for the policy makers and stakeholders** regarding launching renovations and overcoming renovation barriers in both technically and socially challenging environments.

- **Achieve the energy transition and climate objectives outlined in various national action plans** (Tartu Energy 2030+, Estonia's long-term renovation strategy etc.).
- **Foster a sense of community in a culturally rich yet often overlooked area** that is frequently excluded from urban development initiatives.

In the Tartu case, the **PEN principles are applied on a building level**: after switching to joint purchase of electricity, the residents will become an energy community – amending their internal charter to reflect this and producing and consuming their own electricity, thereby maximising on local production as there are limited opportunities to share surplus energy. Additionally, the thermal heat solution by GREN will contribute to district heating by coupling many energy sources across a community network, releasing heat when demand peaks. This helps balance generation and consumption, shave peaks and fuel use, raise the share of renewables and improve reliability and affordability for a wide mix of producers and consumers.

However, there are **several barriers** to why PEN cannot be fully realised in Estonia. From the energy production and sharing perspective, the key ones include:

- **Limited flexibility in energy sharing between and within apartment** buildings poses challenges for the collective consumption of locally produced electricity. Currently, this approach is restricted to common areas, as supplying electricity directly to private apartments necessitates a unified contract with the electricity DSO. Additionally, it requires internal sub-metering and all owners to transition from individual retail contracts to a collective energy purchasing model.
- **Insufficient legislation governing energy sharing among housing associations**: while virtual sharing could theoretically be possible, there are no relevant regulations or existing practices.
- **Costly storage arbitrage**: high network transfer fees and double grid taxation of stored electricity undermine the business case for batteries and other flexibility assets and services.
- **Limited DSO incentives:** the network operator has few drivers to enable numerous small urban PV and storage connections; system planning favours centralised capacity and grid reinforcement.

6.4.2. Governance structure and models

The emerging Tartu PEN is governed by a grid of stakeholders who own the interventions: residents, service and technology providers and the local government. The **governance of the Tartu PEN is organised through a multi-layered structure**:

Municipal leadership: The City of Tartu acts as the initiator and catalyst, coordinating the PEN, co-funding RaaS, and facilitating stakeholder engagement in various ways: information events, workshops, public consultations and more.

Housing associations: These remain the ultimate decision-makers for private apartment buildings, with collective voting procedures determining participation in renovation and energy investments. In an energy community, the residents participate in energy production and consumption and make collective decisions for the management of their energy system via collective voting.

Service providers: Enefit (EV charging and storage) and GREN (district heating and thermal storage) operate as asset owners and service providers with limited integration into a neighbourhood-wide governance framework. Construction companies offer renovation services, which are secured through procurements, based on current market prices.

Research and consultancy partners (TREA, University of Tartu, TalTech, IBS) provide technical validation and citizen engagement support for the PEN projects.

Decision-making authority is distributed. Housing associations hold final voting power on whether their building undergoes renovation. The city orchestrates the overall process, but consultants act as gatekeepers, since state rules require their involvement in renovation grant applications. This creates a multi-actor governance model where influence is shared across public, civic and private stakeholders.

6.4.3. Operational models

As mentioned above, on a building level, the Uus 1 and Mõisavahe 67 apartment buildings will **produce and consume their own energy**, storing the surplus in a battery or selling it back to the grid. In case of the former building, the owner of the systems and the main decision-making body is the housing association. Regarding the Mõisavahe 67 social house, the owner is Tartu city government with the battery and EV chargers belonging to the service provider (Enefit).

Energy systems integration:

- GREN, a local district heating and cooling provider, supplies the neighbourhood with district heating, which incorporates an innovative heat storage solution that uses renewable, waste, and surplus heat.
- Enefit manages the EV chargers and the existing EV network of the district.
- Enefit manages the battery and the battery management system that controls the battery.
- Electricity is provided by various suppliers, which the consumers (local government, housing associations, or private residents) can choose from.

Maintenance and monitoring of these systems is conducted by their respective owners.

In case of the Uus 1 housing association, **home automation solutions** will assist them in smart monitoring of their building's energy output and consumption. Apartment owners will be able to monitor, control and automate the room temperature and sun protection blinds; to monitor air humidity, CO_2 and total volatile organic compounds level, water and electricity consumption, building PV production and current power source, building total energy consumption and outdoor weather indicators. The building manager will be able to remotely control the heating and ventilation systems, monitor total consumptions and building digital twin, get technical alert messages and send messages to apartment owners.

6.4.4. Financial models

The PEN financial model related to deep energy renovation is designed around minimising resident burden while delivering systemic value. For residents, the renovation model provides support in renovation planning (e.g,. RaaS in Tartu), financing and implementation, reducing complexity and transaction costs. For the public sector, it delivers progress on strategic climate and innovation goals. For private companies, it serves as a testbed for new products and services. **The deep energy renovation projects in the PEN are financed partly through EU project funding** (for example oPEN Lab and Life IP BuildEst projects in Tartu) and municipal contributions, complemented by national renovation grants (EIS) and bank loans taken by housing associations (see Figure 37).

In case of the Uus 1 apartment building, the state renovation grant and bank loan cover 45% each, with EU project support covering the remaining 10%. Municipal support was offered in the form of technical support, experience sharing and know-how. The Mõisavahe 67 social house represents an exception as there, the municipality was the main financer of the renovation due to the ownership structure.

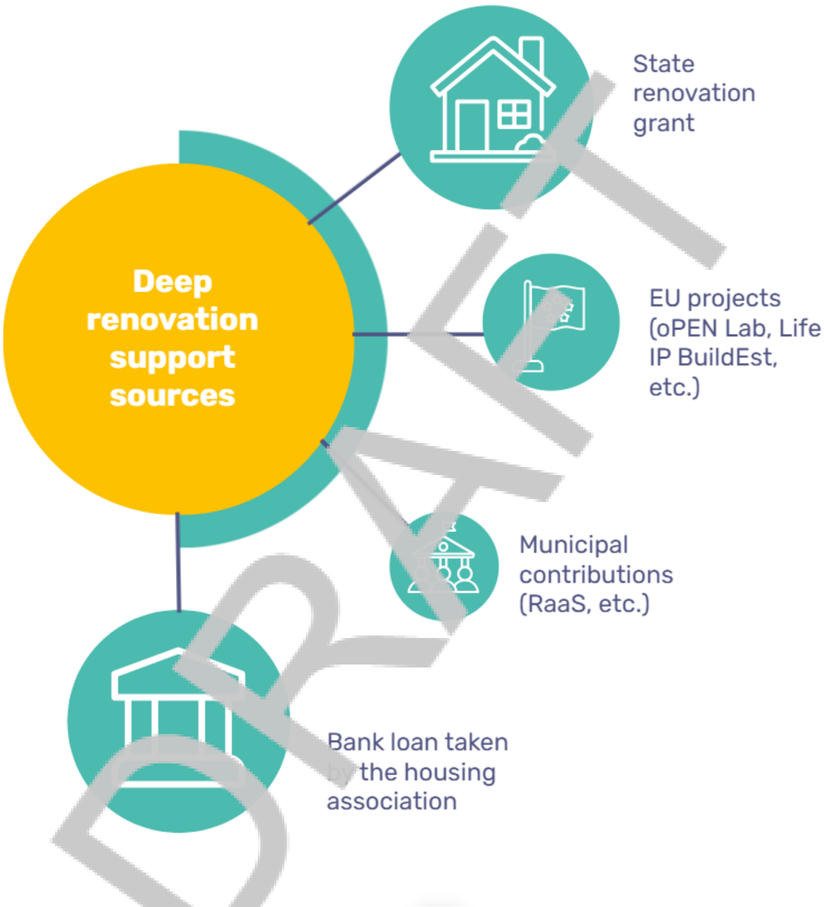


Figure 36: Deep renovation support sources in the emerging Tartu PEN. Source: authors.

The renovation grant scheme in Estonia by the Estonian Business and Innovation Agency (EIS; formerly KredEx) [88] is meant for the renovation of residential buildings. Grants support either full, deep energy renovation or targeted measures like replacing gas/solid-fuel/electric heating with renewable systems or connecting to district heat. Eligible buildings are typically pre-2000 apartments with an active housing association and works must match the approved main design project. Calls open in the state e-grants portal for a defined window whereby the applicant is the apartment association (or the municipality if it owns the whole building), and a housing association resolution is required, i.e., a majority vote by the owners in favour of renovation. However, in large apartment buildings with hundreds of apartment owners, reaching consensus is very challenging. To address this issue, dedicated renovation consultants are available to advise housing associations; however, most of the effort still relies on volunteer-led housing associations.

Despite financial models, the **ambition for major renovations remains insufficient for PEN applications**. Estonia mandates an Energy Performance Certificate (EPC) class C for major renovations (energy use of 126–150 kWh/m²·year), which falls short of what is needed for a neighbourhood to achieve a positive energy balance. Additionally, there is also no requirement to add on-site renewables in the National Long-Term Renovation Strategy (LTRS). Coupled with only less than 10% of buildings having a valid EPC (a precondition to state-backed renovation), and the caution of banks regarding storage and flex assets (e.g., batteries), investment in PEN solutions remains low.

Revenue model

Due to various regulatory and financial barriers (see more in the *Tartu PEN context* chapter), the financial models in Tartu PEN are still in the planning stages. However, there are a few possible ways of funding and sustaining the Tartu PEN:

- **Selling electricity to the grid** – With effective management of production and consumption, a housing association could sell their surplus energy to the grid at a favourable price. However, the current high grid tariffs, restricted access to the grid (max power of 15kW), and the high rate of on-site consumption limit this opportunity.
- **Revenues from frequency services** – a battery energy storage system (paired with the solar park) can increase the on-site consumption rate, export stored energy to the grid, and provide grid-balancing (frequency regulation) services. This typically requires a contract with a service provider that dispatches the battery using optimisation algorithms. Revenues from frequency services can help finance the PEN building; for example, the revenue can help cover loan repayments. On the other hand, grid balancing strategies might limit local energy balance optimisation and risk PEN objectives as the battery operator does not focus on local consumption.
- **Using solar energy as energy sources for EV chargers** – in the Tartu PEN, EV chargers will be installed near the two renovated houses. The housing association could channel the solar energy directly or via batteries into EV charging stations, billing the respective users of the service (either external or residents of the house). However, this is a theoretical option, as it is not currently achievable. When it comes to sharing financial risks, then beyond the warranty period, those are always covered by the owner.
- **Renovation grants** – in Estonia, apartment building renovations are financed primarily with state grants and bank loans with additional support from the municipality or EU projects, where applicable.

Still, relatively low energy prices in Estonia **undermine the self-sustaining business case**. Calculations demonstrate that expected energy savings alone cannot cover deep energy renovation costs. In addition, double grid fee taxation of storage, restrictions on collective self-consumption and the lack of DSO obligations to buy local renewable energy limit opportunities for additional revenue from surplus electricity or flexibility services. EV charging fees and surplus sales remain theoretical.

In summary, the Tartu PEN financial model relies mostly on **grants, municipal support and loans**, with little incentive for private investment. Additional revenue opportunities from local energy production remain rather low. Without regulatory reform and new financial products that value environmental, social and governance impacts, the model risks being difficult to sustain without continued public support.

6.4.5. Ownership models

Ownership structures in the Tartu PEN are **fragmented** across multiple actors:

- Housing associations own building-level assets such as PV systems and renovated building elements.
- The municipality owns social housing assets and coordinates shared services in municipal land.
- Private energy companies own and operate specific infrastructure: Enefit manages EV charging points and batteries in public space, while GREN owns thermal storage assets in the district heating system.
- Technical consultants as required by the national renovation grant scheme hold a unique governance role: although they do not own physical assets, their legal role in grant procedures gives them significant influence over renovation pathways.

This financial and ownership setup underlines the fragmented organisational reality of the Tartu PEN. **No single actor** integrates financial flows or ownership responsibilities across the neighbourhood. This fragmentation increases transaction costs, complicates coordination and limits risk-sharing. It also makes it challenging to establish a PEN-level ownership and operation model that would integrate energy flows across buildings. Nonetheless, the current ownership structure demonstrates that municipalities and housing associations can co-exist with private providers, creating a hybrid ownership regime. The challenge ahead lies in developing mechanisms that allow joint ownership, cooperative models, or contractual frameworks (e.g. Energy Performance Contracting or Energy Services Companies) to better integrate responsibilities.

6.5. Summary of the emerging Tartu organisational PEN model

Tartu shows how **strong municipal leadership, advanced digital tools and multi-actor coordination** can drive energy transition in a high-density, post-socialist housing context. The city's approach builds on years of experimentation in smart city projects, combining technical precision with social sensitivity. Through the oPEN Living Lab and the RaaS model, Tartu reduces transaction costs and mobilises homeowners, utilities and research partners around shared goals. While the PEN is still in formation, its evolution demonstrates how municipal-led innovation can gradually transform fragmented apartment districts into integrated, energy-efficient and data-informed neighbourhoods.

6.5.1. Context level

Structures

Tartu operates within a **solid policy framework** that actively promotes energy renovation through national energy efficiency standards, municipal climate strategies and innovative schemes such as RaaS. These instruments create a favourable foundation for PEN development, particularly in the city's dense housing estates. The presence of a district heating network and the construction of a large-scale thermal storage facility provide the technical infrastructure needed for sector coupling, peak management and greater renewable integration. However, the fragmented ownership typical of post-socialist apartment blocks and the intermittent availability of funding continue to slow progress. Although policies and institutions are well aligned with PEN objectives, regulatory barriers on collective energy sharing and limited long-term financial mechanisms constrain the shift from individual building renovation to neighbourhood-scale transformation.

Cultures

The cultural context of Tartu's Annelinn district reflects both its **diversity and its history**. The area combines long-term residents with younger and migrant populations, creating a varied social context where attitudes towards renovation and sustainability differ widely. While many households value comfort and reliability, financial caution and limited awareness can reduce engagement in energy initiatives. To address these challenges, the city and its partners have invested in inclusive and multilingual communication, working through community intermediaries such as the Annelinna Association. This emphasis on dialogue and accessibility helps build trust, enabling residents to see renovation as both a technical and a social improvement. Over time, this approach has strengthened community cohesion and increased openness to collective solutions, positioning culture as a key enabler of long-term behavioural change.

Networks

Tartu's institutional and innovation networks form one of its greatest strengths. The municipality leads coordination and strategic planning, supported by the Tartu Regional Energy Agency, universities and private companies such as Enefit and GREN. Together, these actors create a **coherent ecosystem** that connects research, policy and implementation. This cross-sector collaboration allows for effective testing and scaling of new concepts such as digital twins, prefabricated renovation and district-level energy storage. While public and research partners provide technical and organisational stability, continued integration of private actors and community representatives will be essential for the network to evolve into a self-sustaining governance structure.

6.5.2. oPEN Lab level

Organisational setup

The oPEN Lab in Tartu functions as a **collaborative platform** that bridges municipal policy, technical innovation and social experimentation. The City of Tartu coordinates the initiative, coordinating technical partners and ensuring alignment with local energy and climate objectives. Regular working group meetings and transparent communication foster cooperation among public, private and civic stakeholders. The RaaS model simplifies complex renovation processes by pooling technical expertise, financing and project management under one framework, thus lowering barriers for apartment associations. Through this structure, the oPEN Lab has become a practical driver of large-scale renovation, translating strategic ambitions into operational reality.

Citizen engagement and co-creation

Citizen engagement in Tartu builds on a **long tradition of participatory governance and open communication**. Residents are involved through workshops, consultations and pilot demonstrations that focus on both technical and social dimensions of renovation. Interactive tools, home automation showcases and participatory budgeting initiatives give residents tangible ways to influence local decisions. However, engagement intensity varies across buildings, reflecting differences in motivation and leadership within housing associations. The city's consistent effort to sustain dialogue - through multilingual communication and on-site intermediaries - has been vital to maintaining trust and participation in a diverse community environment.

Technological solutions

The technological foundation of Tartu's emerging PEN integrates prefabricated deep renovation packages, building-integrated photovoltaics, battery storage and smart energy management systems. A high-fidelity digital twin supports planning, validation and real-time optimisation, improving both design quality and investment reliability. The integration of large-scale thermal storage into the district heating network enhances flexibility and enables greater renewable uptake. This combination of technologies shows how **innovation can be adapted to a dense urban environment**, balancing advanced solutions with practical feasibility and social inclusiveness.

6.5.3. PEN level

PEN vision

Tartu's vision for its PEN is incremental and pragmatic. Rather than aiming for immediate energy autonomy, the city focuses on building a replicable model of smart, low-carbon living. The goal is to transform high-density apartment areas into **energy-efficient, comfortable and socially cohesive neighbourhoods** through deep renovation, digitalisation and coordinated energy management. The emphasis is on creating the conditions for a future PEN - technically, institutionally and socially - rather than achieving full energy positivity in the short term.

Governance structure and model

The governance model is **multi-layered and cooperative**. The City of Tartu provides overall coordination and policy direction, while housing associations act as key decision-makers for building-level renovation. Utilities, universities and energy agencies contribute technical, financial and communication support. Although the arrangement enables inclusive participation and cross-sector coordination, it remains largely project-based and lacks a permanent structure dedicated to PEN governance. The challenge ahead lies in institutionalising these collaborative mechanisms to ensure continuity beyond the current project cycle.

Operational model

Operationally, the Tartu PEN is developing around **building-level energy communities** connected through shared infrastructure such as the district heating network and thermal storage. Prefabricated renovation, home automation and smart energy systems optimise consumption patterns and enable flexible operation. However, due to regulatory restrictions, direct energy sharing between buildings remains limited. The city therefore focuses on local optimisation and long-term planning, laying the groundwork for future inter-building exchange once regulations evolve.

Financial model

The financial framework combines EU project funding, national renovation grants, municipal support and private financing from banks and homeowners. While this blended approach allows projects to proceed, it remains **vulnerable to grant discontinuities** and limited access to affordable credit. Energy sales and flexibility markets do not yet provide sufficient returns to sustain investment independently, making the financial model heavily reliant on public support and coordination.

Ownership model

Ownership structures in Tartu reflect the **complexity of post-socialist housing systems**, with most buildings managed by apartment associations and technical assets owned by separate public or private utilities. This fragmentation complicates collective investment and long-term operation. Efforts to develop shared governance and maintenance models are under way, but a unified ownership or cooperative framework for the PEN as a whole has yet to emerge.

6.5.4. Emerging Tartu organisational PEN model

Tartu PEN in Annelinn is a **municipality-led, dynamic model** that interacts with the electricity grid and the district-heating network. The city orchestrates governance and financing through a living lab set-up and RaaS support, aligning the work with wider climate goals and coordinating a hybrid governance structure consisting of various important public, private and civic actors. While the local community is always engaged as the ultimate decision-makers to private homes renovation, the community governance approach is still a work in progress as the neighbourhood continues to evolve and rejuvenate.

The Tartu PEN also has a distinctly **technologically driven side**: prefabricated deep energy renovations at Uus 1 and Mõisavahe 67, upgrades and installations at Raatuse School, building-integrated photovoltaics with batteries, EV charging and home automation, all guided by a high-fidelity digital twin that supports scenario testing, hourly balancing and optimisation. Sector coupling is further strengthened by linkage to a large-scale innovative thermal storage solution, which improves flexibility, peak management and increases the share of renewables.

Operationally, **building-level energy communities** maximise on-site use. Due to various barriers within the supporting ecosystem (such as regulatory limits on electricity sharing across buildings) coupled with modest market incentives, mean that progress relies on grants, loans and partnerships rather than pure market returns. Even so, **the approach advances towards annual positivity** while delivering comfort, resilience and a replicable pathway for dense, high-rise retrofit contexts.

The core characteristics of the nascent Tartu PEN include:

- **Municipality as a driver**: using a living-lab set-up and RaaS to steer multi-owner retrofits and engagement.
- **Deep energy renovations coupled with innovation**: renovations that deploy prefabricated panels, BIPV with batteries, EV charging and home automation**.**
- **District heating storage**: the innovative thermal storage solution enables peak-shaving and flexibility while remaining connected to the electricity grid.
- **Building-level energy communities**: maximising on-site consumption**.**
- **Digital-twin–enabled planning and validation:** assessing scenarios, optimising envelopes and RES placement, and managing hourly demand/supply.

As such, the Tartu PEN best represents a **dynamic PEN archetype** with its grid-interactive, renovation-led, district-heating-coupled approach. It is not autonomous in terms of energy demand yet, nor is virtual energy sharing enabled due to regulatory barriers. The PEN creation is mostly **municipality-led** and coordinated with a growing emphasis on co-creation and training to fit a culturally diverse district.

The Tartu PEN is an effective model due to various reasons:

- **High-density apartment block context**: as Annelinn's five- to nine-storey apartment blocks have limited roof area and complex ownership, a dynamic, grid-interactive model that couples BIPV with district heating and storage makes higher renewable uptake feasible within tight space and fabric constraints.
- **Regulatory constraints**: current regulations limit electricity sharing across buildings, so a dynamic PEN that imports and exports within clear boundaries, and maximises on-site self-consumption where possible, may be the most practical pathway under present legislation in Estonia.
- **Social acceptance and inclusion**: city-led engagement, training and co-creation fit a culturally diverse district, building trust and capability where purely bottom-up models would most likely struggle to reach consensus at scale.

As for **replicability and scale,** prefabricated deep renovation with BIPV, standardised PV battery packages, EV charging and district heating coupling are modular and replicable, allowing the city to extend the approach across similar districts or beyond while progressing towards annual positivity.

Steering factors

Tartu's PEN development benefits from **strong municipal leadership** and an established **living lab framework** that effectively coordinates stakeholders and lowers transaction costs through the RaaS model. The city leverages its **district heating network** and newly developed **large-scale thermal storage** to achieve sector coupling, peak shaving and increased renewable energy integration. A **high fidelity digital twin** supports precise, hour-by-hour energy modelling, investment validation and operational optimisation, which enhances planning accuracy and reduces project risk. The implementation of **standardised, prefabricated deep-renovation packages** for high-rise buildings - combined with BIPV, batteries, EV charging and home automation - strengthens scalability and cost-efficiency. Additionally, **active partnerships** between the municipality, utilities, universities and the regional energy agency ensure technical robustness, credibility and effective citizen engagement. Access to **blended financing**, including EU and national grants alongside municipal support, further underpins Tartu's capacity to pilot and replicate PEN solutions.

Hindering factors

Despite these strengths, several structural and regulatory barriers continue to constrain the full realisation of PENs in Tartu. Current **regulations on collective self-consumption and energy sharing** prevent seamless energy exchange between buildings, while **unanimous consent requirements** for joint procurement slow decision-making in multi-owner apartment blocks. The **business case for storage and flexibility** remains weak due to double grid fees, high network tariffs and relatively modest energy prices. **Fragmented ownership structures** across numerous apartment associations create coordination challenges and delays in renovation decisions. Financial barriers persist as **grant availability fluctuates**, banks remain cautious towards novel energy assets and existing renovation standards lack ambition. On the technical side, **physical limitations** in dense high-rise estates - such as restricted roof space, shading and outdated building envelopes - complicate renewable integration. Finally, **inflation and supply-chain volatility** have increased capital costs and delivery risks, underscoring the need for stronger long-term financial and regulatory stability to sustain the city's transition towards fully operational PENs.

For a **summary** of the emerging organisational PEN model in Tartu, see Figure 38 below.

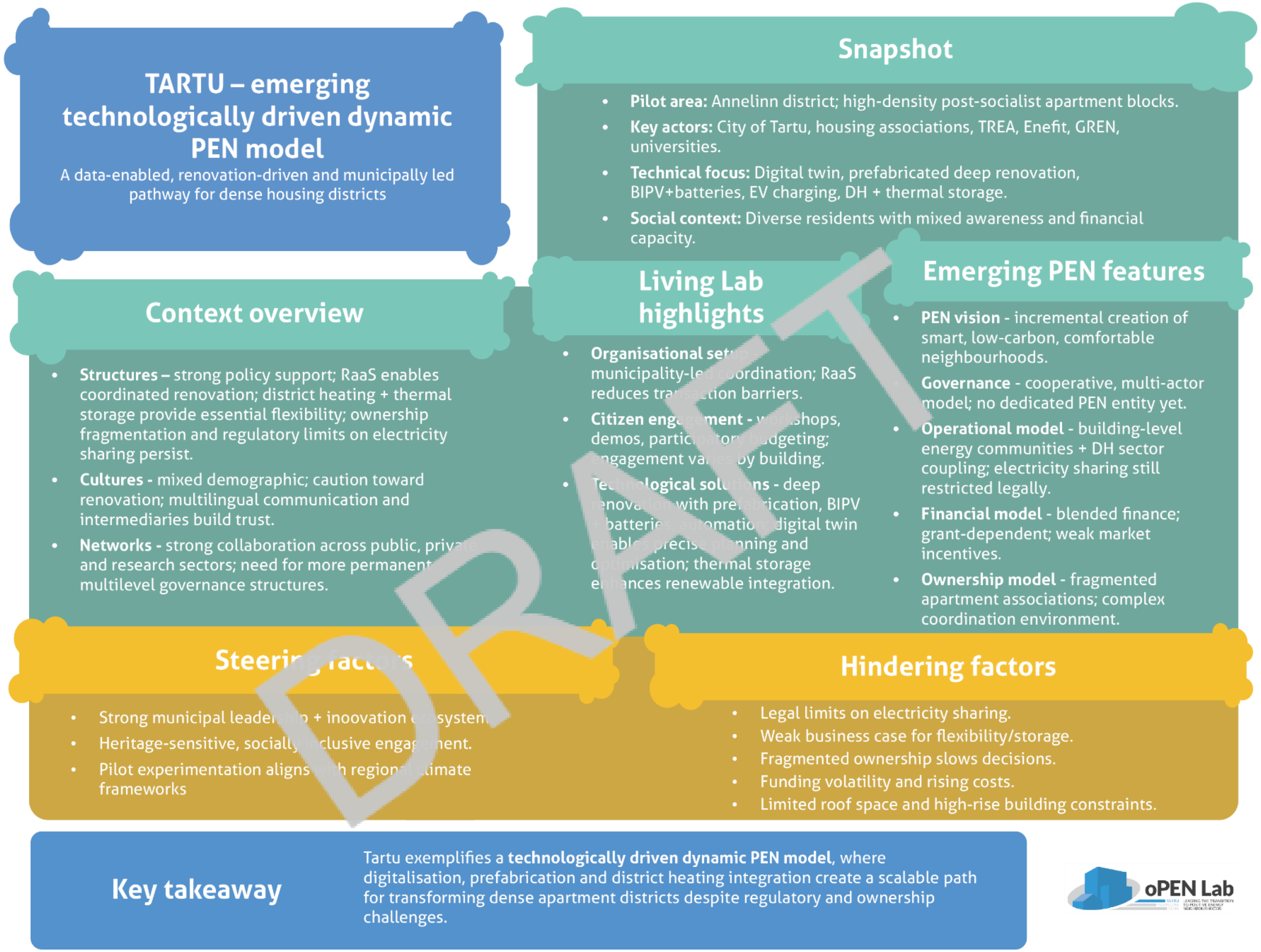


Figure 37: Emerging organisational PEN model in Tartu. Source: authors.

7. Emerging PEN organisational models in oPEN Lab

The comparative analysis presented in this chapter benchmarks the three oPEN Lab case studies - Genk, Pamplona and Tartu - to **identify patterns, differences and transferable lessons** in the development of PENs. The benchmarking approach builds on the three analytical levels (context, Living Lab and PEN) and integrates two complementary archetype frameworks resulting from the literature analysis: (i) **organisational archetypes**, describing governance orientation - technologically driven, community-centric or policy-driven; and (ii) **systemic archetypes**, describing the energy boundary and system configuration - autonomous, dynamic or virtual. This integrated framework allows each case study to be positioned both in terms of its organisational logic (who drives the transition and how) and its systemic operation (how energy is produced, exchanged and balanced).

7.1. Comparison and benchmarking of emerging PEN organisational models in oPEN Lab

7.1.1. Comparison across analytical levels

Across all three cases, **municipalities act as key orchestrators** of PEN development. Technologically, the trajectories highlight the **use of advanced solutions**, but organisationally, it is very much an ongoing process with no finished models. All three PENs remain transitional, moving from pilot-based coordination towards more systemic, self-sustaining neighbourhood energy models, while local factors such as heritage protection, housing typologies, regulatory design and social dynamics shape how each city defines and operationalises the PEN concept (see Table 5 below).

Analytical level	Genk	Pamplona	Tartu
Context level	Post-industrial city with strong municipal leadership, supportive but fragmented policy framework, focus on heritage-sensitive and social housing renovation.	Policy-mature city with integrated climate strategy, strong citizen focus and renewable integration, limited financial autonomy.	Technically advanced smart city, robust energy infrastructure, complex ownership and regulatory barriers in high-rise housing.
Living Lab level	Municipality-led experimental environment centred on Thor Park, collaboration with EnergyVille, moderate citizen involvement.	Co-governed by city, academia, and community, strong citizen participation through co-creation and visualisation tools.	Municipality-led RaaS framework, deep integration of research and private partners, participatory engagement via housing associations.
PEN level	Early-stage PEN focused on renovation and efficiency in Waterschei and Nieuw Texas, fragmented ownership and strong reliance on public funding.	Virtual energy sharing between a public and private site, digital integration and participatory governance, currently project-funded.	Emerging PEN integrating district heating, BIPV, storage and digital twin, no energy sharing yet, blended finance and fragmented ownership.

Table 5: Case study comparison across analytical levels. Source: authors.

7.1.2. Comparison by organisational archetype

The three cases represent distinct governance logics within the organisational archetype framework (see also Table 6). Genk exemplifies a **policy-driven** model, where municipal and regional authorities guide direction. Pamplona embodies a **community-centric** approach, leveraging citizen engagement and shared learning to drive transformation. Tartu aligns with a **technologically driven** archetype, using data and innovation as the primary enablers of systemic change. While these categories simplify complex realities, the cases show increasing **hybridity** - combining elements of technology, policy and participation. The most promising PENs are those able to integrate these three orientations coherently.

Archetype dimension	Genk	Pamplona	Tartu
Dominant orientation	Policy-driven	Community-centric	Technologically driven
Main governance driver	Municipality and regional policy frameworks	Citizen co-creation and municipal facilitation	Municipal leadership supported by research and other stakeholders
Role of innovation actors	EnergyVille and Thor Park as technical backbone	City Council and UPV/EHU as participatory facilitators	Cooperation with universities, utilities, service providers, regulators, and other stakeholders
Citizen role	Moderate, guided by institutional structures	Strong, embedded in design and decision-making	Structured but willingness to participate varies across housing associations
Policy alignment	High (LEKP, Flemish climate targets)	High (SECAP 2030, national energy community frameworks)	High (national renovation strategy, local climate and smart city goals)
Replication potential	High in policy-led post-industrial cities	High for socially inclusive and virtual energy models	High in apartment building dominated, district-heating contexts

Table 6: Case study comparison by organisational archetype. Source: authors.

7.1.3. Comparison by energy system archetype

Systemically, Pamplona represents the most advanced **virtual** model, demonstrating how energy sharing can occur across non-contiguous assets via digital platforms. Tartu and Genk, meanwhile, fall under the **dynamic** archetype, focusing on grid-interactive operation and time-shifted balancing within defined spatial boundaries. Across cases, the move towards autonomous configurations remains limited, largely due to national regulatory constraints on local energy markets and self-consumption frameworks. See comparison in Table 7.

Dimension	Genk	Pamplona	Tartu
Archetype position	Dynamic (moving towards local balancing)	Virtual (multi-site aggregation)	Dynamic (district-integrated with digital optimisation)
System boundary	Fixed neighbourhood (Waterschei-Nieuw Texas)	Virtual linkage between dispersed sites	Fixed neighbourhood (Annelinn)
Energy exchange type	Limited, export-focused, no collective self-consumption	Virtual import/export via digital energy flows	High self-consumption on building level, integration with district heating grid
Autonomy level	Low - dependent on grid imports	Medium - virtual balancing between sites	Medium - local flexibility and district heating integration
Operational focus	Energy efficiency and renovation	Real-time optimisation and energy community development	Storage, flexibility and demand optimisation

Table 7: Case study comparison by energy system archetype. Source: authors.

7.1.4. Comparison of steering and hindering factors

Across all three cities, **strong local governance and cross-sector collaboration** are key enabling factors, while **regulatory rigidity and financial fragmentation** remain persistent barriers (see also Table 8). The comparative analysis confirms that systemic scaling of PENs will require sustained regulatory reform, long-term financing mechanisms and institutionalised governance structures.

Category	Genk	Pamplona	Tartu
Steering factors	Strong municipal leadership, integration with regional policy, robust research ecosystem, heritage-sensitive innovation.	Progressive policy context, high citizen participation, virtual energy-sharing model, strong education and outreach.	Strong governance and planning capacity, advanced digital and technical infrastructure, effective PPPs.
Hindering factors	Regulatory barriers to collective self-consumption, fragmented funding and ownership, dependence on project cycles.	Financial dependency on public grants, limited regulatory clarity for virtual energy, uncertain long-term citizen engagement.	Regulatory constraints on energy sharing, complex property ownership structures, limited financial incentives for flexibility and storage.

Table 8: Case study comparison of steering and hindering factors. Source: authors.

7.1.5. Cross-case synthesis and takeaways

The benchmarking reveals three complementary trajectories for PEN development in oPEN Lab (Table 9). **Genk** demonstrates how policy leadership can catalyse systemic innovation in post-industrial contexts. **Pamplona** exemplifies the social dimension of the energy transition through virtual community models. **Tartu** illustrates the role of technology and data in integrating systems at scale. Together, they form a **continuum of PEN evolution**, showing that successful neighbourhood transformation relies on balancing policy, community and technology according to local conditions.

Case	Organisational archetype	Systemic archetype	Maturity stage	Core strength	Key constraint
Genk	Policy-driven	Dynamic	Early stage	Strong public coordination, regulatory experimentation	Limited energy-sharing and financing integration
Pamplona	Community-centric	Virtual	Early stage	Participatory governance and digital energy exchange	Grant dependency and regulatory ambiguity
Tartu	Technologically driven	Dynamic	Early stage	Integration of digital twin, sector coupling, RaaS	Limited financial incentives and regulatory barriers

Table 9: Cross-case synthesis. Source: authors.

Genk is an example of an **emerging policy-driven, dynamic organisational model**. This model reflects the city's strong municipal coordination capacity and alignment with regional and national climate frameworks, positioning the municipality as a system orchestrator rather than a single project implementer. The Genk PEN operates within a **dynamic systemic configuration** - it remains grid-connected and dependent on external energy flows, but increasingly experiments with local balancing, renewable generation and building retrofitting at neighbourhood scale. Its strength lies in **institutional leadership and partnership integration**, particularly through Thor Park and EnergyVille, which provide a strong research and innovation backbone. However, the model's progress is constrained by **regulatory fragmentation, funding discontinuity and limited community-level ownership**, which keep it in an early, preparatory stage of PEN development. Genk thus illustrates how a policy-anchored city can leverage innovation ecosystems to build the governance, technical and financial preconditions for full neighbourhood-scale energy transition.

Pamplona is an example of an **emerging community-centric hybrid model with dynamic–virtual characteristics**. Its organisational setup combines municipal leadership with cooperative and citizen engagement, forming a distributed governance arrangement that balances institutional structure with local participation. The PEN's systemic boundary is **hybrid in nature**: while it maintains a fixed local geography, it also pilots virtual integration of energy assets and services across multiple sites, aligning with Spain's enabling regulatory environment for collective self-consumption. The model's key strength lies in **inclusive governance and social legitimacy**, which allow experimentation with cooperative ownership, future local financing and energy-sharing schemes. At the same time, the approach faces constraints related to **dependency on municipal facilitation and limited long-term business models**. Pamplona's trajectory reflects an emerging PEN ecosystem, trying to transition from project-based engagement towards a more permanent, multi-actor governance framework that can support broader urban decarbonisation goals.

Tartu is an example of an **emerging technologically driven, dynamic-autonomous model**. It builds on a mature municipal governance structure and a well-developed technical foundation integrating digital twins, district heating, thermal storage and a prefabricated renovation approach. Organisationally, it exemplifies **municipal-led governance**, where the city coordinates stakeholders, research partners and private firms to operationalise data-driven energy management. Systemically, Tartu represents the **dynamic archetype** - still relying on the grid but increasingly capable of local optimisation, flexibility and storage-based balancing. The city's key strengths include **high digitalisation, technical integration and effective cross-sector collaboration**, enabling it to act as a frontrunner in systemic innovation. Yet, the model remains limited by **complex apartment/property ownership structures, regulatory constraints on energy sharing and uncertain financial incentives for both deep renovations and flexibility**, which hinder full self-sufficiency. Tartu thus represents a technologically advanced but institutionally evolving PEN ecosystem, demonstrating how digitalisation can accelerate the transition towards autonomous and sustainable urban energy districts.

7.2. Comparison and benchmarking takeaways

The benchmarking reveals that while each PEN operates within distinct institutional, technical and cultural conditions, several **common organisational features** underpin their emergence and potential for replication across contexts:

- **Municipal leadership as the organisational anchor.** In all three cities, local governments act as the primary orchestrators of PEN development, either through direct management (Genk, Tartu) or through facilitative governance frameworks (Pamplona). Municipal coordination ensures policy continuity, legitimacy and integration with broader climate and energy objectives, even when technical implementation is delegated to partners.
- **Collaborative governance structures enabling inclusiveness and legitimacy.** Each case demonstrates the growing importance of multi-actor arrangements - from public–private partnerships and research consortia to community energy groups - in structuring decision-making, sharing risk and ensuring local acceptance. These hybrid governance forms balance institutional authority with participatory mechanisms, strengthening ownership and accountability.
- **Integrated and cross-sectoral operational models.** The most effective configurations link building renovation, renewable generation, mobility and digital systems into a coherent neighbourhood-scale logic. Such integration improves energy efficiency, enables real-time optimisation and enhances user engagement. However, this complexity requires well-defined coordination mechanisms, robust data management and clear role division among actors.
- **Evolving financial architectures and business models.** None of the analysed PENs currently operate on a fully self-sustaining basis. Financial viability depends on layered funding - combining EU or national grants, municipal support and, in some cases, private investment. Long-term sustainability will require stable revenue models and enabling regulatory frameworks for collective investment.
- **Contextual and adaptive design as a precondition for success.** The benchmarking demonstrates that there is no universal PEN blueprint. Effective organisational setups

are those tailored to local regulatory, market and social conditions, aligning governance capacity, technological maturity and community priorities. Adaptation, rather than replication, is therefore the key to scaling PEN concepts across diverse European urban contexts.

The study reveals that **there is no single organisational blueprint for PENs**. Instead, PENs develop as **context-specific and evolving systems**, influenced by local governance capacities, social dynamics, regulatory conditions and technical maturity. The comparative analysis of Genk, Pamplona and Tartu demonstrates that each city is charting its own pathway towards neighbourhood-scale energy transition, shaped by its institutional traditions, planning culture and socio-economic conditions.

The analysis also highlights that the **PENs in Genk, Pamplona and Tartu are still in early, formative stages of development**. None of the cities yet operates a fully functional PEN with integrated, autonomous energy management systems. Instead, each represents a **snapshot of an evolving ecosystem**, where local institutions, technologies and communities are progressively aligning around the PEN concept. In this sense, the archetypes identified in this deliverable - whether policy-driven, technologically driven or community-centric; autonomous, dynamic or virtual - should be understood as **emerging patterns rather than definitive categories**. They capture the direction in which each city is moving, not a finalised organisational or technical state.

The current findings thus offer a **baseline understanding** of how diverse urban contexts are converging towards the PEN model. Genk exemplifies a **policy-driven and innovation-oriented pathway**, led by strong municipal coordination and institutional partnerships. Pamplona represents a **hybrid governance model**, balancing municipal leadership with cooperative and private-sector participation. Tartu demonstrates a **technologically advanced and data-driven approach**, leveraging its digital twin, district heating infrastructure and living lab governance to test scalable solutions. Together, these cases illustrate the range of organisational configurations that European cities can adopt as stepping stones towards fully operational PENs.

For a **cross-case summary** of the three case studies and their emerging PEN models, see Figure 39 below.

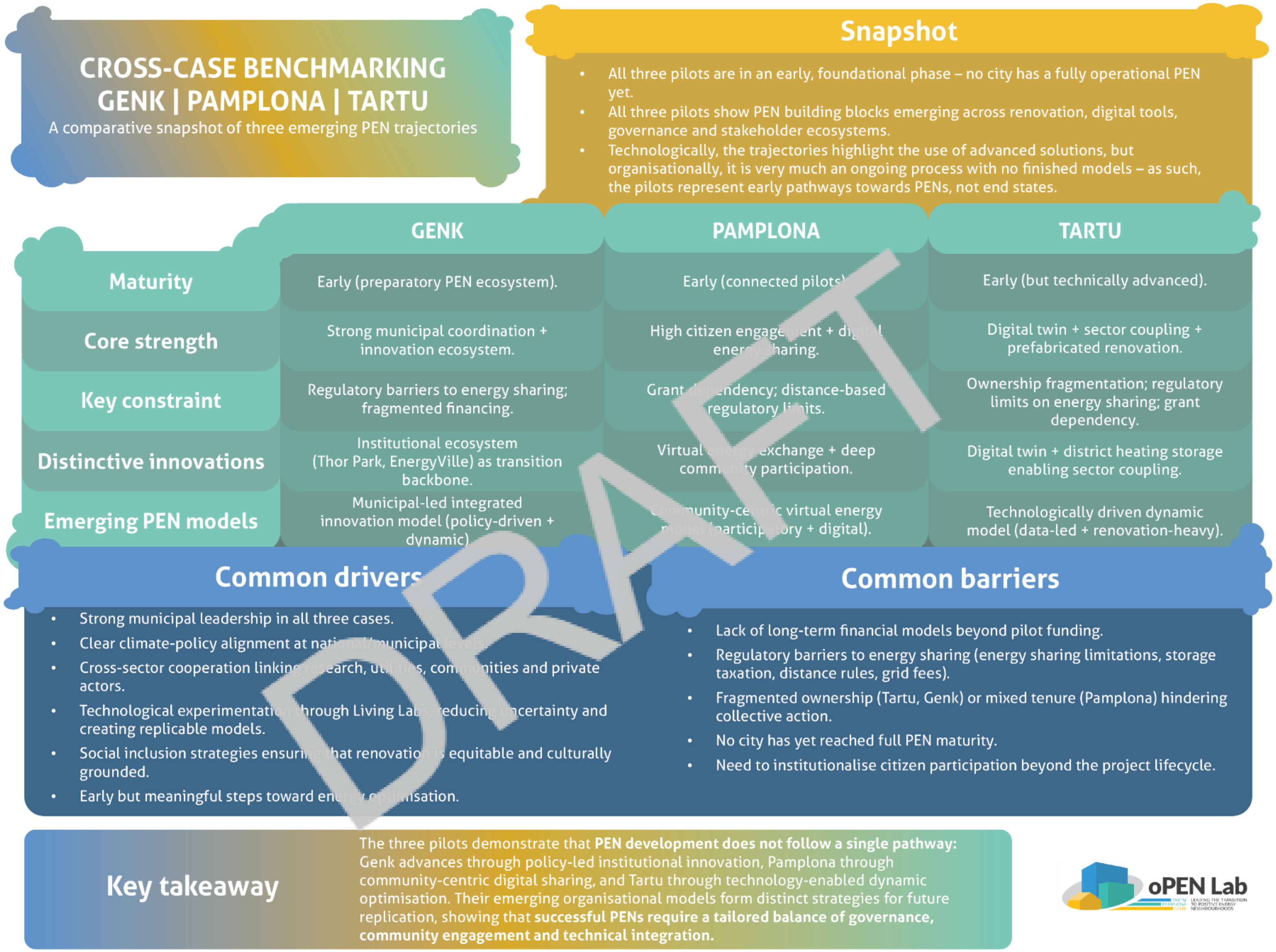


Figure 38: Cross-case summary of the emerging organisational PEN models in Genk, Pamplona and Tartu. Source: authors.

7.3. Policy and replication implications

Moving forward, **scaling and replication** will require structural adjustments that, most of all, go beyond individual building-level projects. Institutionalising the lessons from these early examples depends on coherent multi-level policy frameworks, regulatory flexibility for collective ownership and energy sharing, and mechanisms to link demonstration projects with long-term urban development strategies. Future replication efforts should therefore prioritise:

1. **Strengthening regulatory flexibility and multi-level policy alignment**, enabling municipalities to coordinate energy, mobility and housing policies and to act as integrators of neighbourhood-scale energy systems;
2. **Shifting from project-based experimentation to systemic integration**, by embedding PEN-related innovations into permanent governance structures, stable financing mechanisms and long-term urban planning processes;
3. **Fostering structured learning, capacity building and cross-city exchange**, allowing cities to adapt PEN concepts to different starting points, governance capacities and local constraints without duplicating efforts;
4. **Developing enabling European regulatory frameworks for collective action**, including shared ownership models, collective self-consumption, fair treatment of storage and flexibility, and recognition of neighbourhood-scale actors in energy markets.

First, the comparison underscores that **regulatory flexibility and multi-level policy alignment** are prerequisites for mainstreaming PENs. Cities such as Genk, Pamplona and Tartu demonstrate that neighbourhood-level innovation flourishes when local authorities have both the **mandate and institutional autonomy** to coordinate energy, mobility and housing policies. Future EU and national programmes should therefore prioritise frameworks that empower municipalities to act as integrators of multi-sectoral energy systems and facilitators of collective action.

Second, the benchmarking reveals that **PEN development requires a shift from project-based experimentation to systemic integration**. While pilot initiatives are valuable for demonstrating technical feasibility, their long-term impact depends on the institutionalisation of results through **permanent governance mechanisms, stable financing instruments and knowledge exchange platforms**. European funding programmes - particularly within Horizon Europe, the Mission for Climate-Neutral and Smart Cities and Cohesion Policy instruments - can play a decisive role in bridging this transition by linking innovation pilots to mainstream policy implementation and investment planning.

Third, **capacity building and cross-city learning** emerge as critical enablers of replication. The diversity of pathways observed - policy-led in Genk, cooperative in Pamplona and technology-oriented in Tartu - illustrates the need for flexible guidance that recognises different starting points and governance capacities. A structured framework for peer learning and exchange, combined with open-access knowledge tools, would allow cities to adapt PEN concepts to their local realities without duplicating efforts.

Finally, **the European regulatory environment must evolve to support collective ownership, shared energy services and dynamic market participation**. Enabling frameworks for collective self-consumption, fair grid tariffs for storage and flexibility, and the recognition of neighbourhood-scale actors as legitimate energy market participants will be essential for turning emerging PENs into stable, self-sustaining entities.

In sum, the results of this report underline that the evolution of PENs is both a **technical and institutional innovation process**. The archetypes identified are not endpoints as such, but

trajectories of governance and operation through which cities advance towards energy-positive futures.

The case study cities described in this report continue to evolve. How these approaches develop into sustainable PENs over time may provide useful continuous **lessons for future research and policymaking**. Understanding such developments can support the wider transition from pilot-scale projects towards more systemic urban and European energy transformations.

8. Conclusions & recommendations

The report applies a multi-level analytical framework to assess and benchmark the organisational evolution of PENs in oPEN Lab. By combining the **context, Living Lab and PEN** level structure with two complementary archetype typologies - **organisational (technology/community/policy)** and **systemic (autonomous/dynamic/virtual)** - the methodology provides a structured, but still flexible means of comparing the diverse local processes and PEN ecosystems.

This approach could be useful in revealing how **contextual, institutional and technical variables interact to shape PEN governance, organisation and implementation**. It also underscores the value of hybrid models that integrate policy direction, citizen agency and technological innovation rather than relying on any single driver.

The comparative analysis shows that while each city has progressed along different pathways, their experiences converge on **several key lessons**:

1. **Municipal leadership** is indispensable - local authorities act as orchestrators, aligning stakeholders and coordinating the complexity of emerging PENs.
2. **Regulatory frameworks** remain the decisive constraint across all contexts, limiting energy sharing and market participation.
3. **Citizen engagement** is both an enabler and a challenge - social trust, inclusion and continuity are necessary for sustained participation.
4. **Financial sustainability** is yet unresolved - all PENs depend on public funding rather than mature business models[25]
5. **Digitalisation and integration** - especially through data-driven tools and sector coupling - represent critical enablers of operational efficiency and scaling potential.

Across Genk, Pamplona and Tartu, PENs emerge not as fixed models, but as evolving and dynamic **organisational ecosystems**. Their success ultimately depends on how effectively local actors combine governance, technology and community engagement into adaptive frameworks.

For wider application beyond the pilot contexts, **three enabling conditions** consistently emerge. Rather than suggesting direct replication, the findings indicate that PEN development requires careful local adaptation supported by:

- **Institutional continuity.** PEN governance should be formalised within municipal structures to avoid project dependency.
- **Market readiness.** Clearer regulatory support for local energy sharing and collective ownership is needed.
- **Social anchoring.** PENs thrive when citizens are co-designers and beneficiaries of the transition, not just end-users.

Ultimately, the report reveals that there is **no single PEN model**, but rather a set of adaptable organisational ecosystems shaped by context. The benchmarking framework introduced in this deliverable offers a replicable tool for comparing and categorising future PENs, as a means to develop place-based solutions supporting achieving energy and climate policy goals across Europe.

Future work could build on this comparative foundation to explore the **governance transitions that enable PENs to move from project-based pilots to stable institutional**

[25] For PEN financing solutions, see the report *Enabling finance for neighbourhood renovations* (2025) [24].

configurations. Key questions include how to sustain citizen participation beyond project cycles, how to integrate neighbourhood-level energy management into citywide systems and how to design financial mechanisms that reward collective action and flexibility. At the policy level, this requires bridging the gap between demonstration and regulation, ensuring that lessons from local PEN experiments inform broader frameworks for climate-neutral urban transformation.

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