COST Action 19126

Positive Energy Districts European Network

Deliverable 3.5

Devise the concept of a virtual PED Lab for demonstrating new technologies and solutions

(Concept on the development of a virtual PED Lab)

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Executive summary

PED Labs act as catalysts to drive PED innovation and implementation, playing a crucial role in defining pathways towards climate-neutral and sustainable cities. The complexity of PED implementation requires advanced digital tools and methodologies to support design, planning, and decision-making processes. In this context, Virtual Positive Energy District Laboratories (VPEDLs) become essential digital platforms that facilitate these processes through simulation, stakeholder engagement, and regulatory testing.

The main aim of this report is to define the concept of a Virtual PED Laboratory and to identify its main characteristics, applications and functionalities.

The introduction, while summarising the differences between physical PED Labs and Virtual PED labs, highlights existing gaps in PED Labs that need to be addressed to accelerate the transition towards Positive Energy Districts.

Section 2 presents a structured review of key concepts related to Virtual PED Labs. The review is organized according to two integrative aspects: PED Labs and their related concepts, and Virtual Labs and their related concepts. Main correlation to *Digital Targets for 2030* EU Policy program, the “twin green and digital transition” and the urban digital twin are presented.

Definitions, key characteristics and features are presented in section 3, while classification criteria and typologies in section 4.

Section 5 provides a description of the digital tools, components and functionalities that characterize Virtual PED Labs.

In the last section, 2 case studies are presented as representative of (Virtual) PED Labs: the Research Centre in Lubia (Spain) CEDER-CIEMAT and the Cascais Smar Pole Living Lab in Carcavelos (Portugal): technical information, key strategies and tools, as well as standardization and upscaling strategies are reported.

This latest report of WG3 lays the foundation for future collaborations with all research groups involved in this project as a starting point for other collaborations aimed at improving processes for the achievement of the goals of climate-neutral cities and positive energy districts.

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1. INTRODUCTION

Positive Energy District (PED) Labs are urban innovation hubs focused on developing and testing solutions for creating Positive Energy Districts. These labs bring together various stakeholders, including researchers, city planners, businesses, and citizens, to collaborate on projects that aim to make districts energy-efficient, produce renewable energy, and ultimately achieve net-zero greenhouse gas emissions. PED Labs act as catalysts for driving innovation and implementation of PEDs, playing a crucial role in the journey towards climate-neutral and sustainable cities.
When introducing PED Labs it is important to take into consideration:

- **Focus on PEDs:** Their core mission is to facilitate the creation of PEDs, which are areas or groups of buildings that generate more renewable energy than they consume annually.
- **Collaborative Approach:** They emphasize collaboration among diverse stakeholders, recognizing that achieving PEDs requires a holistic approach involving various perspectives and expertise.
- **Real-World Testing:** PED Labs involve real-world testing and demonstration of innovative technologies and solutions in actual urban settings. This allows for practical evaluation and refinement of these approaches.
- **Knowledge Sharing:** They serve as platforms for knowledge sharing and learning, disseminating best practices and lessons learned from PED projects to accelerate the transition towards sustainable urban development.
- **Supporting Policy Development:** PED Labs contribute to the development of supportive policies and regulations that enable the widespread adoption of PEDs.

1.1 Physical labs as a starting point

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

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

1.2 Physical/virtual labs

The table summarizes the differences between a physical PED Lab and virtual PED lab.

Physical PED lab	Virtual PED Lab
These labs have a dedicated physical location, like an office, co-working space, or dedicated building.	These labs exist primarily in the digital realm, utilizing online platforms and tools to connect stakeholders and facilitate collaboration.
They facilitate in-person meetings, workshops, and events, fostering direct interaction and collaboration among stakeholders.	They enable remote participation and collaboration through video conferencing, online forums, and shared workspaces.
Physical labs can serve as a showroom or demonstration site for innovative technologies and solutions related to PEDs.	Virtual labs can be more accessible to a wider audience, overcoming geographical limitations and allowing for broader participation.
They can act as a community hub, providing a space for residents, businesses, and other stakeholders to engage with PED initiatives.	They can serve as a central repository for data, information, and resources related to PEDs, making it easily accessible to stakeholders.
Physical labs might house resources like libraries, databases, or equipment related to PED development.	Virtual labs offer flexibility in terms of scheduling and participation, allowing stakeholders to engage at their convenience

1.3 Existing gaps in PED Labs

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

Standardized Methodologies and Metrics:

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

Long-Term Performance and Resilience:

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

Integration and Scalability:

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

Social and Behavioral Aspects:

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

Technological Innovation and Integration:

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

Policy and Regulatory Frameworks:

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

Addressing these knowledge gaps will require collaborative efforts from researchers, policymakers, industry stakeholders, and communities. By investing in research, developing standardized methodologies, and fostering knowledge sharing, we can accelerate the transition towards Positive Energy Districts and create more sustainable and resilient cities.

1.4 Relations and Interdependencies

For this research, 98 PEDs from 33 projects were analysed, as shown in Figure 1.

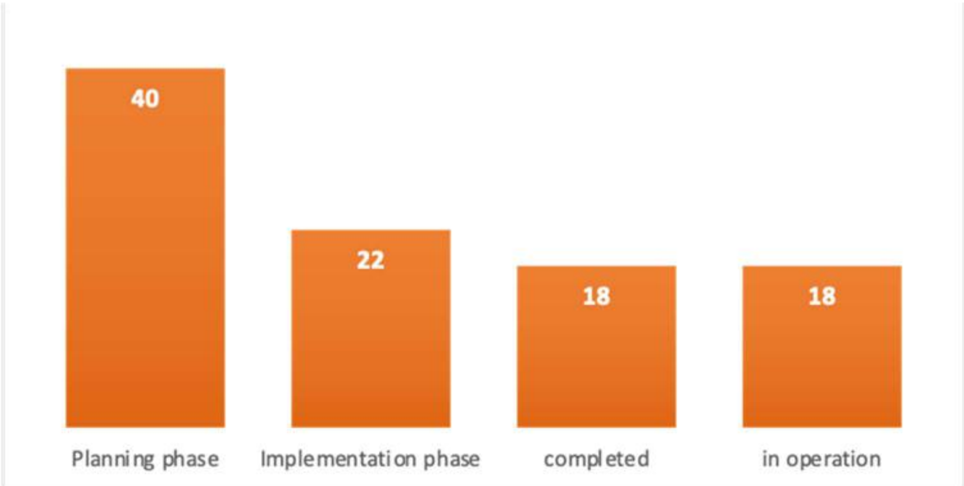


Figure 1: PEDs from PED database [PED-EU-NET, 2025]

Figure 1 gives the life cycle stage of the PEDs. 40 are in the planning phase, 22 are in implementation, 18 are completed, and 18 are in operation. In total, 100 PEDs are collected in the PED database [PED-EU-NET, 2025], 42 of these are PED case studies, while 18 are PED Labs and 38 are PED-relevant case studies (see Figure 2).
The PED-EU-NET COST CA19126 database maps 100 PED sites across Europe, categorizing them based on their level of ambition and development stage. Within this classification, PED case studies are defined as district-level projects with high aspirations for energy efficiency, flexibility, and production, aligning with the JPI UE PED Framework and aiming for an annual energy-positive balance. PED-relevant case studies share similar goals but do not necessarily meet the energy-positive requirement, while PED Labs serve as pilot initiatives for PED planning and deployment, fostering innovation across technological, spatial, regulatory, financial, legal, social, and economic dimensions. In terms of development and complexity, PED Labs are the most advanced, followed by PED case studies, while PED-relevant cases offer strong upscaling potential. The database consolidates information to evaluate the effectiveness of strategies in mapped PED case studies while remaining adaptable for dynamic

updates, integrating new data sources and ontologies. This ensures ongoing relevance and supports the creation of archetypes or “library concepts” for scenario evaluations.

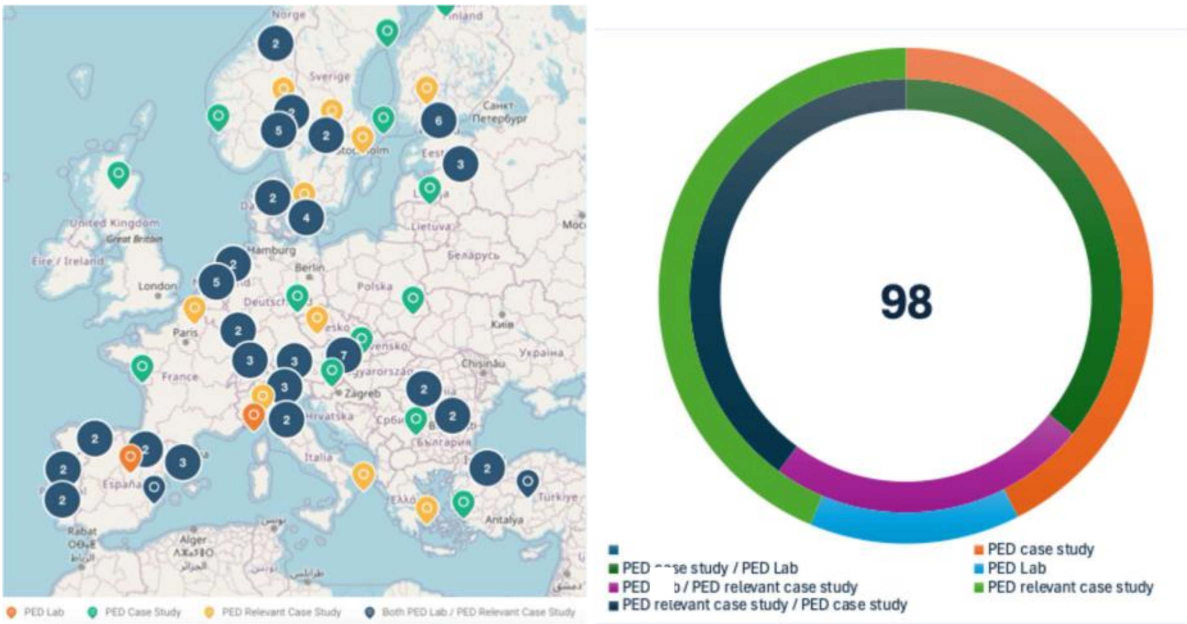


Figure 2: PED relevant case studies and PED Labs in the PED database (status: Dec 2024)

2. REVIEW OF CONCEPTS RELATED TO VIRTUAL PED LABS

The concept of a Virtual PED Lab arises from the integration of two concepts: the Positive Energy District (PED) Lab and the Virtual Lab. The previous section provided an overview of the relationships and differences between physical labs and PED Labs, as well as between (physical) PED Labs and Virtual PED Labs. Consequently, this section does not focus on the relationship between physical and virtual PED Labs but instead offers a structured review of key concepts related to Virtual PED Labs. The review is organized according to two integrative aspects: PED Labs and their related concepts, and Virtual Labs and their related concepts.

2.1 PED Labs and Urban Living Labs

As discussed in the introduction, the relationship between (physical) PED Labs and virtual PED Labs lies in their complementary roles: while physical PED Labs provide real-world environments for hands-on testing, stakeholder engagement, and demonstration of innovative technologies, virtual PED Labs extend accessibility, enabling remote collaboration, digital simulations, and data-driven decision-making to support and enhance PED development beyond geographical constraints.

PED Labs can serve as the initial foundation or research and test area for the development of Virtual PED Labs, forming the basis upon which the virtual dimension – digital environment is constructed and contextualized.

Building on previous WG3 findings, this report revisits the concept and definition of PED Labs, Urban Living Labs, and adds insights on Sustainability-oriented labs in real-world contexts. As highlighted in the WG3.1 report (Vettorato et al., 2022), the concept of a PED Lab was first formally introduced through the SET PLAN Action 3.2 (European Commission, 2018). The Action defined PED Labs in relation to Positive Energy Districts (PEDs), providing a foundational framework for distinguishing PED Labs and their roles. The SET PLAN Action 3.2 introduces the PED Labs as follows:

> *<< PED Labs, as a* ***seeding ground for new ideas, solutions and services****, will be developed according to place-based needs and local context baselines. PED Labs will follow an integrative approach including technology, spatial, regulatory, financial, legal, social and economic perspectives. >>*
>
> *<< PED Labs will be pilot actions of cities towards PEDs. PED Labs are designed for cities' needs and support concrete next steps in the planning and deployment phase, which includes a range of activities and steps towards PEDs (e.g. test new technologies, test new forms of stakeholder engagement, test new regulations, test new funding mechanisms). PED Labs should support cities in the development of innovative solutions (that can then be used and replicated in all PEDs). A systematic analysis of experiences and lessons learnt from already existing PEBs and PEDs should inform the set-up and specificities of PED Labs. The goal is to create, collect, qualify, compare and analyse data from the 100 European PEDs, which then contribute to the PED Lab. The identification of how each system innovation evolves in specific settings helps to plan and manage the spatial diffusion of such PED innovations and to strategically feed into the value chains. >>*

WG3.1 Report further highlights that the concept of Positive Energy Districts (PEDs), and by extension PED Labs, is rooted in a series of experiments initiated nearly two decades ago under the framework of Smart (Energy) Cities (Mosannenzadeh & Vettorato, 2014; Mosannenzadeh et al., 2017). Over time, these initiatives evolved and integrated into broader frameworks, including Nearly Zero Energy Buildings (NZEB), Zero Energy Buildings (ZEB), Zero Energy Districts (ZED), and Positive Energy Buildings (PEB) (Lindholm, Rehman, & Reda, 2021; Albert-Seifried et al., 2022).

Closely related to PED Labs is the concept of the Urban Living Lab, a term that, while lacking a universally accepted definition, encompasses a range of local experimental projects with participatory approaches. As described by Steen and van Bueren (2017), the term is often used interchangeably with "testing ground," "hatchery," "incubator," "making space," "testbed," "hub," "city laboratory," "urban lab," or "field lab". This broad terminology reflects the dynamic and experimental nature of initiatives aimed at addressing urban challenges and fostering innovation in sustainable development (Vettorato et al., 2022). As reviewed by McCrory at al. (2020) Urban Living Labs merge urban experimentation (Evans & Karvonen, 2011), (Bulkeley et al., 2016) with user-innovation studies (Liedtke et al., 2012), emphasizing user-centric, real-life innovation (Følstad, 2008). They also address sustainability governance and are largely shaped by European multi-city projects and the European Network of Living Labs (Voytenko et al., 2016), focusing on urban and environmental applications (McCrory et al., 2020).

Regarding positioning PED Labs within the broader European policy landscape, 3.1 Report highlights initiatives such as the Climate Neutral City Contract and the New European Bauhaus. These frameworks, still evolving, align with ongoing sustainability discussions and reinforce PED Labs as an integral part of the international discourse on urban development. Drawing from preliminary consultations on “Testing Platforms as Drivers for Positive-Energy Living Laboratories” (Soutullo et al., 2020), the report emphasizes the positioning of PED Labs within the evolving international discourse, rather than attempting to establish a rigid definition. A diagram in the report further illustrates PED Labs’ origins and positioning within Smart Energy Cities, NZEB, ZEB, ZED, and experiences from urban labs, living labs, and city incubators, all of which have shaped Positive Energy Districts (PEDs).

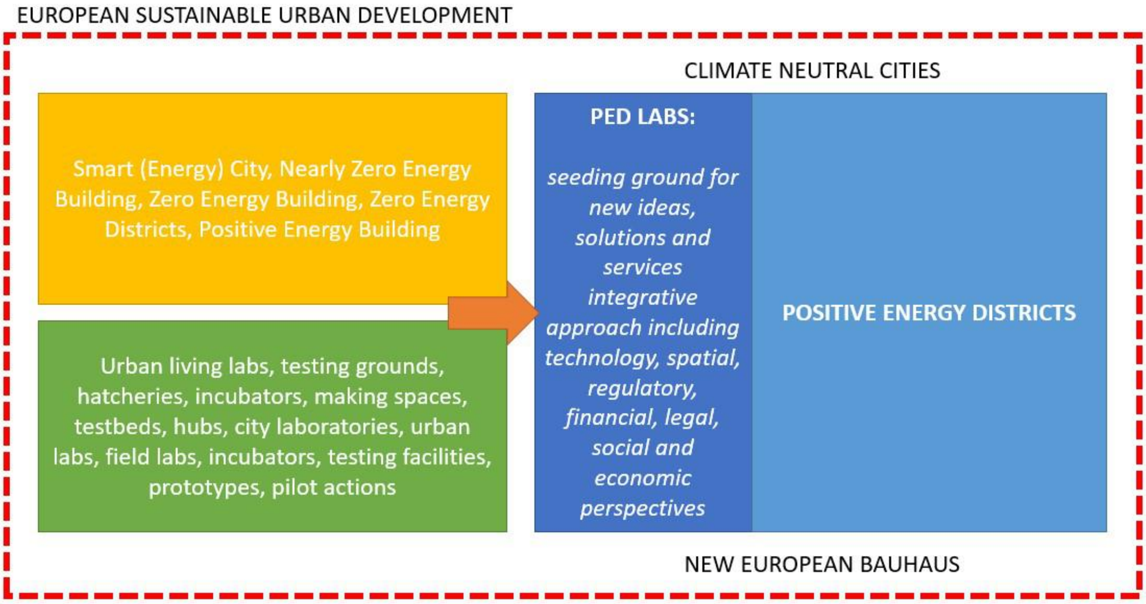


Figure 3: Positioning of PED-LAB concept in the European sustainable urban development debate, (Vettorato et al., 2022)

2.2 Sustainability-oriented labs in real-world contexts

PED Labs and Urban Living Labs are positioned within the broader spectrum of sustainability-oriented labs that operate in real-world contexts. Research by McCrory et al. (2020) highlights the growing presence and potential of these labs in governing sustainability transitions across diverse contexts, conceptualizations, and cases. The conducted study provides an overview of their distribution, thematic focus, and setup, mapping them across seven research communities (Living, Urban Living, Real-world, Evolutionary Learning, Urban Transition, Change, and Transformation labs). Within this classification of lab concepts, PED Labs align with Urban Living Labs and Real-World Labs.

As noted by McCrory et al. (2020), real-world laboratories have emerged as multi-stakeholder approaches to transition governance (Nevens et al., 2013; Schapke et al., 2018), providing spaces for experimenting with sustainability solutions (Bulkeley & Castan Broto, 2013; Evans et al., 2016). Situated within defined physical sites, they operate at the margins of existing structures, integrating top-down, bottom-up, and hybrid arrangements to co-produce radical alternatives within constrained space and time (Charli-Joseph et al., 2018). These labs span multiple fields, including user and open innovation, sustainable product-service systems, urban governance for transformation, and climate change mitigation, particularly in decarbonisation and urban transition initiatives (McCrory et al., 2020).

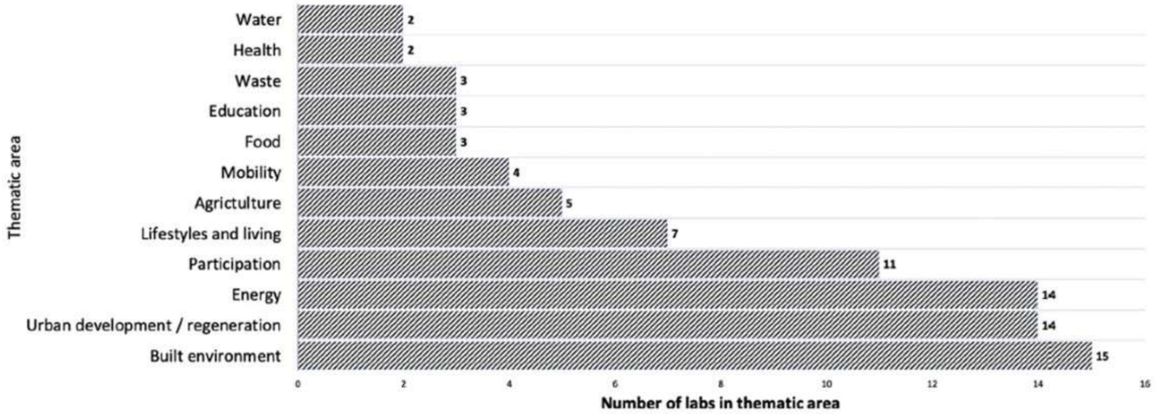


Figure 4: Thematic focus of sustainability-oriented labs that operate in real-world contexts (McCrory et al., 2020)

Lab concept	Description	Central Analytical constructs	Exemplary literary roots
Urban Living Lab	Governance instrument with a focus on the urban; prioritises geographical embeddedness, experimentation and learning, participation and user involvement, leadership and ownership, and evaluation and refinement	Co-creation Governance Experimentation	Evans and Karvonen (2011); Liedtke et al. (2012); Bulkeley and Castán Broto (2013); Sengers et al. (2016); Voytenko et al. (2016)
Living Lab	A pragmatic, user-centred innovation approach and environment; innovation and design process; co-creation of tech; products, services and ways of living, technology lifecycle	User needs Co-creation Usability Value User innovation	Eriksson et al. (2005); Følstad (2008); Liedtke et al. (2012); Ballon and Schuurman (2015); Voytenko et al. (2016)
Real-World Lab	Transformative transdisciplinary research approach; real-world problems and contexts; intervention object and study subject; co-design, co-production and co-evaluation	Transdisciplinarity Co-production Learning Experimentation	Lang et al. (2012); Schneidewind (2014); De Flander et al. (2014)
Evolutionary Learning Lab	A systems-based approach to understand and respond to complex issues; process as well as a setting; test mental models	Systems thinking Mental models Complexity Leverage points	Freeman (2010); Bosch et al. (2013)
Urban Transition Lab/Transition Management	Transition governance by experimentation. Deliberate process towards the governance of systemic change, including visioning, agenda setting, experimentation and learning	Experimentation Complexity Selective participation Governance Power	Loorbach (2007); Nevens et al. (2013)
Change Laboratory	Seeking transformation of cultural activity systems. A place and a process, including problem analysis and solution development in contexts	Expansive learning Double Stimuli Contradictions	Engeström (1987, 2001); Engeström et al. (1996)
Transformation Lab (T-Lab)	Interactive, participatory innovation spaces that allow for experimentation with new social-ecological technological system configurations and sustainability pathways	Resilience Adaptation Agency	Olsson et al. (2014); Westley et al. (2011)
Other	Experimental spaces, urban planning processes, learning environments	Non-overlapping constructs	Unidentified roots

Figure 5: Conceptual delineation of sustainability-oriented labs (McCrory et al., 2020)

Regarding the virtual aspect and the emerging concept of Virtual PED Labs, several EU frameworks, along with advanced digital concepts and solutions, are particularly relevant. If Virtual PED Labs are defined as digital environments that simulate, model, analyse, and visualize urban energy and sustainability-related processes while enhancing accessibility, enabling remote collaboration, and facilitating data-driven decision-making to support and advance PED development beyond geographical constraints, then the frameworks of *digital transformation* and sustainable digital technologies, particularly the *twin transition - green and digital transition* - are directly applicable. Among digital concepts, besides virtual lab, digital twinning is the most closely related, while broader frameworks such as 3D City Models, Spatial Information Infrastructure Models, Smartness and Smart Readiness, and Distributed Cognition Environments are also highly relevant.

2.3 Digital Decade Transformation

The Europe's Digital Decade: Digital Targets for 2030 policy program presents a comprehensive framework for advancing Europe's digital transformation by 2030. This program defines specific targets across four key domains: Digital Skills, Digital Infrastructure, Digitalization of Businesses, and Digitalization of Public Services (European Commission, n.d.). The development and implementation of Virtual PED Labs align with the objectives of the Digital Decade by fostering advanced digital competencies, utilizing digital infrastructure, accelerating business digitalization, and supporting the modernization of public services.

Virtual PED Labs positioning within Europe's Digital Decade: digital targets for 2030	
Digital skills	Developing and operating Virtual PED Labs necessitates advanced digital skills among professionals, including expertise in digital simulation, data analysis, and virtual collaboration tools.
Digital Infrastructure	Virtual PED Labs rely on robust digital infrastructure, such as high-speed connectivity and advanced computing resources, to facilitate complex simulations, data processing, automatization of processes and monitoring.
Digitalization of Businesses	By fostering innovation in energy management and urban planning through virtual simulations, Virtual PED Labs encourage businesses to adopt and develop new digital technologies, contributing to the broader digitalization of the industry.
Digitalization of Public Services	Insights from Virtual PED Labs can inform the development of digital public services, such as smart energy management systems and interactive urban planning platforms, enhancing the accessibility and efficiency of public services.

2.4 The twin green & digital transition

The European Union's *Twin Transition: The twin green & digital transition: How sustainable digital technologies could enable a carbon-neutral EU by 2050* refers to the simultaneous pursuit of green and digital transformations, aiming to achieve a climate-neutral and digitally advanced economy (European Commission, 2022). This integrated approach recognizes that digital technologies can significantly enhance environmental sustainability, while sustainable practices can drive innovation in the digital sector (Dæhlen, 2023):

> *The **digital transition** of society consists of all processes at all levels in society involving infrastructure, services, applications and human behaviour that depend on the digital representation of knowledge and computer power.*

> *The **green transition** of society is about reducing greenhouse gas emissions, preserving and restoring nature, reversing environmental degradation and ensuring that the majority of energy comes from renewable sources.*
> *The **twin transition** is about how the dynamics and strength of the digital transition of society affect the green transition of society, and how these two transitions mutually influence each other and should be combined in the coming years.*

Research areas in the digital realm that are central to the green and the twin transition of society (Dæhlen, 2023), also directly implemented in Virtual PED Labs are as follows:

Central research areas in the twin transition, integral to Virtual PED Labs:	
data science and computing	connectivity sciences
sensor technologies	digital governance

In terms of the energy transition digital technologies are regarded as a fundamental enabler, ensuring that renewable energy sources can be effectively and reliably integrated, distributed, and stored**.** According to Dæhlen (2023), key technological concepts relevant to the energy transition, that are also integral to devising Virtual PED Labs include:

Key technological concepts within the Virtual PED Labs in support of energy transition	
Smart Energy Grids	Grid flexibility, real-time adjustments between energy supply and demand to accommodate intermittent renewables like wind and solar power.
AI and Machine Learning	Optimize energy distribution and storage, predicting consumption patterns and improving decision-making in power grids.
Digital Twin Technology	Virtual models of energy infrastructure, digital twins allow for real-time monitoring, testing, and optimization without physical risks or costs.
IoT and Sensor Networks	Real-time data collection for efficient energy management, identifying inefficiencies and facilitating demand-response mechanisms.
Data-Driven Decision-Making for Energy Systems	**Big data analytics** - accurate forecasting of energy demand and generation, allowing for proactive energy management and improved resource allocation. **Cloud computing and edge computing -** enhancing the processing of vast energy-related datasets, ensuring real-time insights and operational efficiency. **Blockchain technology -** peer-to-peer energy trading, enabling decentralized exchanges between producers and consumers, fostering a more flexible and resilient energy market.

Virtual PED Labs can become a key part of the twin transition infrastructure, seamlessly merging digital and green innovations within the Smart Cities framework to generate urban data. They enable testing and managing virtual platforms for real-world PED Labs and Districts, offering scalable, cost-effective environments for technology evaluation before and during PED implementation. Their development integrates research in digital technologies, energy management, urban planning, and design.

Within the twin transition framework Virtual PED Labs can be devised as follows:

Devising a Virtual PED Lab concept within the twin transition framework.	
Decision making, Distributed Cognition Environments	• Integration of long-term decision-making with short-term operational activities • Decision-making and problem-solving depend on cognitive processes distributed across social and technological systems
Collaboration and knowledge sharing, Remote participation, Integrative Stakeholder Engagement	• To develop and test solutions • Integrated solutions across technologies, energy management systems, urban planning, and design.
Data collection and metrics	Real-time data collection for efficient energy management, IoT and Sensor Networks, connectivity
Energy management – Virtual environments for data interpretation Smart energy grids	AI techniques and digital twin technologies ensuring: • efficiency and reliability in energy systems • simulation, monitoring, testing, replicability, integration and scalability
Energy management – physical infrastructure Storage systems optimisation Decentralised energy management	• Optimisation of storage systems, to achieve high penetration of locally produced renewable energy • Decentralised energy management - inclusion of energy generated close to where it is used • Use of local renewable energy

Relevant to PED Labs, exemplifying virtual lab and the virtual management of distributed energy resources, the Virtus Project (Virtual Power Plant) showcases:

> *Through the use of advanced ICT systems, the project intends to provide energy providers with the possibility of managing the growing presence of renewable sources, aggregating the flexibility of DER and supporting conventional generation in the management of the electrical system. Direct testing of scientific methodologies and technological solutions in real experimental sites, of an industrial and tertiary nature, will allow the potential impacts of the expected results to be assessed. (Virtus Consortium, 2020)*

The project's experimental sites encompass (1) a physical industrial site, (2) an energy microgrid, and (3) a virtual power plant, forming an interconnected virtual and physical infrastructure within a VPP distributed architecture.

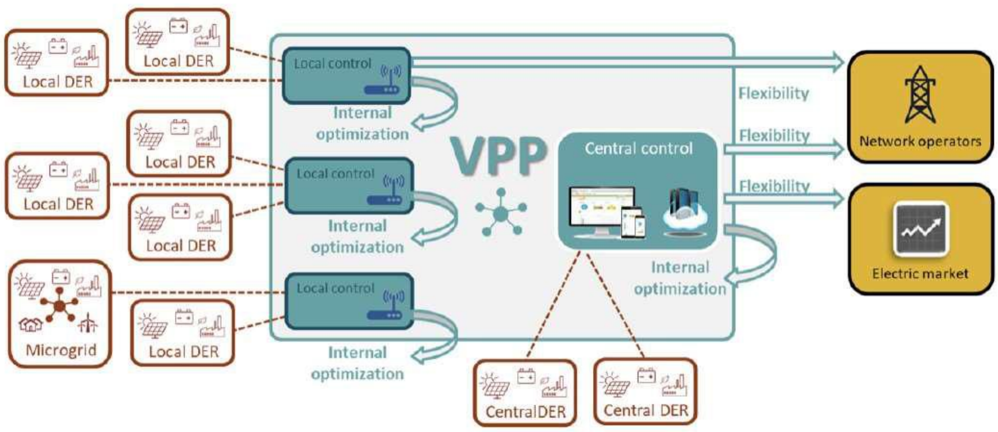


Figure 6: A VPP Distributed Architecture (Bianchi et al., 2021)

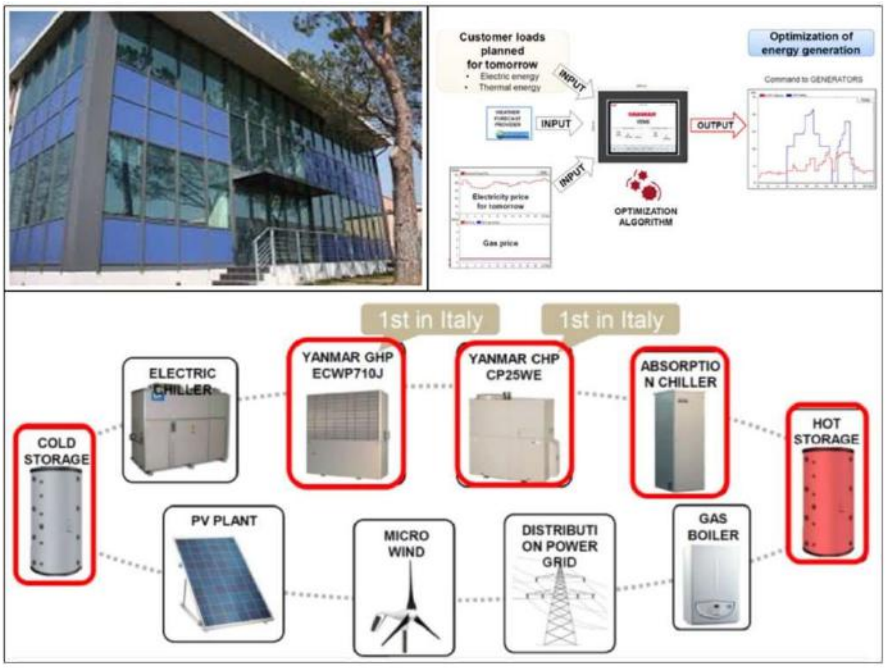


Figure 7: Pointlab Experimental Area – Industrial site equipped with intelligent resource control (Virtus Consortium, 2020)

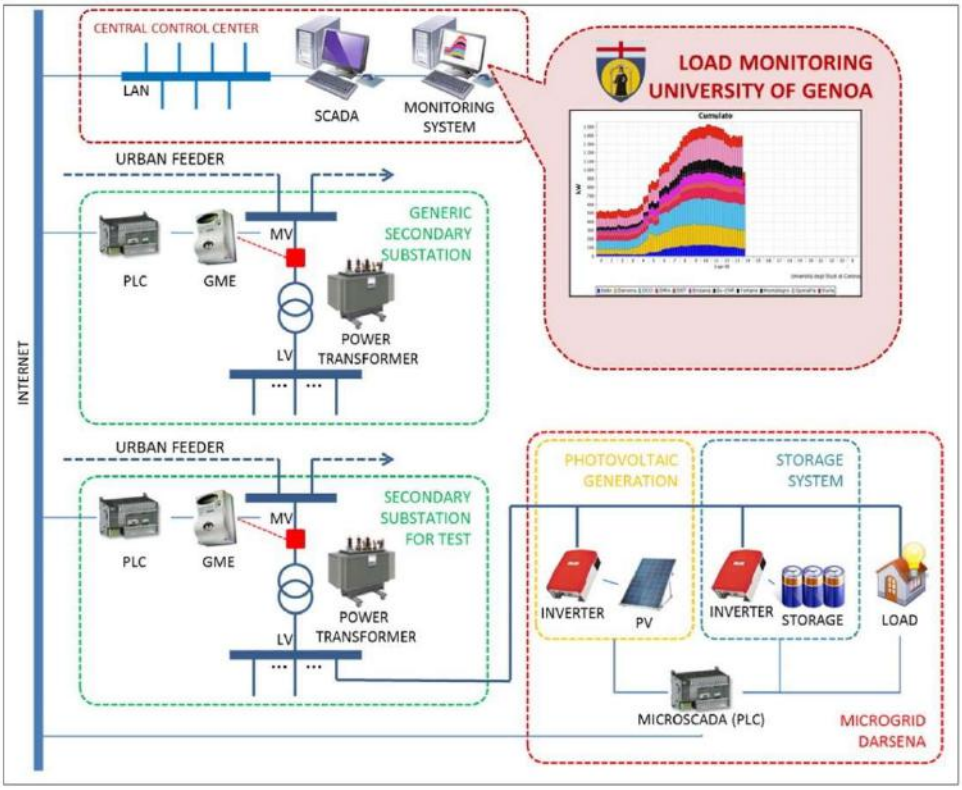


Figure 8: University of Genoa and Darsena microgrid – consumption monitoring and control system (Virtus Consortium, 2020)

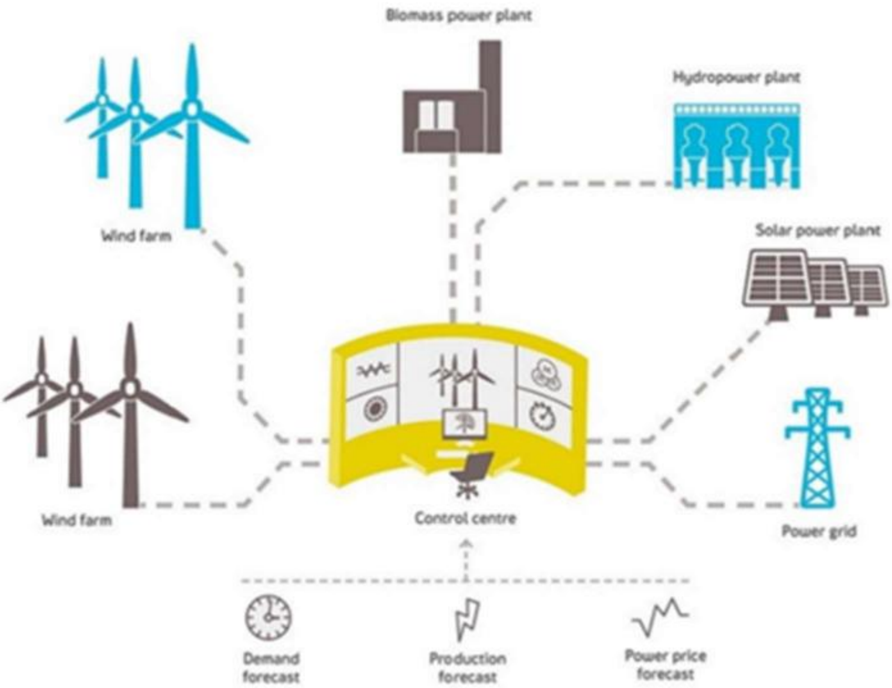


Figure 9: Virtual Power plant (Virtus Consortium, 2020)

2.5 Virtual Labs

The concept of a Virtual Lab varies across scientific fields, with definitions differing based on purpose and scope, leading to ambiguity. The literature presents inconsistent terminology, often using terms like remote, e-, web, online, and distributed learning laboratories interchangeably (Li & Liang, 2024).

Virtual laboratories are digital environments where experiments are conducted using computer operations, simulations, or animations, allowing users to manipulate experiment variables (Li & Liang, 2024). At the core of these labs are simulation and modelling, which have been further enhanced by advancements in digital twins. These innovations now enable virtual labs to combine the benefits of both simulations and remote experimentation (Li & Liang, 2024). Additionally, interactivity plays a key role in making complex concepts and technologies more accessible (Escolà et al., 2010). By allowing users to explore how different parameters influence system behaviour, interactive elements facilitate understanding without requiring deep prior knowledge (Dormido et al., 2005; Sánchez et al., 2004). Interactive Virtual Laboratories (IVLs) are software-driven environments designed to replicate real-world systems (Escolà et al., 2010). Even when not explicitly labelled as interactive, most virtual labs integrate interactive features to enhance user engagement and learning.

In the context of PEDs, virtual labs should be examined through the lens of engineering sciences (sustainability and energy engineering), where they are primarily defined as computer-based environments that enable users to interact with them and conduct experiments or simulations (Hasan, 2024) without physical laboratory equipment. These platforms facilitate variable manipulation and outcome observation through interactive interfaces, and specialised software tools, offering a safe and cost-effective alternative to traditional labs. However, Virtual PED Labs are not intended to replace physical lab equipment or traditional laboratory settings. Instead, they function as an extended, supportive virtual layer that complements real-world PED Labs or serves as a dedicated experimental environment for PED research. As discussed in the Introduction, the term "lab" in the context of PEDs signifies a collaborative and experimental approach rather than a conventional laboratory setup—an idea that equally applies to Virtual PED Labs.

Beyond engineering applications, Virtual PED Labs also extend into urban planning and design, shifting from technical contexts and applications to collaborative and participatory approaches. While policy and research stress the importance of stakeholder engagement in urban development (Wang & Lin, 2023; Omar & Leh, 2009; UN Habitat, 2019; Irvin & Stansbury 2004; Martinez & Olander, 2015), and systems thinking through scale jumping (Reith & Brajković, 2021), integrating virtual tools and 3D modeling for non-expert communication remains challenging (Imottesjo & Kain, 2022). Emerging technologies such as virtual reality (VR), augmented reality (AR), and mixed reality (MR) are seen as essential for enhancing the inclusion, engagement, and communication of various stakeholders. Meanwhile, metaverse environments create new spatial and social interaction patterns, merging physical and digital realities through multi-sensory experiences in a persistent multi-user space (Wang & Lin, 2023; Mystakidis, 2022). When effectively engaging stakeholders, virtual labs go beyond their experimental role to function as communication platforms in urban planning. Conventional participation methods, such as public hearings, remain constrained by time and resources (Jutraz et al., 2011). Digital tools create new opportunities for engagement, with emerging studies, such as Amado et al. (2010), proposing innovative evaluation and validation processes to enhance public participation in sustainable planning. Studies also emphasize the need for digital city models that cater to both experts and the public (Jutraz et al., 2011). Schoenwandt's (2008) "third-generation" planning theory underscores the dynamic interaction between experts ("planning world") and the public ("life-world"), structured through key processes such as "Comprehension of the Situation," "Elaboration of Instructions," "Communication about Behavior," "Interventions," "Settings," and "Outcomes." Digital models support this exchange by enabling visualization of past, present, and future urban scenarios (Jutraz et al., 2011).

2.6 Digital Twinning

Digital Twin (DT) concept has significantly evolved from a conceptual framework to practical applications across various fields. DTs are broadly defined as virtual replicas of physical objects, systems, or processes, enabling real-time simulation, monitoring, and analysis of real-world behaviour. Originating from Product Lifecycle Management, the DT concept plays a key role in shaping current trends related to customer requirements, design constraints, complexity, data security, and integrity (Iliută et al., 2024).

Among the many definitions, a review study by Iliută et al. (2024) highlights the following:

- Grieves et al. (2016) define the Digital Twin theoretical model as consisting of three main components: (a) real environment physical products, (b) virtual products in virtual space, and (c) the information and data links that connect real and virtual products.
- Negri et al. (2017) describe DT as a production system virtual representation that can be executed in various simulation environments. This involves synchronization between the real and virtual systems using mathematical models, appropriate information, connected intelligent devices, and mathematical models.
- Autiosalo (2018) define DT as the cyber component of a cyber-physical system (CPS).
- Boschert & Rosen (2018) define the Digital Twin vision as a complex description at both the functional and physical layers of a system, product, or component. It integrates useful data that can be relevant for all phases of the ongoing and subsequent life cycles.

- Thao et al. (2018) state that a full Digital Twin should integrate five key components: services, data, connections, virtual components, and physical components.
- Zeng et al. (2018) describe DT as an integrated system capable of monitoring, simulating, regulating, computing, and controlling a system's process and status.

DTs are widely applied across sectors such as Smart Cities, Energy Management, the Oil Industry, Industry 4.0, and others, with extensive research and implementations.
The concept of Virtual PED Labs correlates closely to the concept of Digital Twinning, but differences apply:

	Digital Twin	Virtual PED Lab
Purpose: Twin vs. Lab	Twin: replica/representation of physical object, system, or process, enabling real-time simulation, monitoring, and analysis of real-world behaviour. In context of PEDs: Real-time monitoring & optimization	Lab: collaborative and experimental environment, approach focused on developing and testing solutions for real-world cases - Simulation & experimentation.
Functionality	Real-world data integration, predictive analytics, performance optimization.	Hypothetical modelling, scenario testing, policy evaluation.
Application	Operational decision-making & efficiency improvements.	Testing new technologies, strategies, and policies before implementation, strategic decision-making.
Scope	A specific, existing real-world twin/PED.	Broader PED research, design, and development.
Data Usage and Integration	Continuous synchronization with physical systems, real-time sensor & IoT data. IoT, AI, and data analytics for dynamic adaptation.	Works with simulated, projected, or experimental data, not necessarily real-time; focused on simulation and scenario testing. Integrates multiple Digital Twins, AI, and simulation tools.
Stakeholder Engagement	Technical experts, energy managers, city planners, AI-driven analytics. Limited direct input from broader stakeholders.	Academia, policymakers, technology developers, communities, city planners, businesses, and citizens. More inclusive to diverse stakeholder groups.
Decision making	Real-time, data-driven decision-making. Operational & Technical Level.	Scenario-based decision-making Strategic & Policy-Level
Social and Behavioural Aspects	Limited stakeholder and public interaction; mostly serves technical experts and infrastructure operators. Does not directly influence behavioural change.	Participatory nature, involving various stakeholders in co-creation Stakeholder-driven decision-making. Explore behavioural shifts

In conclusion:

- **Purpose & Function:** Digital Twins are real-time virtual replicas for monitoring and optimization, while Virtual PED Labs are collaborative environments for experimentation, testing and managing PED concepts.

- **Decision-Making:** Digital Twins aid technical, data-driven decisions, whereas Virtual PED Labs support strategic, scenario-based decision-making involving multiple stakeholders.
- **Scope & Integration:** Digital Twins focus on individual systems and assets, using IoT and AI, while Virtual PED Labs operate at a district scale, integrating multiple Digital Twins and simulation tools.
- **Social Engagement:** Digital Twins have limited public interaction, whereas Virtual PED Labs foster participatory governance, involving diverse stakeholder groups in energy transition planning.

2.7 3D City Models - Spatial Information Infrastructure Models

Spatial information infrastructure technologies, underlying the concept of digital twinning, are also relevant to the development of the Virtual PED Labs concept. The Infrastructure for Spatial Information in the European Community (INSPIRE), established in 2007, aims to create a unified **European Spatial Data Infrastructure (SDI)** to enhance data sharing, public access, and cross-border policy-making (European Commision n.d; Sjoukema et al., 2022). For Virtual PED Labs, INSPIRE's standardized spatial data infrastructure can support PED simulation, analysis, and management, enabling more accurate urban modelling, energy solution evaluation, and improved stakeholder collaboration in sustainable urban planning.

Key concepts in spatial information infrastructure include Geographic Information System (GIS) and Building Information Modelling (BIM) (Patacas, Dawood, & Kassem, 2020). GIS captures, stores, analyses, and visualizes spatial data for large-scale mapping and urban planning, while BIM digitally represents buildings and infrastructure for detailed modelling, collaboration, and lifecycle management (Guyo, Hartmann, & Ungureanu, 2021). GIS and BIM differ in data standards, spatial scales, and levels of detail, making their integration an ongoing challenge that remains largely experimental. Integrating these domains will merge their individual features, driving advancements in emergency response, site safety, supply chain management, and sustainable urban design (Guyo, Hartmann, & Ungureanu, 2021). Recent trends emphasize the development of interoperable and flexible GIS-BIM solutions to enhance the understanding of infrastructure behaviour within its environment (Cepa, Alberti, Pavón, & Calvo, 2024).

3D city models (3D GIS) are essential for digitally representing the built environment, integrating semantic data on urban elements and landscapes. CityGML, an international standard by the Open Geospatial Consortium (OGC, 2012), enables cross-platform city-related data exchange. It serves as an open data model and exchange format for storing digital 3D representations of cities and landscapes (Ledoux et al., 2019), supporting the representation of key urban features such as buildings, streets, bridges, and green and blue infrastructure. CityJSON is a JSON-based encoding for 3D city models, providing a developer-friendly alternative to the GML encoding of the CityGML data model. CityJSON supports multiple level of Details (LoDs) for 3D objects, enabling varied resolutions for different applications (Shaw, 2018; Ledoux et al., 2019). Both CityGML and CityJSON are key enablers of Smart Cities**,** functioning as data models for representing, storing, and exchanging 3D city models. While CityGML offers detailed, structured modeling, CityJSON provides a simplified, web-friendly alternative, making them complementary tools for urban digitalization.

In the context of Virtual PED Labs, CityGML and CityJSON offer structured 3D spatial data models that are essential for enabling precise urban simulations, energy flow analysis, and collaborative decision-making in the development of PEDs. As standardized formats, they enhance interoperability with Digital Twins and GIS-based simulations, allowing Virtual PED

Labs to integrate multi-source data, conduct scenario-based policy testing, and optimize energy solutions through AI-driven automation.

2.8 Smartness & Smart Readiness

Virtual PED Labs rely on smart infrastructure, including smart grids and buildings that should seamlessly integrate. The Smart Readiness Indicator (SRI) evaluates buildings' smart-ready capabilities and readiness to implement these services, essential for decarbonisation. A building's smartness lies in its capacity to sense, interpret, communicate, and respond to changes in systems, the environment, and occupant needs.

SRI evaluation of buildings
Capacity to perform three key functions:
- Optimize energy efficiency and overall in-use performance. - Adapt operations to meet occupant needs. - Respond to signals from the grid, such as enabling energy flexibility
Assessments of nine technical domains:
Heating, cooling, domestic hot water, ventilation, lighting, dynamic building envelope, electricity, electric vehicle charging, and monitoring and control systems.
Each domain evaluated according seven impacts:
Energy efficiency, maintenance and fault prediction, comfort, convenience, health, well-being and accessibility, information to occupants, and energy flexibility and storage.
Benefits:
Building automation and electronic monitoring of systems including heating, hot water, ventilation, and lighting.

The aggregated results provide an overall SRI class and score, indicating the building's level of smart readiness. The SRI legal framework, established by the 2018 revision of the EPBD and Commission Delegated Regulation (EU) 2020/2155, defines the structure and principles of its calculation methodology (European Commission, n.d.).

The smartness of systems, grids and buildings within Virtual PED Labs is a crucial factor in shaping their conceptual framework. The smartness of Virtual PED Labs integrates Smart Readiness Indicator (SRI) technical domains and seven defined impacts while extending far beyond these parameters. It encompasses not only technical aspects but requires systems thinking, strategic development and governance of PEDs, social, and behavioural dimensions—including collaboration protocols, knowledge sharing, and communication streams of the lab environment. Virtual PED Labs integrate a range of smart technologies to facilitate various functions:

Virtual PED Labs Smartness Spectrum
Energy Efficiency & Management – Simulations, optimizing, integration of RES, adaptation and responsiveness of the grid.
Interoperability & Digital Twins – Seamless integration between models, urban-scale simulations and decision support.
AI & Automation – Predictive analytics for energy consumption, AI-driven automation for optimizing energy flows, and scenario-based testing of sustainability strategies.
Multi-Source Data Integration – Use of IoT, real-time monitoring, and diverse datasets to provide accurate insights into urban dynamics.

User-Centric & Adaptive Systems – Smart control over energy demand, integrating feedback from users, occupants, and infrastructure to optimize comfort and efficiency, while also enhancing knowledge sharing, collaborative processes, communication protocols, and behavioural insights.	
Scalability & Replicability – Virtual PED Labs support scalable solutions that can be replicated across different cities, ensuring adaptability to various urban contexts.	

2.9 Distributed Cognition Environments

By leveraging smart technologies and human-machine interactions to support PEDs, Virtual PED Labs function both conceptually and operationally as Distributed Cognition Environments (DCEs).

The concept of distributed cognition run deep, but the field emerged under its current name in the mid-1980s (Hutchins, 1995). The 1978 English publication of Vygotsky's *Mind in Society* explored how cognitive development is shaped by social interaction, cultural tools, and language. In 1985, Minsky's *Society of Mind* proposed that cognition arises from a network of simple, interacting agents rather than a unified entity, offering a computational perspective on intelligence, and investigating relationship between artificial intelligence and cognitive science. Hutchins (1995) made significant contributions to the development of the concept of distributed cognition, analysing how cognitive processes are distributed across individuals, artefacts, and external structures within specific contexts. Hayles (1999), in her discussion of posthuman future, posits the shift from autonomous human to distributed cognition, arguing that dynamic human-machine interactions within DCEs produce more effective outcomes than isolated responses.

> *Hutchins (1995) proposes three characteristics of any distributed cognition environment. First, in such an environment, knowledge is shared or communicated among multiple people or by an external device that makes knowledge visible on some sort of display. Second, in a distributed cognition environment, all shared knowledge is pooled together, so that any member of the environment can use any of the knowledge for the benefit of all. Third, the members of a distributed system are reliant on each other for the completion of the task. (Hayles, 1999)*

Building on Hutchins' framework, research has examined distributed cognition across various contexts. (Tindale, Winget, & Hinsz, 2020) examine team dynamics in these environments, emphasizing technology's role in storing and sharing information. As AI continues to advance, their study suggests that teams will increasingly depend on technology for task execution, underscoring the importance of its strategic design in supporting collective cognition.

In technological contexts, Distributed Cognition Environments (DCEs) refer to systems where cognitive processes are extended beyond individuals to include technological tools, digital platforms, and artificial intelligence (AI)**.** Grounded in Hutchins' distributed cognition theory, DCEs integrate human-computer interaction, real-time data exchange, and automation to enhance decision-making and problem-solving. They are evident in smart cities, intelligent transport, collaborative robotics, and AI-driven research. In cyber-physical systems (CPS), cognitive tasks—such as perception, decision-making, and action execution—are increasingly distributed between humans and AI, enhancing efficiency in domains such as healthcare and autonomous vehicles (Radanliev et al., 2021), as well as energy grids. With advancements in machine learning, cloud computing, and the Internet of Things (IoT), Distributed Cognition Environments have integrated intelligent agents, digital twins, and augmented reality (AR) interfaces. These systems facilitate seamless knowledge integration among stakeholders, enhancing collaboration in distributed workspaces, virtual labs, and AI-assisted decision-support systems.

Virtual PED Labs can maximise their function by adopting DCEs principles and functioning as smart interactive platforms where cognitive tasks are distributed across human and artificial agents. By integrating simulation, modelling, testing and data-driven decision-making, these labs enable real-time DC collaboration, adaptive learning, and optimization of PED strategies. As AI-driven automation and human-machine collaboration evolve, Virtual PED Labs will play a crucial role in advancing smart, adaptive, and knowledge-rich environments for sustainable urban development.

In conclusion, an overview of concepts related to Virtual PED Labs is given in the table below:

VIRTUAL PED LABS related concepts	
PED Labs, Urban Living Labs & Sustainability-Oriented Labs	• PED Labs as Innovation Hubs: Experimental spaces for testing urban energy solutions and stakeholder engagement. • Urban & Real-World Labs: Enable co-creation, governance, and sustainability experiments. • Holistic Approach: integration of technology, policy, regulatory, finance, and social aspects. • Policy Alignment: Linked to Climate Neutral City Contracts, New European Bauhaus, and Smart Cities.
EU Digital Transformation & EU Twin Transition	• Alignment with Europe's Digital Decade: Digital Targets for 2030: digital infrastructure, skills, and sustainable innovation. • Alignment with The twin green & digital transition concept (Simultaneous green and digital transformation to support climate goals.)
Digital Twinning & Spatial Information Infrastructure	• Digital Twins: Virtual replicas of real-world systems for real-time monitoring and decision-making. • European Spatial Data Infrastructure (SDI) • 3D City Models & GIS: Spatial data tools for urban planning and energy simulations. • Building Information Modeling (BIM)
Smartness Gigital Technologies AI, Machine Learning, IoT, Big Data & Cloud Computing	• Smart Grids: energy flexibility and renewable energy integration. • AI & Machine Learning: Optimization of energy demand and efficiency. • IoT & Sensor Networks: Real-time data collection for efficient energy management. • Decentralized Energy Systems: Peer-to-peer energy trading, local renewable energy use. • Edge & Cloud Computing: High-performance computing for real-time energy system simulations.
Virtual Labs & Distributed Cognition Environments	• Virtual Labs: Simulation-based virtual experimentation. • Simulation, Modelling, & Testing virtual environments • Collaborative Digital Platforms: Stakeholder engagement, participatory decision-making. • Scenario Planning & Policy Testing**:** Using scenario-based modelling for urban planning. • Distributed Cognition Environments (DCEs): AI-human interaction for improved decision-making.

3. DEFINITION OF VIRTUAL PED Labs

A **Virtual PED Lab** is a digital platform designed to simulate, model, and evaluate urban energy systems and sustainability initiatives within a virtual environment. It provides a scalable, data-driven space where stakeholders—such as urban planners, engineers, policymakers, and citizens—can collaborate to design, test, and refine solutions for Positive Energy Districts (PEDs). Unlike physical PED Labs, which rely on tangible infrastructure, Virtual PED Labs leverage computational tools and real-time data to create dynamic, interactive models of districts. This digital approach offers advantages like cost efficiency, risk reduction, and the ability to rapidly iterate on complex urban systems without the constraints of physical experimentation.

3.1 Key Characteristics

Virtual PED Labs are distinguished by several core features:

- **Digital Simulation:** These labs replicate energy flows, infrastructure interactions, and environmental impacts using advanced computational models. For example, they can simulate the integration of rooftop solar panels across a district, predicting energy generation under varying weather conditions (Ahrens Kayayan et al., 2025).
- **Scalability:** Virtual PED Labs are adaptable to different scales, from individual buildings to city-wide districts. This flexibility enables testing solutions at a micro level (e.g., a single smart building) or a macro level (e.g., an entire urban grid) (Soutullo et al., 2020).
- **Accessibility:** By enabling remote participation and collaboration, Virtual PED Labs break down geographical barriers, allowing global experts and local stakeholders to engage in real-time experimentation and decision-making (Steen & Van Bueren, 2017).

The primary purpose of a Virtual PED Lab is to bridge the gap between theoretical planning and practical implementation, providing a risk-free environment to explore innovative ideas before they are deployed in the real world. This aligns with the broader goals of PEDs, which aim to achieve energy-positive urban areas while enhancing sustainability and resilience (Sareen et al., 2022).

3.2 Theoretical Underpinnings

The conceptual framework of Virtual PED Labs is rooted in several established theories and models in urban planning and sustainability:

- **Systems Thinking:** Virtual PED Labs adopt a holistic view of urban systems, recognizing the interdependencies between energy, transportation, waste, and social systems. This approach is essential for modeling the complex interactions within PEDs, as highlighted by Nagorny-Koring and Nochta, (2018), who argue that systems thinking is critical for sustainable urban transitions.
- **Digital Twinning:** The concept of **digital twins**—virtual replicas of physical systems—forms the backbone of Virtual PED Labs. Originally popularized by Zhang et al (2022), digital twins allow for real-time monitoring and simulation of urban infrastructure, enabling predictive maintenance and optimization of energy systems.
- **Participatory Governance:** Virtual PED Labs also draw from participatory planning models, emphasizing stakeholder engagement in decision-making processes. Research by Krangsas et al. (2021) underscores the importance of inclusive governance in sustainability initiatives, a principle that Virtual PED Labs operationalize through collaborative digital tools.

These theoretical foundations ensure that Virtual PED Labs are not merely technical platforms but also social and governance-oriented spaces designed to foster innovation and collective action.

3.3 Operational Mechanisms

Operationally, Virtual PED Labs function through a combination of advanced technologies and user-centric design:

- **Simulation Engines:** At the core of the lab is a simulation engine capable of modeling energy production (e.g., from renewables), consumption patterns, and grid interactions. Tools like EnergyPlus or CityGML are often integrated for detailed energy and spatial simulations (Koirala et al., 2024).
- **Data Integration:** Real-time data from IoT sensors, smart grids, and urban databases are fed into the lab to ensure simulations reflect current conditions. This data-driven approach enhances the accuracy of predictions and supports evidence-based decision-making (Stecula et al., 2023).
- **Collaborative Interfaces:** User-friendly dashboards, 3D visualizations, and interactive tools allow diverse stakeholders to engage with the platform, even those without technical expertise. This democratizes access to complex simulations, fostering broader participation in PED development (Steen & Van Bueren, 2017).

By combining these mechanisms, Virtual PED Labs provide a versatile environment for testing hypotheses, optimizing designs, and evaluating the long-term impacts of PED strategies.

3.4 Role in Sustainable Urban Development

Virtual PED Labs play a critical role in advancing sustainable urban development by:

- **Accelerating Innovation:** They allow for rapid prototyping and testing of new technologies, such as smart grids or energy storage systems, reducing the time from concept to implementation (Koirala et al., 2024).
- **Enhancing Resilience:** By simulating extreme scenarios (e.g., heatwaves or power outages), Virtual PED Labs help planners design districts that are resilient to climate change and other disruptions.
- **Promoting Equity:** The accessibility of virtual platforms ensures that marginalized communities and non-expert stakeholders can participate in the planning process, aligning with the principles of inclusive urban development (Steen & Van Bueren, 2017).

In this way, Virtual PED Labs not only support the technical aspects of PEDs but also address the social and governance challenges inherent in sustainable urban transformations.

3.5 Key Features of Virtual PED Labs

Virtual PED Labs are innovative digital platforms designed to simulate, optimize, and scale sustainable urban solutions within Positive Energy Districts (PEDs). Their effectiveness stems from a set of distinguishing features: **integrated modeling**, **advanced simulation tools**, **stakeholder collaboration**, **real-time data integration**, and a **focus on energy positivity**. Each of these characteristics contributes to creating a robust environment for addressing the complexities of urban sustainability. This section provides a detailed examination of these features, reinforced by insights from academic literature.

- **Integrated Modeling**

Integrated modeling is a cornerstone of Virtual PED Labs, enabling the synthesis of multiple urban systems—such as energy networks, infrastructure, and socio-economic factors—into a unified digital framework. This holistic approach is essential for understanding the intricate interdependencies that define PEDs, where energy performance, urban planning, and human behavior intersect. Integrated modeling is critical for sustainable urban development, as energy systems interact with physical infrastructure and social dynamics. By simulating these relationships, Virtual PED Labs allow stakeholders to identify synergies (e.g., combining renewable energy with efficient building designs) and trade-offs (e.g., balancing cost with environmental benefits). This comprehensive perspective ensures that solutions are not siloed but instead address the multifaceted goals of PEDs.

- **Advanced Simulation Tools**

Virtual PED Labs employ cutting-edge simulation tools to model the dynamic behavior of urban systems with precision. These tools, often based on technologies like digital twins—virtual replicas of physical systems—simulate energy flows, transportation networks, and environmental impacts. Zhang et al. (2021) highlight the value of digital twins in improving simulation accuracy and operational efficiency, a principle that Virtual PED Labs adapt to urban contexts. For instance, these labs can simulate scenarios such as fluctuating energy demand due to weather changes or population growth, predicting their effects on a district's energy balance. This capability enables stakeholders to test and refine system designs, ensuring they are resilient and adaptable to future conditions. The precision of these tools is vital for optimizing PED solutions before real-world implementation.

- **Stakeholder Collaboration**

Collaboration lies at the core of Virtual PED Labs, which provide digital workspaces, communication tools, and participatory interfaces to unite diverse stakeholders—researchers, urban planners, policymakers, and citizens. Steen & Van Bueren (2017) argue that stakeholder engagement is indispensable for sustainable urban projects, as it ensures solutions are both socially acceptable and economically feasible. Virtual PED Labs facilitate this by offering shared platforms where participants can co-create, evaluate, and refine urban strategies. For example, a city planner might propose a new energy grid layout, while citizens provide feedback on its practicality. This collaborative environment fosters innovation by integrating technical expertise with local knowledge, aligning solutions with community needs and priorities. It also builds consensus, increasing the likelihood of successful PED implementation.

- **Real-Time Data Integration**

Unlike static simulation platforms, Virtual PED Labs incorporate real-time data from sensors, IoT devices, and external databases, ensuring that models reflect current urban conditions. Li et al. (2019) assert that real-time data integration is crucial for developing dynamic, responsive urban models that support informed decision-making. In Virtual PED Labs, this feature enables continuous monitoring of variables like energy consumption or air quality, allowing simulations to adapt to live changes. For instance, a sudden spike in energy use detected by IoT sensors can prompt immediate adjustments in a lab's simulation, testing mitigation strategies on the fly. This real-time capability also supports predictive analytics, helping stakeholders anticipate trends—such as seasonal energy demands—and plan proactively, enhancing the labs' practical relevance.

- **Focus on Energy Positivity**

A defining feature of Virtual PED Labs is their emphasis on energy positivity, aligning with the primary goal of PEDs: districts that generate more energy than they consume. This focus distinguishes them from generic urban simulation tools, as they prioritize optimizing energy balances through renewable generation, efficiency measures, and demand management. Trulsrud and Leer (2024) note that achieving energy positivity demands a targeted approach that integrates these elements seamlessly. Virtual PED Labs support this by offering tools to simulate and adjust factors like solar panel placement or energy storage capacity, ensuring districts meet or exceed energy targets. Beyond energy, they track sustainability metrics—such as carbon emissions and resource consumption—to assess broader environmental impacts, reinforcing their role in holistic urban sustainability.

- **Relationship to Physical PED Labs**

Virtual and Physical Positive Energy District (PED) Labs are interconnected platforms that work together to accelerate the creation and implementation of sustainable urban solutions. Physical PED Labs offer real-world environments for testing technologies and strategies, while Virtual PED Labs extend these efforts into the digital realm, providing flexibility, scalability, and a space for risk-free experimentation. This section delves into their complementary relationship, highlighting how their synergy drives innovation and supports the broader objectives of urban energy transitions.

- **Complementary Roles in Innovation**

Virtual and Physical PED Labs serve distinct yet mutually supportive roles in fostering innovation. Physical PED Labs act as practical testing grounds where renewable energy systems, urban designs, and sustainability strategies are deployed in actual urban settings. These labs provide concrete data on performance, user acceptance, and environmental outcomes. However, physical experimentation can be slow and resource-heavy, restricting the range of testable scenarios. Virtual PED Labs overcome this limitation by enabling rapid, cost-effective simulations of diverse ideas—such as varying energy mixes or urban layouts—without physical resource demands. This allows stakeholders to explore a wide array of innovative concepts digitally, which can then be fine-tuned and validated in Physical PED Labs. The result is a feedback loop: virtual simulations guide physical experiments, and physical results refine virtual models, speeding up the innovation process.

- **Scalability and Contextual Adaptation**

A key challenge in PED development is ensuring solutions can scale and adapt to diverse urban contexts. Virtual PED Labs excel here by simulating districts of different sizes and conditions—from small neighborhoods to large cities—under varying demographic, climatic, and infrastructural scenarios. For instance, a virtual lab might test how a PED solution optimized for a temperate climate performs in a tropical one, pinpointing necessary adjustments. Physical PED Labs, though tied to specific locations, provide the real-world data needed to confirm these adaptations. By integrating virtual scalability with physical validation, stakeholders can craft solutions that are both locally relevant and widely applicable, supporting replication across global urban settings.

- **Risk Mitigation and Cost Efficiency**

Deploying untested solutions in physical settings poses risks like technical failures, financial setbacks, and community resistance. Virtual PED Labs reduce these risks by acting as a preliminary testing arena where potential problems—such as grid instability or energy inefficiencies—can be identified and resolved digitally before physical rollout. This preemptive approach, often leveraging digital twins, minimizes costly mistakes in real-world implementation. Additionally, Virtual PED Labs cut experimentation costs by reducing reliance on physical infrastructure, making sustainable innovation more accessible to resource-constrained cities and broadening the reach of PED initiatives.

- **Enhanced Stakeholder Engagement and Accessibility**

Physical PED Labs excel at engaging local stakeholders and fostering community involvement in sustainability projects. Virtual PED Labs complement this by expanding participation to a global audience through digital platforms, enabling remote collaboration among diverse stakeholders (Steen and Bureen, 2017). For example, virtual workshops can gather input from citizens worldwide, including marginalized or distant communities, ensuring inclusivity in planning. This dual approach strengthens PED development: Physical Labs deepen local ties, while Virtual Labs integrate global expertise and perspectives, enriching the overall process.

- **Iterative Learning and Continuous Improvement**

The interplay between Virtual and Physical PED Labs creates an iterative learning cycle that drives ongoing enhancement. Data from Physical PED Labs—such as energy metrics or user feedback—feeds into Virtual PED Labs, improving the accuracy of digital simulations. As virtual models become more reliable, they better inform future physical tests. Conversely, virtual experiment insights shape subsequent physical trials, forming a continuous loop of refinement. This iterative process ensures PED solutions adapt to both simulated and real-world challenges, boosting their resilience and effectiveness over time.

4. CLASSIFICATION OF VIRTUAL PED LABORATORIES

The transition toward Positive Energy Districts (PEDs) is a key strategy for achieving climate neutrality in urban environments. However, the complexity of PED implementation requires advanced digital tools and methodologies to support design, planning, and decision-making processes. Virtual Positive Energy District Laboratories (VPEDLs) have emerged as essential platforms that facilitate these processes through simulation, stakeholder engagement, and regulatory testing. To maximize their effectiveness, it is crucial to establish a structured classification that differentiates VPEDLs based on their functions, technological scope, and stakeholder involvement.

The classification of Virtual PED Labs (VPEDLs) is based on a structured approach considering their function, technological scope, and stakeholder involvement.

Specific criteria have been selected on the basis of the characteristics outlined in the previous chapter in order to identify the typologies of Virtual PED Labs.

4.1 Classification Criteria for VPEDLs

A possible classification can be made based on the following aspects:

- **Function & Purpose**
  - The primary role of the laboratory: whether it focuses on simulation, stakeholder engagement, energy management, regulatory testing, or hybrid physical-digital integration.
  - This criterion determines how the VPEDL supports PED development and implementation.
- **Technological Scope**
  - The key digital tools and methods employed, such as digital twins, IoT monitoring, GIS-based decision-making, blockchain, or hardware-in-the-loop (HIL) simulations.
  - This criterion distinguishes laboratories based on their technological capabilities and applications.
- **Stakeholder Involvement**
  - The type of actors participating in the VPEDL, including researchers, policymakers, urban planners, developers, energy operators, and citizens.
  - This aspect helps classify VPLs based on their level of interdisciplinary collaboration.
- **Application Domain**
  - Whether the laboratory is used for technical validation, participatory planning, real-time energy management, or regulatory testing.
  - This criterion ensures that VPEDLs are classified based on their intended impact on PED implementation.

4.2 Typologies and Classification of VPEDLs

According to the criteria defined in 4.1, we can consider the following 5 typologies of VPEDLs:

1. **Digital Simulation Laboratories** → Focus on energy modeling and performance analysis.
2. **Stakeholder Co-Creation and Decision-Support Platforms** → Facilitate participatory planning and policy decisions.

3. **Smart Energy Management and Control Laboratories** → Develop and test real-time energy optimization strategies.
4. **Virtual Regulatory and Market Testing Sandboxes** → Simulate energy policies and business models before real-world application.
5. **Hybrid Virtual-Physical Testbeds** → Bridge virtual modeling with real infrastructure to validate PED technologies.

The identified typologies are discussed below.

- **Digital Simulation Laboratories**
  - Purpose: Focus on energy modeling, performance analysis, and optimization of PEDs before implementation. This VPEDLs should enable integration or co-simulation between tools.
  - Key Technologies: Digital twins, building energy simulation (BES), urban-scale energy modelling (USEM), computational fluid dynamics (CFD), and multi-agent systems.
  - Stakeholders Involved: Architects, engineers, urban planners, energy modelers, and software developers.
  - Use Case: A research institution simulates energy flows in a PED using dynamic simulation tools (e.g., EnergyPlus, TRNSYS, or OpenModelica) to predict energy balance.

- **Stakeholder Co-Creation and Decision-Support Platforms**
  - Purpose: Facilitate collaborative decision-making among stakeholders, including policymakers, developers, and citizens. This VPL should enable iterative and multi-criteria decision making.
  - Key Technologies: GIS-based planning tools, participatory digital platforms, serious gaming, and AI-assisted decision-support systems.
  - Stakeholders Involved: Municipalities, energy communities, citizens, real estate developers, policymakers, and regulatory bodies.
  - Use Case: A local government uses an online co-creation platform where citizens can explore various PED scenarios and provide feedback on urban energy transition policies.

- **Smart Energy Management and Control Laboratories**
  - Purpose: Test and develop intelligent energy management strategies for real-time PED optimization. This VPL should enable optimization of flows based on priorities and objectives.
  - Key Technologies: IoT-based monitoring, predictive analytics, demand-response strategies, and blockchain for energy trading.
  - Stakeholders Involved: Smart grid operators, energy aggregators, DSOs (Distribution System Operators), and energy researchers.
  - Use Case: A utility company tests AI-driven energy balancing algorithms to optimize energy exchange between PEDs and the main grid.

- **Virtual Regulatory and Market Testing Sandboxes**
  - Purpose: Provide a controlled virtual environment for testing energy policies, market models, and regulatory frameworks before real-world application. This VPL should encourage innovative experimentation with different urban solutions and casuistic.
  - Key Technologies: Agent-based modeling, blockchain for energy trading, and regulatory impact simulations.
  - Stakeholders Involved: Policymakers, regulators, market operators, and energy economists.
  - Use Case: The European Commission runs a digital regulatory sandbox to evaluate how different pricing models affect PED investment and operation.

- **Hybrid Virtual-Physical Testbeds**
  - Purpose: Bridge the gap between virtual and real-world PED applications by integrating physical prototypes with digital simulations. This VPL should enable the assessment of different present and future scenarios by modifying their boundary conditions.
  - Key Technologies: Hardware-in-the-loop (HIL) simulation, digital twins, and living lab integration.
  - Stakeholders Involved: Universities, research centers, technology providers, and startup incubators.
  - Use Case: A research center connects a virtual PED simulation to real-life smart meters and storage systems to validate energy balancing strategies.

4.3 Table Overview of VPLs Classification

This classification ensures that Virtual PED Laboratories are not confused with the PED typologies themselves. It highlights their role in supporting PEDs through modeling, decision-making, energy management, regulatory testing, and hybrid integration. This approach ensures an interdisciplinary framework for sustainable energy transition planning.
Here's a structured table summarizing the classification of Virtual Positive Energy Districts Laboratories (VPEDLs):

Classification of Virtual Positive Energy Districts Laboratories (VPLs)				
Category	**Purpose**	**Key Technologies**	**Stakeholders Involved**	**Use Case Example**
Digital Simulation Laboratories	Energy modeling, performance analysis, and optimization of PEDs before implementation	Digital twins, BES (EnergyPlus, TRNSYS), USEM (CitySim, URBANopt) , CFD, multi-agent systems	Architects, engineers, urban planners, energy modelers, software developers	Simulating energy flows in a PED using dynamic modeling tools to predict energy balance
Stakeholder Co-Creation and Decision-Support Platforms	Facilitate collaboration among stakeholders for decision-making and participatory design	GIS-based planning tools, serious gaming, AI-assisted decision support	Municipalities, energy communities, citizens, developers, regulatory bodies	Citizens engage in an online platform to provide feedback on PED scenarios and policies

Smart Energy Management and Control Laboratories	Develop and test intelligent energy management strategies for PEDs	IoT-based monitoring, predictive analytics, demand-response strategies, blockchain for energy trading	Smart grid operators, energy aggregators, DSOs, energy researchers	A utility company tests AI-driven energy balancing algorithms for optimized PED-grid interaction
Virtual Regulatory and Market Testing Sandboxes	Simulate energy policies, market models, and regulatory frameworks before real-world application	Agent-based modeling, blockchain, regulatory impact simulations	Policymakers, regulators, market operators, energy economists	The European Commission evaluates new pricing models and their effects on PED development
Hybrid Virtual-Physical Testbeds	Integrate physical prototypes with virtual simulations to validate energy solutions	Hardware-in-the-loop (HIL) simulation, digital twins, living lab integration	Universities, research centers, technology providers, startups	A research center connects real-life smart meters and storage systems to a virtual PED model

5. TOOLS AND FUNCTIONALITIES

5.1 Introduction

The Virtual PED Labs, through the use of digital tools and models, provide a digital representation to evaluate specific indicators of the technological systems and processes of a district/city using data analytics and machine learning to support simulation models that can be updated and modified (in real-time) as their physical equivalents vary.

Virtual PED lab allows to analyze the energy response of the city/district building stock, simulate the inclusion of new projects in urban planning as a support for territorial and environmental sustainability assessments, as well as evaluate design alternatives, policies and/or incentives.

The evaluation of PED Lab using digital tools has different functionalities. On the one hand, it enables the integrated management of the laboratory in any of its life cycle phases, optimizing its performance based on input requirements, flows and objectives. On the other hand, it allows preventive maintenance to be carried out to reduce failures and improve the district´s efficiency. This virtual laboratory allows the evaluation and prediction of future urban operations and regulatory scenarios. However, these VPEDLs also make it possible to assess and optimize policies and business models. Finally, the virtual laboratory supports and enhances the participation of stakeholders in decision-making processes, providing different KPIs.

The main advantages of this virtual laboratory are the creation of a simulation environment that provides very flexible tests, great dynamism in the tests to be carried out and the possibility of analyzing different physical, social, economic, political or climatic scenarios.

The operation of the virtual laboratory is carried out through a simulation environment where all the models necessary to evaluate different district scenarios are coupled. To do this, it is necessary to include numerical models, templates and libraries that allow the evaluation of different district components in a combined manner.

5.2 Classification of tools

The virtual laboratory environment must integrate or couple different simulation tools, which are selected based on the objectives, requirements, levels of detail and resolution. Most of the tools available to simulate the district behavior cover energy aspects, followed by environmental aspects. In contrast, social, full life-cycle assessment and mobility aspects are considered by a smaller number of tools. Natanian et al. (2024), have studied a total of 43 tools with the aim of classifying them based on their scope, methods or metrics, identifying their availability when integrating them into different phases of the design process.

The table reported in the following Figure 10 shows a classification of PED tools as well as their domains of interest: energy, environmental boundary, indoor environment, outdoor environment, economic or social (Natanian et al, 2024).

Tool	DOMAIN OF APPLICATION							
	Energy			Environmental boundary	Indoor environment	Outdoor environment	Economic	Social
	Energy demand	Energy supply	Mobility					
Intelligent Community Design (iCD) [59]	H&C, DHW, EL	REN, NO-REN		CO_{2eq}-UP			O&M	other[1]
Insight [88]	H&C, EL	REN, NO-REN			DL		IC, PBT, O&M	
Urban Modeling Interface (UMI) [82]	H&C, DHW, EL	REN, NO-REN		CO_{2eq}-LC, EE-LC	DL			other[2]
Sefaira [81]	H&C, DHW, EL	REN, NO-REN		CO_2-UP	DL, TC		O&M	
ClimateStudio [83]	H&C, DHW, EL	REN		CO_2-UP	DL, TC		O&M	
Ladybug [86]						TC		
Honeybee [84]	H&C, DHW, EL	NO-REN		CO_2-UP	DL, TC			
Dragonfly [87]	H&C, DHW, EL	REN, NO-REN	X	CO_2-UP		UHI	IC	
Butterfly [88]					TC	TC		
Pollination [89]	H&C, DHW, EL	NO-REN			DL, TC			
Eddy3D [90]						TC		
Morpho [91]						TC		
Envimet [92]						TC		
CityBES [93]	H&C, DHW, EL	REN, NO-REN		CO_{2eq}-LC		TC, UHI	IC, PBT, O&M	
URBANopt [94]	H&C, DHW, EL	REN, NO-REN		CO_{2eq}-UP				
COFFEE [95]	H&C, DHW, EL	NO-REN						
CitySim [96]	H&C, DHW, EL	REN, NO-REN						
SEMANCO [97]	H&C, EL	REN, NO-REN		CO_2-UP			O&M	
SimStadt [77]	H&C, DHW, EL	REN, NO-REN		PE-UP, CO_2-UP			IC, O&M	
LakeSIM [64]	H&C, DHW, EL		X					
City Energy Analyst [60]	H&C, DHW, EL	REN, NO-REN	X	CO_{2eq}-CUPM, PED-CUPM			IC, O&M	
Tool For Energy Analysis and Simulation For Efficient Retrofit (TEASER) [62]	H&C	REN, NO-REN						
Calliope [65]	H&C, DHW, EL	REN, NO-REN					O&M	
energyPRO [66]	H&C, EL	REN, NO-REN					IC, PBT, NPV, O&M	
oemof (Open Energy Modeling	H&C, EL	REN, NO-					IC	

Framework) [78]		REN						
MANGO [68]	H&C, DHW, EL	REN, NO-REN		CO_2-UP			IC, O&M	
ICL (Intelligent Communities Life Cycle) [85]	H&C, DHW, EL	REN, NO-REN	X	CO_2-UP			IC, PBT, O&M	
DER-CAM [98]	H&C, DHW, EL	REN, NO-REN		CO_2-UP			IC, PBT, O&M	
Making City (ENERKAD®) [99]	H&C, DHW, EL	REN		CO_2-UP			O&M	
DeCodingSpaces Toolbox [69]	Not applicable[1]							
Urbano [70]								other[3]
DigiWo [70]	Not applicable[2]							
Design Explorer/ Thread[3][74,73]	H&C, EL				DL			
Colibri[3] [72]	H&C, EL							
Opossum [75]	Not applicable[4]							
Octopus [76]	Not applicable[4]							
EnergyPlus [63]	H&C, DHW, EL	REN, NO-REN		CO_{2eq}-UP	DL, IAQ, TC		IC, O&M	
trnsys [100]	H&C, DHW, EL	REN, NO-REN			TC		IC, O&M	
DOE-2 [101]	H&C, DHW, EL	REN, NO-REN			DL		O&M	
eQUEST [102]	H&C, DHW, EL	REN, NO-REN			DL		O&M	
ESP-r [103]	H&C, DHW, EL				DL, TC			
OpenIDEAS [104]	H&C, DHW, EL	NO-REN					O&M	
DesignBuilder [105]	H&C, DHW, EL	REN, NO-REN		CO_{2eq}-LC	DL, IAQ, TC		IC, O&M	

Table 1 legend:

covered by the tools (green) — not covered by the tool (orange)

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

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

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

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

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

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

Other[2]: Jobs created, walkability

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

Figure 10: classification of the tools to their domains of application(Natanian et al, 2024)

The most common urban-scale energy simulation programs can be classified as integrated modeling tools or co-simulation tools [Sola, 2020]. Integrated tools represent simulation models where different urban elements are coupled. While co-simulation tools are environments that couple different simulation engines, allowing the simultaneous and autonomous analysis of different solutions. In this study, the modelling capabilities of the energy simulation tools are classified in fourteen categories: urban climatology modelling, building stock location, individual building characterization, demand modelling approach, endogenous/exogenous demand modelling, building energy demand types, impact of user behavior on building energy demands, non-residential type of buildings, transport energy demand modelling, modelling of energy generation, modelling of energy distribution, optimization analysis, time scale and practical considerations.

Particularly in building energy simulation, the use of one or the other tool depends on several factors such as the target audience, the target scale (spatial and temporal), the modelling methodology (top-down or bottom-up), the quality and availability of the input data or the expected outputs. (Hong et al., 2020)

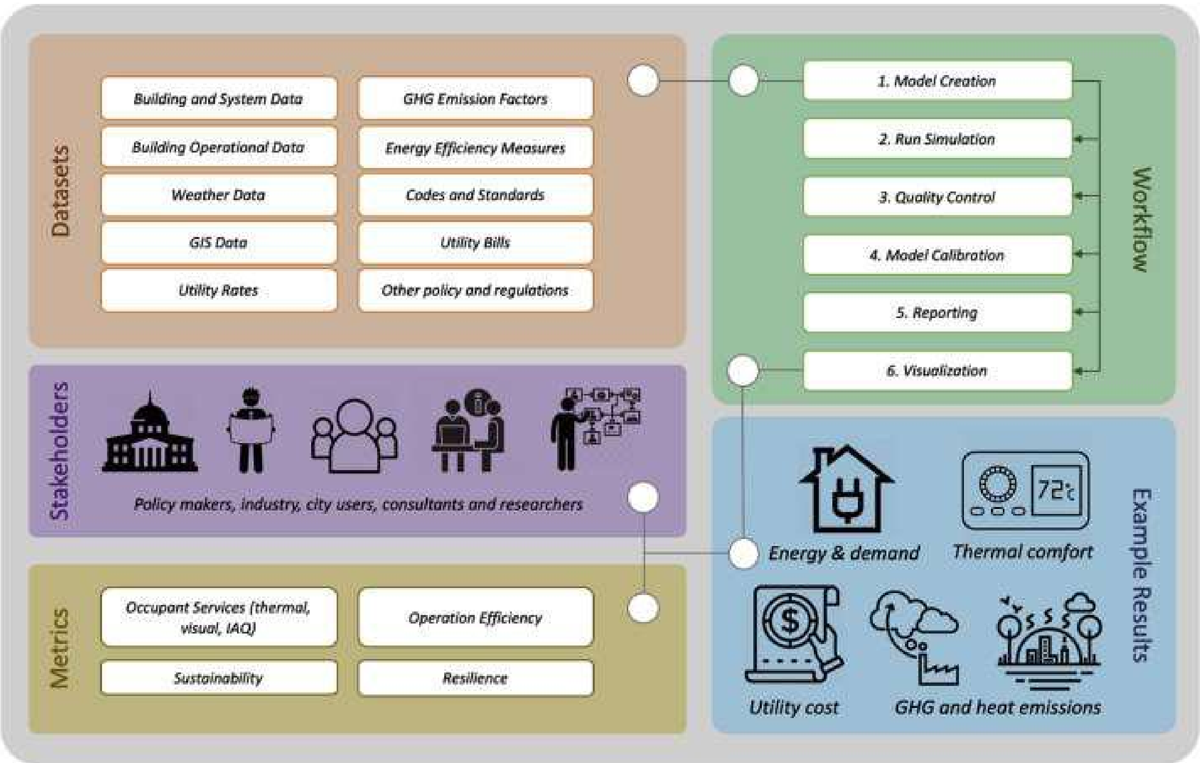


Figure 11: factors influencing the choice of a tool (Hong et al., 2020)

There are many **challenges** identified in energy modelling of urban systems, classified mainly into three aspects: technical, methodological and institutional challenges (Yazdanie et al., 2021). Technical challenges mainly concern data (quality, availability or granularity), transparency and reproducibility of models. The methodological challenges mainly concern the uncertainty of the models and the modelling process of certain processes. In both cases, there are common challenges such as the integration and management of models, the balance between model resolution, complexity or computational traceability. Finally, institutional challenges are related to organizational, educational, collaborative, financial or structural gaps that complicate the use of urban modelling tools for urban energy planning.

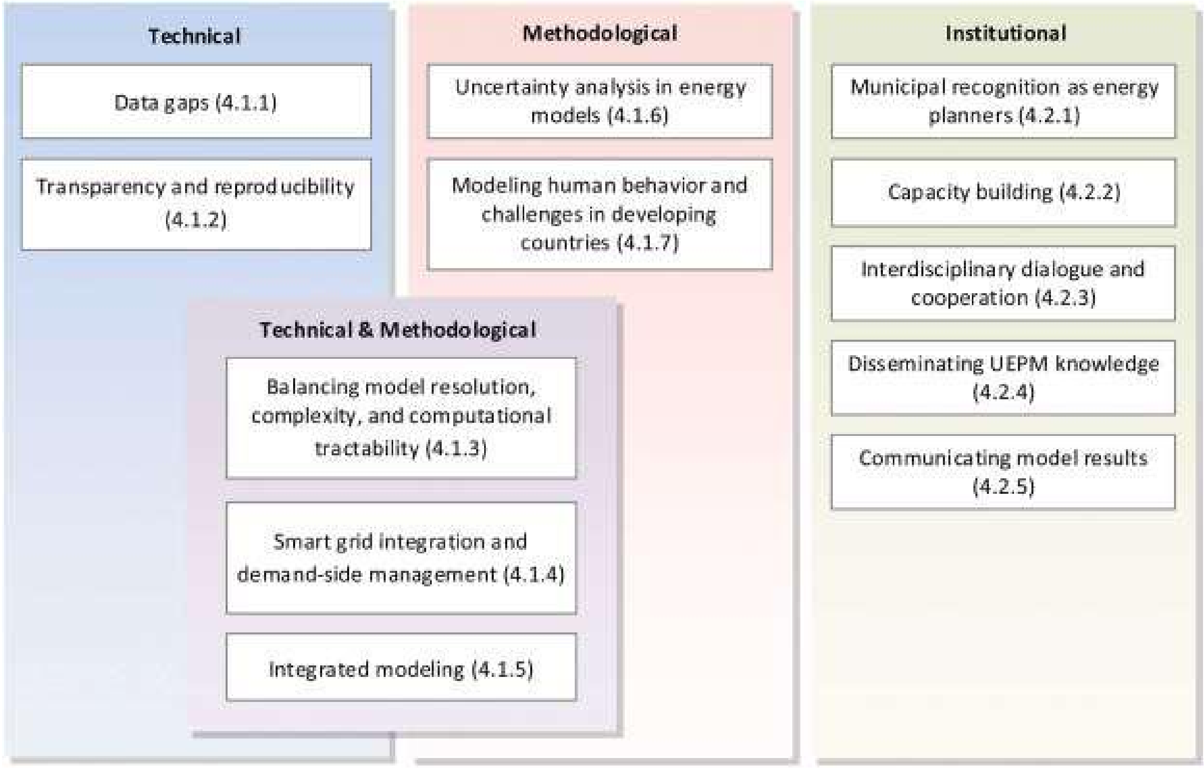


Figure 12: challenges identified in energy modelling of urban systems (Yazdanie et al, 2021)

The reliability of the estimation of the virtual laboratory's performance is carried out through **validation** studies between the theoretical results obtained and the experimental values measured in a real case. Therefore, it is necessary to have databases from experimental campaigns obtained in the laboratory when it is operating under real conditions of use. A first validation consists of the comparison between the predictions obtained with the theoretical model and the experimental measurements, evaluating the degree of correlation reaching. Subsequently, the uncertainty bands obtained between both databases (real and theoretical) must be compared. Finally, the level of acceptability of the virtual laboratory by the target stakeholders must be checked.

A first real scenario of a district must be defined where these validation studies are carried out, both globally (general model of the district) and in isolation from its components (partial models). Subsequently, a calibration of the models is carried out in order to limit and minimize the error obtained. The calibration of these models is developed through an iterative process, which aims to minimize the error committed with the estimation of the output values of the model and those with which it is compared, at a reasonable cost and with an acceptable degree of reliability.

The processes of v**alidation and calibration** are carried out progressively, starting with the partial models and increasing the levels of aggregation. This procedure will provide the virtual laboratory with great validity, increasing the range of application and allowing extrapolation to other situations with a greater margin of certainty, given that the uncertainties generated, and their origin are known.

5.3 Key Tools and Components

The effectiveness of a Virtual PED Lab hinges on the integration of several key tools and components, each serving a specific function in simulating, testing, and optimizing PED strategies. Below, we explore each component in depth, drawing on academic research and practical applications.

- **User Interface (UI)**

The User Interface (UI) is the primary interaction point for users, designed to be accessible and user-friendly for a diverse range of stakeholders, from technical experts to community members. Dashboards provide a centralized view of real-time data, key performance indicators (KPIs) such as energy surplus or carbon emissions, and simulation outcomes, allowing users to quickly assess the district's energy and environmental performance. Interactive tools, such as sliders, input fields, and scenario selectors, enable users to adjust parameters like renewable energy capacity or building insulation levels and observe their immediate impacts, supporting exploratory "what-if" analyses. Data visualizations, including 3D district models, heatmaps of energy consumption, and time-series graphs, make complex data more comprehensible, enhancing spatial understanding. For instance, a 3D model can illustrate energy flows between buildings, providing a visual aid for urban planning decisions.

- **Simulation Engine**

The Simulation Engine is the computational backbone of the Virtual PED Lab, enabling detailed modeling of urban energy dynamics. It processes multiple variables and algorithms to simulate energy flows, encompassing generation from renewable sources like solar panels and wind turbines, energy distribution, and consumption across the district, factoring in renewable integration (Amaral et al., 2018). It also models interactions between energy systems and other urban components, such as transportation networks or waste management, to assess their combined sustainability impact. Additionally, the engine evaluates environmental impacts, including carbon emissions, air quality changes, and biodiversity effects, aiding planners in balancing development with ecological goals (Koirala et al., 2024). Common tools like EnergyPlus and CityGML ensure both precision and scalability in these simulations, as noted by Widl et al. (2021) in their study on energy simulation with CityGML.

- **Data Integration**

Data Integration is crucial for anchoring the Virtual PED Lab in real-world contexts, ensuring that simulations reflect actual conditions. It aggregates diverse data sources, including Geographic Information Systems (GIS) for spatial data on building layouts, land use, and infrastructure networks (Li et al., 2019). Real-time sensor data from IoT devices, smart meters, and environmental sensors track energy use, weather patterns, and pollution levels, enhancing simulation accuracy (Stecula et al., 2023). Historical and demographic data, such as past energy consumption trends and population statistics, enrich the simulation context, providing a comprehensive view. This integration creates a responsive, data-driven model capable of adapting to real-time changes and delivering accurate insights.

- **Collaboration Tools**

Collaboration Tools are essential for engaging diverse stakeholders in the PED planning process, given the interdisciplinary nature of urban sustainability. These include shared workspaces where users can upload data, run simulations, and share findings in real time, fostering co-creation. Communication platforms, such as built-in messaging, video calls, and forums, streamline discussions and decision-making across teams (Steen & Van Bueren, 2017). Version control and feedback loops allow for tracking model iterations, proposing changes, and refining designs collaboratively, transforming the Virtual PED Lab into a hub for interdisciplinary knowledge sharing.

- **Modeling Tools**

Modeling Tools allow users to construct detailed representations of specific urban systems within the PED, providing granular insights for planning. Energy modeling software like EnergyPlus or TRNSYS simulates building energy efficiency and renewable energy contributions, essential for optimizing district performance. Transportation modeling software, such as SUMO (Simulation of Urban Mobility), analyzes traffic flows and their energy implications, integrating mobility into sustainability strategies. Environmental impact assessment tools measure carbon footprints, water usage, and ecological impacts, aligning with sustainability objectives.

- **Analytics Suite**

The Analytics Suite processes simulation outputs to deliver meaningful evaluations, turning raw data into evidence-based recommendations. It includes performance metrics, such as energy surplus, cost efficiency, or emission reductions, which gauge PED success. Sustainability indicators, tied to frameworks like the UN Sustainable Development Goals (SDGs), assess social, economic, and environmental outcomes. System behavior analysis tracks trends, predicts future performance, and identifies bottlenecks, enhancing decision-making.

- **Feedback Mechanisms**

Feedback Mechanisms enhance the lab’s adaptability and accuracy, ensuring it remains dynamic and responsive. They include real-time adjustments, where users can modify variables like battery storage size and see immediate results, facilitating rapid experimentation. Validation checks compare simulation outputs with real-world data to ensure reliability. Iterative improvement tools suggest optimizations or flag areas needing refinement, promoting continuous enhancement.

- **Integration with Emerging Technologies**

Integration with Emerging Technologies ensures the Virtual PED Lab remains innovative and forward-thinking. Artificial Intelligence (AI) enhances predictive analytics, optimizes energy distribution, and detects inefficiencies, as explored by Stecuła et al. (2023). Virtual Reality (VR) and Augmented Reality (AR) create immersive visualizations for stakeholder engagement and public education, improving accessibility (Natanian et al., 2024). Blockchain supports secure, transparent energy trading and data management within the district, offering a novel approach to urban energy systems (He and Zhang, 2024).

To illustrate the relationships between these components, consider the following table, which highlights their functions and interdependencies:

Component	Primary Function	Interdependence
User Interface (UI)	Facilitates user interaction and data visualization	Relies on Simulation Engine for data output
Simulation Engine	Models energy flows and environmental impacts	Depends on Data Integration for inputs
Data Integration	Aggregates real-world data for simulations	Feeds into Simulation Engine and Analytics Suite
Collaboration Tools	Enables stakeholder engagement and co-creation	Supports UI and Feedback Mechanisms

Modeling Tools	Constructs detailed system representations	Integrated within Simulation Engine
Analytics Suite	Processes outputs for decision-making	Uses data from Simulation Engine
Feedback Mechanisms	Enhances adaptability and accuracy	Interacts with all components for refinement
Emerging Technologies	Integrates AI, VR, AR, and Blockchain for innovation	Enhances all other components' capabilities

This table underscores the interconnected nature of the components, emphasizing their collective role in advancing PED strategies.

Implications and Future Directions

The integration of these components in Virtual PED Labs has significant implications for urban planning, particularly in fostering sustainable, energy-positive districts. An unexpected detail is the potential of emerging technologies like AI and blockchain, which not only enhance simulation accuracy but also introduce new paradigms for energy trading and public engagement, potentially transforming urban governance models. Future research could explore how these labs scale across different urban contexts, addressing challenges like data quality and user adoption.

6. CASE STUDY: RESEARCH CENTRE IN LUBIA (SPAIN), CEDER-CIEMAT

6.1 Introduction

The public Centre for the Development of Renewable Energy (CEDER) is situated in the northern-central region of Spain, specifically in Lubia, Soria. It specializes in applied research, development, and the promotion of renewable energy technologies. Among its facilities is the urban laboratory known as CEDER-CIEMAT, whose primary objective is to evaluate the performance of various energy network configurations at the district level.

Figure 13: Localization of the PED-Lab in Lubia, province of Soria (Spain). (Source: Google Earth, OpenStreetMap)

This Positive Energy District Laboratory (PED-Lab) encompasses an energy district covering an area of 640 hectares, integrating six office buildings with energy generation installations via two interconnected energy networks: an operational electrical grid and a thermal network currently in the implementation phase. The buildings within the PED-Lab function as both energy consumers and suppliers, depending on climatic and operational conditions. While the

majority of these buildings employ conventional construction technologies, some incorporate efficient and sustainable design measures.
The thermal network comprises two biomass boilers, each with a power output of 300 kW, and water tanks providing 90 kWh of thermal storage. This network is undergoing expansion to include both a low-temperature ring (90°C) and a high-temperature ring (ranging from 150°C to 250°C). The low-temperature ring consists of two Stirling engine cogeneration boilers—one utilizing biomass gasification and the other a gas-fired boiler. The high-temperature ring integrates a thermal generator that incorporates Fresnel solar concentrators and an Organic Rankine Cycle (ORC) cogeneration system, which is directly powered by the solar concentrator. These two thermal rings are interconnected through an oil/water heat exchanger.
Additionally, the thermal network incorporates diverse thermal energy storage systems, including aquifer storage, borehole thermal storage, phase-change materials, cold storage with geothermal exchange for ground heat recovery, and very low-temperature thermal storage using zeolites.
The electrical grid of the PED-Lab integrates multiple renewable energy generation technologies, including a 50 kW wind turbine and eight distinct photovoltaic systems with a total generation capacity of 116 kW. Furthermore, the system includes a 100 kVA engine generator, a reversible hydraulic system, electricity storage through battery systems, and flexible loads, thereby enhancing the efficiency and adaptability of the energy infrastructure.

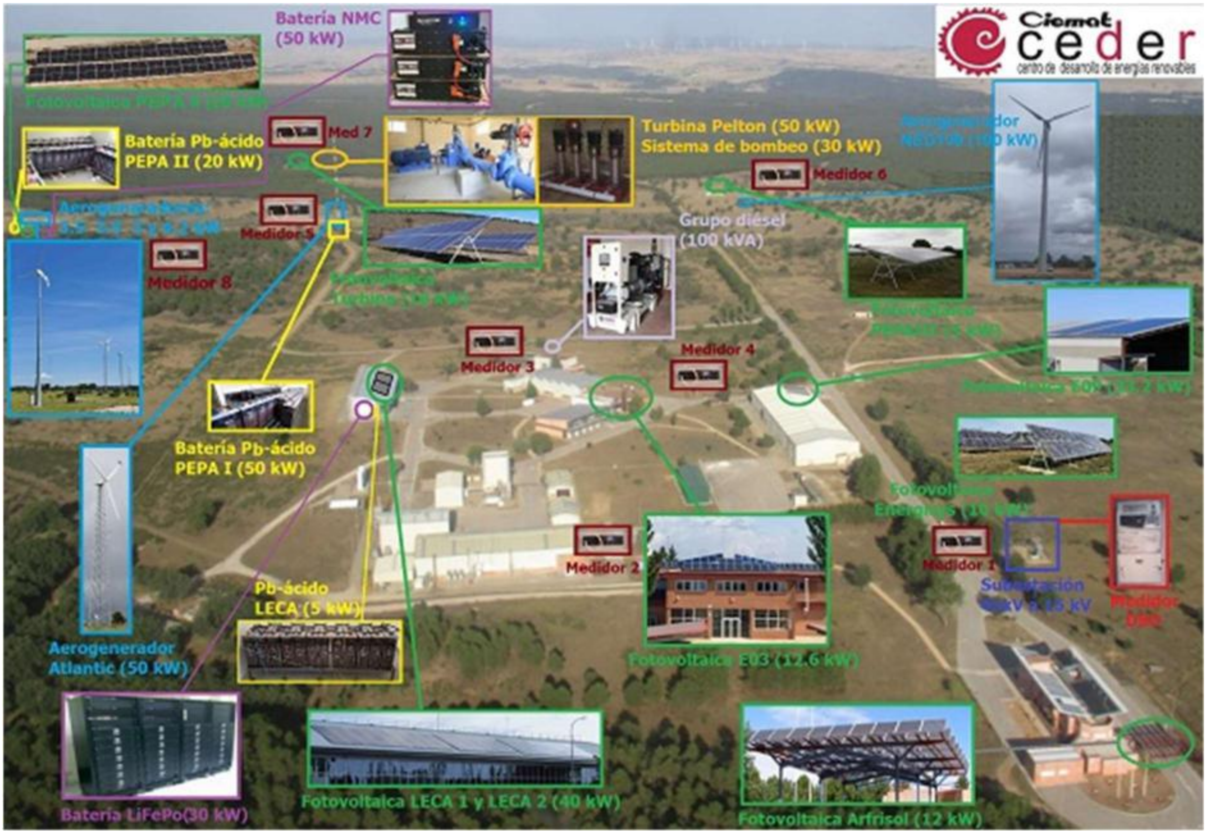


Figure 14: Distribution of the electrical micro-grid elements in the CEDER PED-Lab (Spain). (Source: CEDER-CIEMAT website)

The following table summarizes the main characteristics of this Positive Energy District Laboratory, highlighting the category, components and specifications that compose it.

Lubia PED-Lab Energy Systems Overview		
Component	**Primary Function**	**Interdependence**
Energy District	Area Coverage	640 hectares
	Connected Buildings	6 office buildings
	Energy Networks	Electrical grid (operational), Thermal network (in implementation)
Thermal Network	Biomass Boilers	2 units, 300 kW each
	Thermal Storage (Water Tanks)	90 kWh
	Low-Temperature Ring	90°C; includes two Stirling engine cogeneration boilers (biomass gasification and gas boiler)
	High-Temperature Ring	150–250°C; includes Fresnel solar concentrators and ORC cogeneration system
	Thermal Storage Systems	- Aquifers - Boreholes - Phase change materials - Cold storage with geothermal exchange ground recovery - Very low-temperature storage with zeolites
Electrical Grid	Wind Turbine	50 kW
	Photovoltaic Systems	8 different systems, total 116 kW production
	Engine Generator	100 kVA
	Reversible Hydraulic System	Integrated
	Electricity Storage (Batteries)	Installed
	Flexible Loads	Included for demand management
Building Energy Role	Energy Demand & Supply Capability	Buildings act as energy demanders or suppliers depending on climatic and operational conditions
	Building Technologies	Mostly conventional, some with sustainable efficiency measures

6.2 Technical information

Detailed information on the energy production systems and the energy efficiency and flexibility solutions and equipment adopted throughout the PED Lab at the Lubia Research Centre is provided below, in order to provide a comprehensive reading of the strategies adopted in the implementation of the reference case study.

a) Energy Production

- **Renewable Energy Generation:**
  The PED-Lab integrates various renewable energy sources, contributing to its energy production. These include:
  - Wind energy via a 50 kW wind turbine.
  - Photovoltaic systems with a total generation capacity of 116 kW from eight different systems.
  - Biomass energy via two biomass boilers (300 kW each) that provide thermal energy.
- **Energy Storage:**
  The system incorporates multiple forms of energy storage, including:
  - Thermal energy storage through various technologies like aquifers, boreholes, and phase change materials.
  - Electrical energy storage using batteries, facilitating efficient use of the produced energy.

b) Energy Efficiency

- **Energy Networks:**
  The PED-Lab is designed with two distinct interconnected energy rings:
  - The thermal network operates at two temperature ranges: a low-temperature ring (90°C) using Stirling engine cogeneration boilers and a high-temperature ring (150°C–250°C) using Fresnel solar concentrators and an ORC cogeneration system.
  - These networks support the efficient distribution and storage of thermal energy across the district, optimizing energy use within the connected buildings.
- **Building Technologies**:
  While the majority of the buildings in the PED-Lab are constructed with conventional technologies, some buildings integrate sustainable and efficient design measures that enhance overall energy efficiency in terms of both demand and supply.
- **Low-Temperature and High-Temperature Systems:**
  The use of low-temperature (90°C) and high-temperature (150°C–250°C) rings within the thermal network ensures that various heating and cooling needs can be met with optimal energy efficiency. The oil/water heat exchanger further enhances efficiency by interconnecting the two thermal networks.

c) Energy Flexibility

- **Demand and Supply Adaptability:**
  The PED-Lab buildings are flexible in terms of their role in energy networks, as they can function both as energy demanders and suppliers, depending on climatic and operational conditions. This adaptability allows for more dynamic and efficient energy management across the district.

- **Integrated Energy Systems**:
  The system integrates various renewable energy sources and energy storage technologies, which provides flexibility in managing the supply and demand of both electricity and thermal energy. This setup allows for the optimization of energy use throughout the day and across seasons.

- **Flexible Loads:**
  The inclusion of flexible loads within the electrical grid adds another layer of adaptability, enabling the PED-Lab to adjust energy consumption based on the availability of renewable energy and grid conditions.

The PED-Lab in Lubia emphasises sustainable energy production, efficiency through optimised energy networks and buildings, and flexibility by allowing its buildings to adapt their role in energy demand and supply. This combination ensures that the PED-Lab is an efficient, self-sustaining and adaptable energy system.
Nevertheless, several technical, environmental and socio-economic challenges have been identified for the implementation and operational phase, which need to be addressed to ensure the development of a functional and sustainable operating model.

6.3 Site-specific challenges of Lubia PED Lab

1. Technological Challenges

- **Integration of Renewable Energy Systems**
    - Managing the seamless integration of various renewable energy sources (solar, wind, geothermal) and their interplay with energy storage solutions is complex.
- **Scalability of Technologies**
    - Scaling up tested solutions from lab-scale to real-world district implementations poses significant technical and logistical hurdles.
- **Data Management**
    - Handling and processing large datasets collected from smart meters, energy systems, and microclimate sensors for optimization and decision-making remains a challenge.

2. Environmental Challenges

- **Marginal Lands:**
    - Energy crop cultivation on marginal lands introduces challenges in balancing energy production, soil health, and biodiversity conservation.
- **Adaptation to Local Climate:**
    - Testing systems in a real environment like Lubia means accounting for its unique climatic conditions, which might limit system efficiency or reliability.

3. Economic Challenges

- **Funding for Advanced Research:**
    - Sustaining high-cost projects that require significant investment in cutting-edge technologies like hydrogen systems and advanced energy storage is an ongoing issue.
- **Market Readiness:**
    - Ensuring technologies are economically viable for adoption in broader markets remains a barrier.

4. Governance and Regulatory Challenges

- **Policy and Regulatory Compliance:**
    - Aligning the lab's innovations with evolving energy policies at the national and European levels requires constant adaptation.
- **Coordination Across Stakeholders:**
    - Balancing diverse interests among government bodies, private entities, and researchers to achieve common goals can be challenging.

5. Social and Stakeholder Engagement Challenges

- **Public Awareness and Acceptance:**
    - Engaging the local community to understand and accept new energy systems is critical but often difficult.
- **Inclusion in Decision-Making:**
    - Ensuring equitable participation of all stakeholders, including marginalized groups, is a challenge in collaborative energy projects.

6. Innovation Diffusion Challenges

- **Knowledge Transfer:**
    - Translating experimental results into actionable insights for urban planning or industrial applications can be slow.
- **Barriers to Collaboration:**
    - Establishing efficient collaboration frameworks between CIEMAT and external partners like PED-EU-NET requires significant effort in networking and coordination.

These challenges underscore the need for strategic investments in technology, policy alignment, and robust stakeholder engagement mechanisms to ensure the success of the implementation and replicability of the PED Lab in Lubia.
Through the study of possible solutions for PED labs on the international scene and based on comparisons with similar realities, the research identified the key strategies to be adopted to address the identified challenges, ensuring the feasibility of the interventions based on the involvement of key stakeholders for the implementation and operational phase of the Lubia model, ensuring the replicability of the intervention as a pilot project in the European context.

6.4 Key-strategies and tools for Lubia Virtual PED Lab

Addressing the challenges faced by the Lubia PED Lab requires an integrated approach to ensure the success of Positive Energy District (PED) initiatives. Below are key strategies aligned with the challenges identified:

1. Technological Integration and Scalability

- **Holistic Energy System Design:**
    - Use digital twins to simulate and integrate renewable energy sources (solar, wind, and geothermal) with energy storage systems in a controlled environment before deploying district-wide
    - Adopt modular energy infrastructure to allow incremental scalability while testing reliability.
- **Advanced Monitoring and Optimization:**

- Implement IoT-based smart meters and sensors for real-time data collection and analysis.
- Use AI-driven analytics for predictive maintenance and to optimize energy generation and consumption

2. Environmental and Climate Adaptation

- **Resilient Energy Systems:**
  - Design systems capable of adapting to the climatic and environmental conditions of Lubia, such as intermittent renewable energy availability.
  - Develop hybrid solutions that combine renewables with backup energy systems like hydrogen or biogas
- **Biodiversity-Conscious Approaches:**
  - Conduct detailed environmental impact assessments to balance bioenergy crop production with conservation goals.

3. Financial and Economic Strategies

- **Public-Private Partnerships (PPPs):**
  - Foster collaborations between municipal governments, energy companies, and private investors to share risks and financial burdens
- **Incentivizing Innovation:**
  - Leverage European Union funding programs, such as Horizon Europe, to finance cutting-edge research and technology implementation.

4. Governance and Stakeholder Collaboration

- **Clear Regulatory Frameworks:**
  - Work closely with policymakers to ensure that PED innovations align with national and EU energy policies.
  - Develop guidelines for integrating PED solutions into urban planning frameworks
- **Stakeholder Engagement Platforms:**
  - Use participatory tools to include all stakeholders—local communities, industry, researchers, and authorities—in decision-making processes

5. Social Inclusion and Public Awareness

- **Community Outreach Programs:**
  - Increase public understanding and acceptance of PED projects through workshops and public forums.
  - Demonstrate cost-saving and environmental benefits to residents to encourage their participation.
- **Education and Training:**
  - Provide training for local professionals in managing and maintaining PED technologies.

6. Research and Knowledge Transfer

- **Cross-Border Collaboration:**
  - Partner with other PED labs and research networks (e.g., PED-EU-NET) to share insights, tools, and best practices
- **Iterative Learning Frameworks:**

- Establish feedback loops from ongoing projects to refine methodologies and apply lessons learned in future deployments.

7. Supporting Tools for Implementation

- **Simulation and Modeling Platforms:**
  - Utilize tools like energy simulation software and digital twins for scenario analysis and impact prediction
- **Innovative Energy Storage Solutions:**
  - Prioritize investments in advanced battery technology, thermal storage, and hydrogen systems.

By integrating these strategies, the Lubia PED Lab can overcome its challenges, fostering sustainable, scalable, and community-supported Positive Energy Districts.

7. CASE STUDY: CASCAIS SMART POLE LIVING LAB – CARCAVELOS, PORTUGAL

7.1 Introduction – General Overview

The Cascais Smart Pole (CSP) by NOVA SBE is a Living Lab established in a multifunctional urban area in Carcavelos, Portugal (Cascais Smart Pole, n.d.), integrating a university campus, residential neighbourhood, commercial spaces, public facilities, public spaces, and natural resources, including green areas and a beachfront. The project is funded by the EEA Grant, which supports the development of living lab pilot projects focused on decarbonisation and climate change mitigation. As outlined in the project's final report (Cascais Smart Pole Project Report, 2024):

> *Living labs represent innovative frameworks for fostering innovation. They are defined spatial environments, situated within a delimited area, with a distinct local identity recognizable to the public. These spaces integrate various technological solutions aimed at mitigating carbon emissions while promoting active engagement from citizens, businesses, public authorities, and academic institutions. Within this context, a living lab was established in the municipality of Cascais: the Cascais Smart Pole by NOVA SBE (CSP).*

CSP operated as a Living Lab for four years (2020-2024), through a collaborative partnership between the Alfredo de Sousa Foundation, NOVA School of Business & Economics, Cascais City Council, Cascais Ambiente, Get2C, PRIO BIO, and Veolia**.** The consortium also included the participation of a Norwegian company, Avfallsteknisk Montasje AS. At the 3.3-hectare site multiple stakeholders were involved, including municipal agencies, project partners, university staff, business owners, residents, students, and visitors.

The project's concept involves both a physical and virtual space**,** providing a platform for experimentation aimed at serving as a reference model for the municipality and other cities. Its management follows a Public-Private Partnership (PPP) framework for PEOPLE, fostering collaboration between private and public entities to drive innovation and sustainability (CSP Project Report, 2024).

The project was implemented through nine key activities: (1) the Roadmap for Carbon Neutrality, which outlined strategies for reducing emissions; (2) the Smart Pole Platform, a digital infrastructure enabling data integration and stakeholder engagement; (3) the Smart Pole Community, which fostered local participation and collaboration; (4) Urban Mobility, focused on promoting sustainable transportation solutions; (5) Energy Efficiency, aimed at optimizing resource consumption; (6) the Circular Economy in Waste initiative, which encouraged recycling and waste reduction; (7) Green Living, which enhanced urban green spaces for environmental resilience; (8) the Cascais Smart Pole Market, which developed mechanisms for carbon accountability; and (9) the Cascais Smart Pole World Activity (Communication), which facilitated outreach and public awareness initiatives (CSP Project Report, 2024).

CSP Living Lab, as classified within the PED-EU-NET Database, falls under the PED-relevant case study category, specifically as a district-level project with high aspirations in energy efficiency, flexibility, and production. While the project does not necessarily meet the criteria for an annual energy-positive balance, it aligns with key aspects of the JPI Urban Europe PED Framework Definition (PED-EU-NET Database, n.d).

The continuation of the CSP Living Lab Project involves establishing a Renewable Energy Community (REC) at the site, an initiative engaged by some stakeholders and currently in the early planning stage. The initiative is led by NOVA SBE, the primary stakeholder at the site, given its resources for implementation and management, as well as its energy demands and CO_2 emissions. The initiative is currently focused on finalizing the stakeholder structure and drafting statutory documents. To address regulatory requirements and define the REC grid's infrastructure and operations, the energy company Greenvolt, specializing in Energy Transition, Circular Economy, and Renewable Energy, is guiding the process. However, aligning the potential Public-Private Partnership REC with national REC legislation presents regulatory challenges. Additionally, planning for energy grids and infrastructure faces certain site and technological limitations and stakeholder engagement difficulties, particularly engaging citizens in PED process at the site.

Given these complexities, the CSP Living Lab in Carcavelos, along with its REC phase, serves as a relevant case study for discussing applicability and scalability of VPL concepts in a real-world setting, should the development of a VPL become a goal for the stakeholders involved. While still in the early planning phase, positioning the REC within the Virtual PED Lab framework could provide strategic benefits to its planning. In terms of technological readiness to become a VPL, the CSP Living Lab is currently at a low level. It incorporates fragmented virtual features and solutions developed within Co-Creation and Decision-Support Platforms, Data Integration Platforms, and Smart Energy Management and Control Systems. These solutions can inform discussions on the development of theVPLs and may potentially be adapted or integrated into relevant VPL typologies.

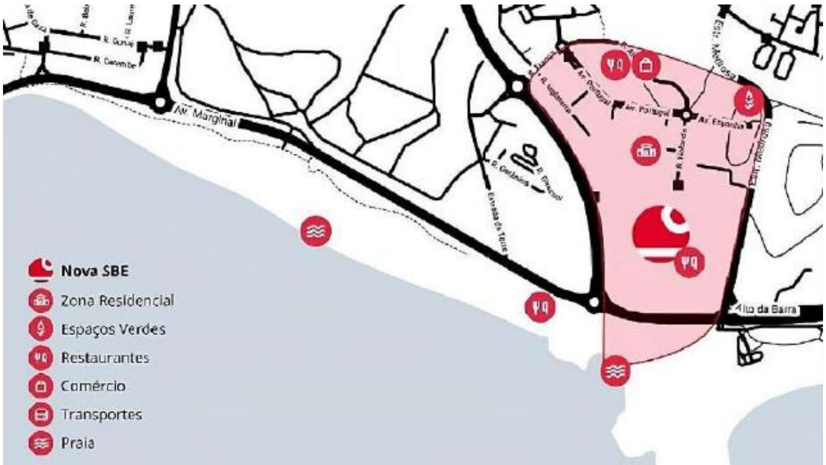
To present relevant data and upscaling potentials, this case study will methodologically rely on two frameworks: in the first part, on parameters specified within the PED-EU-NET database Conceptual Framework, and in the second, on the conceptual framework for VPLs developed in this report. The analysis will integrate relevant parameters and classifications from both frameworks.

The case study will systematically present:

- General data aligned with the PED-EU-NET database framework.
- Positioning of the CSP Living Lab within the Virtual PED Lab concept and framework proposed in this report.
- Identification of main barriers, needs and priorities for future development
- Standardization and upscaling strategies

7.2 CSP Living Lab – General data

	General Aspects
Name of the PED case study	The city of Carcavelos, Municipality of Cascais, Portugal
Categorisation of the PED site	PED relevant case study
Map/aerial view/photos	

	Carcavelos, Cascais Municipality, Portugal – Cascais Smart Pool Living Lab Area  Area Indentification – University campus (Nova SBE), residential area (Quinta de Sao Goncalo), green spaces, restorants, traditonal shops, transport, beaches (Praia do Moinho). Photos below courstasy of NOVA SBE.   
Phase/ Start and End Date	Completed - April 2020 - April 2024
Financial scheme	Public EEA GRANT / 01_Call#4_CascaisSmartPolebyNOVASBE Total Cost – budget – €1,252,051.12
District boundary	Geographic
Environment of the case study area	Urban
District population – Residential / Non-residential	1878 / 6126
Ownership of the case study/PED Lab	Mixed
Ownership land /infrastructure	Multiple Owners
Number of buildings in PED	Over 60 buildings and 3000 residents
Conditioned space	80.000m^2
Total ground area	330.000 m^2

KPIs	•Education; •Mobility; •Energy; •Water; •Waste; •Circular Economy; •Community Engagement
Targets	•Air quality and urban comfort; •Circularity; •Climate neutrality; •Energy Community;
Main objectives/activities and outcomes *virtual features	1. **Roadmap for Carbon Neutrality:** The project developed a comprehensive inventory of 2019 greenhouse gas emissions and modelled the path to carbon neutrality by 2050. Strategic options for decarbonisation were outlined, with a focus on mobility and energy efficiency. The efforts resulted in a 65-ton CO_2 reduction during the project's duration. 2. **Smart Pole Platform:** A participatory digital platform was created, providing data on project activities and allowing public engagement through submissions of ideas. It also included tools like a carbon footprint calculator. The platform gained over 13,000 visits, fostering collaboration among stakeholders. 3. **Smart Pole Community:** Community-focused initiatives included renewable energy workshops and microgreen cultivation activities. Events engaged locals and students, with over 17 activities conducted, such as street fairs and environmental workshops. The Microgreen Community distributed kits to promote urban agriculture. 4. **Urban Mobility:** Sustainable transport behaviours were promoted via a mobile app (MobiCascais), tracking CO_2 emissions saved. Due to delays, some planned features were revised, but the app incorporated mobility KPIs and avoided emissions data. A campaign highlighted the importance of shared mobility. 5. **Energy Efficiency:** Smart energy management systems optimized HVAC and lighting, integrating occupancy data for predictive efficiency. Indoor air quality monitoring systems were deployed, and smart energy counters were installed in classrooms. The project saved energy while addressing privacy concerns. 6. **Circular Economy in Waste:** The initiative collected 19.4 tons of used cooking oil, surpassing the goal by 43%, producing biodiesel for municipal vehicles. A gamified "Pay-As-You-Throw" system incentivized recycling, reducing waste contamination rates. Smart bins monitored waste levels, improving collection efficiency. 7. **Green Living:** Urban green spaces were transformed with native plants and smart irrigation systems, reducing water consumption and enhancing biodiversity. Over 7,000 trees and shrubs were planted, and lawns were replaced with water-efficient meadows. Smart systems optimized water use and tracked conservation progress. 8. **Smart Pole Market:** Originally intended as a carbon credit marketplace, this activity shifted focus to creating a carbon footprint calculator for businesses. The tool provides actionable insights for companies to reduce their emissions. Workshops introduced the software to local entrepreneurs. 9. **Smart Pole World:** Communication efforts included public awareness campaigns, workshops, and art initiatives like "Sustent'Arte." Over 20 events engaged stakeholders, promoting the project's goals. The communication strategy emphasized local impact and scalability to inspire other municipalities.
Technological Aspects	
Fields of application	•Energy efficiency; •Energy production; •E-mobility; •Urban management; •Urban comfort and air quality; •Digital technologies; •Water use; •Waste management; •Air quality;
Renewable resources on-site	The CSP project's photovoltaic panels are set up within a self-consumption unit (UPAC), with a contract in place to share surplus energy with nearby facilities, though

	implementation remains in early stages. This setup is designed to support shared energy use as part of the Renewable Energy Community (REC) initiative. Additionally, the project includes biodiesel production from collected used cooking oil (UCO), which is processed and used in municipal vehicles.
Annual renewable electricity imports from outside the boundary during target year	•PV; •Wind; •Hydro; Energy matrix at national level - 61% is renewable energy
Technological Solutions / Innovations - Energy Generation	•Photovoltaics; •Waste to energy;
Technological Solutions / Innovations - Energy Flexibility	•Information and Communication; •Technologies (ICT); •Energy management system; •Smart metering and demand-responsive control systems;
Technological Solutions / Innovations - Energy Efficiency	•Urban data platforms; •Mobile applications for citizens; •Building services (HVAC & Lighting); •Smart irrigation;
Technological Solutions / Innovations - Mobility	•Measures to reduce traffic; • Promotion of sustainable transport (public transport, shared bicycles); • The smartphone application (APP) for CO_2 Footprint Tracking, includes a quantification feature: it measures, in real time, the CO_2 emissions avoided when a user adopts sustainable modes of mobility; • Data integration - Mobility metrics displayed on the digital platform providing key metrics such as trips taken, kilometres travelled, and tons of CO_2 avoided, supporting the roadmap toward carbon neutrality; • Decision-support tools: Use collected mobility data to inform future urban mobility planning and strategies.
Non-Technological aspects	
Integrated urban strategies	•Strategic urban planning; •District Energy plans; •City Vision 2050; •SECAP Updates;
Social models	•Strategies towards (local) community-building; •Co-creation / Citizen engagement strategies; •Behavioural Change / End-users engagement; •Social incentives; •Quality of Life; •Digital Inclusion; •Citizen/owner; •Involvement in planning and maintenance; •Educational activities and trainings;
Sustainable behaviour	Use of public transport, bicycles, and shared mobility options; using carbon footprint calculators to understand and reduce emissions; recycling and proper waste sorting, including biodiesel production from used cooking oil; adopting smart irrigation systems to conserve water in green spaces; engagement in community composting and home composting to reduce organic waste; preparedness for participation in Renewable Energy Communities (RECs) for shared renewable energy production; switching to energy-efficient technologies like LED lighting and A+ rated appliances; participation in events, workshops, and educational courses on sustainability and climate action.
Environmental strategies	• Net zero carbon footprint; • Pollutants reduction; • Greening strategies; • Nature Based Solutions (NBS);
Legal / Regulatory aspects	• Compliance with Renewable Energy Communities (REC) regulations for energy sharing; • Adherence to General Data Protection Regulation (GDPR) for data privacy in smart systems; • Following EEA Grants public procurement rules for tendering and service hiring; • Meeting urban mobility and transportation regulations for low-emission zones and EV infrastructure; • Fulfilling waste management regulations for biodiesel production and organic waste processing

7.3 Positioning CSP Living Lab within classification of VPEDLs

The CSP Project established a living lab to test and implement innovative solutions across technical, social, economic, political, and environmental dimensions. Its primary objectives include addressing climate challenges, enhancing urban sustainability, and fostering community engagement. It integrates both physical and virtual environments, through tools and functionalities developed within Co-Creation and Decision-Support Platforms, Data Integration Platforms, and Smart Energy Management and Control Systems.

The project's key aspects and KPIs, classified within the Virtual PED Lab (VPL) framework, fall into two main domains:

- **Social Domain**: Digital engagement tools, gamification strategies, and citizen participation initiatives via mobile apps, workshops, and educational campaigns to drive behavioral change.
- **Technological Domain**: Energy generation, efficiency optimization, and smart system deployment, including carbon footprint calculators and energy monitoring tools.

Accordingly, the CSP Living Lab, its developed tools and functionalities, and potential upscaling within the VPL framework can be categorized as:

- **Stakeholder Co-Creation and Decision-Support Platforms**
- **Smart Energy Management and Control Laboratories**

CSP Case study categorization within Classification of Virtual Positive Energy Districts Laboratories (VPLs)				
Category	**Purpose**	**Key Technologies**	**Stakeholders Involved**	**Use Case Example**
Stakeholder Co-Creation and Decision-Support Platforms	Facilitate collaboration among stakeholders for decision-making and participatory design	GIS-based planning tools, serious gaming, AI-assisted decision support	Municipalities, energy communities, citizens, developers, regulatory bodies	Citizens engage in an online platform to provide feedback on PED scenarios and policies
Smart Energy Management and Control Laboratories	Develop and test intelligent energy management strategies for PEDs	IoT-based monitoring, predictive analytics, demand-response strategies, blockchain for energy trading	Smart grid operators, energy aggregators, DSOs, energy researchers	A utility company tests AI-driven energy balancing algorithms for optimized PED-grid interaction

Primarily, the CSP Living Lab can be classified as a Stakeholder Co-Creation and Decision-Support Platform, given its conceptual framework, stakeholder structure, and current focus on establishing a Renewable Energy Community (REC) at the site while engaging citizens in Positive Energy Districts (PEDs).
At the same time, a key objective of the lab is to promote sustainable behaviors and practices, facilitating a clear pathway toward energy efficiency and decarbonization.

CSP Case study – Category – Stakeholder Co–Creation and Decision-Support Platform		
Purpose	**Use case / Key Technologies and Tools**	**Stakeholders Involved**
▪ Facilitate collaboration among stakeholders for decision-making and participatory design ▪ Engaging stakeholders in sustainable behavior and energy efficiency practices ▪ Raising public awareness ▪ Digital Communication Platforms ▪ Interactive Events	**Participatory design and co-creation:** **Smart Pole Platform** - Participatory design interactive digital platform providing data on project activities and allowing public engagement through submissions of ideas. - Integrated with real-time data sharing and public participation features. Benchmarking similar IoT-enabled platforms and creating user-friendly UX/UI designs. **Sustainable Urban Mobility:** **Mobile app (MobiCascais)** - Mobility dashboard for monitoring metrics like avoided CO_2 emissions, trips taken, and kilometres travelled. **Decarbonisation:** **Carbon footprint calculator for business:** - A software by Delta Soluções designed to assist businesses in assessing and reducing their emissions. - The tool provides actionable insights for companies to reduce their emissions. Workshops introduced the software to local entrepreneurs. **Circular Economy in Waste:** **Pay-As-You-Throw Gamified System** - Smart waste bins with monitoring systems and a gamified "Pay-As-You-Throw" (PAYT) system using Citypoints (incentive for citizens) by PRIO. **Communication:** **CSP World** - CSP website, multimedia campaigns, educational programs and Sustent'Arte artistic initiatives. - Leveraging digital communication and interactive events to raise awareness and inspire community-driven sustainability efforts	Municipality, Municipal Agencies, Energy Companies, Developers, Regulatory Bodies, University campus, Citizens Business owners Students Visitors Tourists

The CSP Living Lab can also be classified as a Smart Energy Management and Control Laboratory, as it integrates virtual tools and functionalities aimed at decarbonisation, local renewable energy integration, smart irrigation systems, and sustainable mobility strategies to reduce CO_2 emissions.

CSP Case study – Category – Smart Energy Management and Control Laboratories		
Purpose	**Use case** **Key Technologies and Tools**	**Stakeholders Involved**
▪ Develop and test intelligent energy management strategies for PEDs ▪ Decarbonisation - Roadmap for carbon neutrality- GHG emissions inventory ▪ Green Living – Smart Irrigation Systems	**Smart Energy Systems:** **Energy Efficiency** - Cisco CMX platform for zonal mapping, IAQ monitoring sensors for CO_2 and temperature tracking, intelligent energy systems, including occupancy-based HVAC and lighting controls managed via the Building Management System (BMS) by Veolia. - Integration of Wi-Fi-based occupancy data with HVAC and lighting systems for predictive energy adjustments. - Real-time energy optimization algorithms and data-driven decision-making to improve efficiency and reduce emissions **Roadmap for Carbon Neutrality:** **Inventory of greenhouse gas emissions** - Strategic options for decarbonisation with focus on mobility and energy efficiency. The efforts resulted in a 65-ton CO_2 reduction during the project's duration. - GHG emissions inventory tools and carbon modelling methodologies, with support from Get2C. **Green Living:** **Smart Irrigation Systems** - Urban green spaces were transformed with native plants and smart irrigation systems, reducing water consumption and enhancing biodiversity. Smart systems optimized water use and tracked conservation progress.	Municipality, Municipal Agencies, Energy Companies, Developers, University campus

To provide a **comprehensive overview of the potential CSP VPL structure**, the **main axes** and the **applied tools, strategies, and methods** implemented across them are presented in the table below:

CSP Living Lab – Main Axes, Tools, Strategies and Methods
1. Roadmap for Carbon Neutrality • **Tools:** GHG emissions inventory tools and carbon modelling methodologies, with support from Get2C. • **Methods:** Data collection through surveys, energy use assessments, and direct engagement with stakeholders; scenario modelling for emissions reduction up to 2050. • **Strategies:** Alignment with the Cascais Municipal Roadmap for Carbon Neutrality and development of decarbonization pathways based on predictive modelling.

2. Smart Pole Platform • **Tools:** An interactive digital platform integrated with real-time data sharing and public participation features. Benchmarking similar IoT-enabled platforms and creating user-friendly UX/UI designs. • **Methods:** Benchmarking of similar platforms and custom UX/UI design to track project-specific KPIs like CO_2 emissions and participation rates. • **Strategies:** Enabling transparency and collaboration by integrating APIs for data collection and feedback loops for community input.
3. Smart Pole Community • **Tools:** Social media platforms and engagement tools for organizing events and activities. • **Methods:** Conducting workshops, technical visits, and environmental events to foster collaboration among residents, students, and stakeholders. • **Strategies:** Promoting sustainable habits through participatory activities such as microgreen cultivation and educational campaigns.
4. Urban Mobility • **Tools:** The Cascais Smart Pole platform mobility dashboard for monitoring metrics like avoided CO_2 emissions, trips taken, and kilometers traveled. • **Methods:** Integration of mobility data with platform analytics; promotion of shared transport options like bikes and scooters. • **Strategies:** Public awareness campaigns and gamification to encourage sustainable mobility behaviors and reduce reliance on private vehicles.
5. Energy Efficiency • **Tools:** Cisco CMX platform for zonal mapping, IAQ monitoring sensors for CO_2 and temperature tracking, intelligent energy systems, including occupancy-based HVAC and lighting controls managed via the Building Management System (BMS) by Veolia. • **Methods:** Integration of Wi-Fi-based occupancy data with HVAC and lighting systems for predictive energy adjustments. • **Strategies:** Real-time energy optimization algorithms and data-driven decision-making to improve efficiency and reduce emissions
6. Circular Economy in Waste • **Tools:** Smart waste bins with monitoring systems and a gamified "Pay-As-You-Throw" (PAYT) system using Citypoints by PRIO. • **Methods:** Collection of used cooking oils for biodiesel production, incentivized through gamification. • **Strategies:** Promoting recycling behaviors via smart monitoring and awareness campaigns while integrating circular economy practices
7. Water Use • **Tools:** Installation of water refill stations integrated with a digital mapping system for real-time updates on station locations. • **Methods:** Community campaigns promoting tap water use and workshops highlighting the environmental benefits of refill infrastructure. • **Strategies:** Educating residents and visitors about sustainable water use practices and providing accessible refill infrastructure.

8. Green Living • **Tools:** Smart irrigation systems, including various controllers, including Hunter's ACC2-75D-P controller and the MySOLEM app, with geolocation-based control and sensors for soil moisture, leaks, and water usage. Transformation of urban green spaces with native plants, planting trees. • **Methods:** Conversion of traditional lawns to rainfed meadows; installation of localized irrigation equipment to minimize water consumption. • **Strategies:** Expansion of smart irrigation systems to additional areas, enhancing biodiversity, and involving the community in sustainable practices
9. Smart Pole Market • **Tools:** A carbon footprint calculator – a software by Delta Soluções designed to assist businesses in assessing and reducing their emissions. • **Methods:** Workshops and municipal partnerships to encourage software adoption among local companies. • **Strategies:** Supporting businesses in carbon reporting and neutrality through accessible tools and guidance.
10. Smart Pole World • **Tools:** Cascais Smart Pole World website, multimedia campaigns, educational programs and Sustent'Arte artistic initiatives. • **Methods:** Stakeholder engagement through events like GreenFest and knowledge transfer via workshops and summer schools. • **Strategies:** Leveraging digital communication and interactive events to raise awareness and inspire community-driven sustainability efforts.

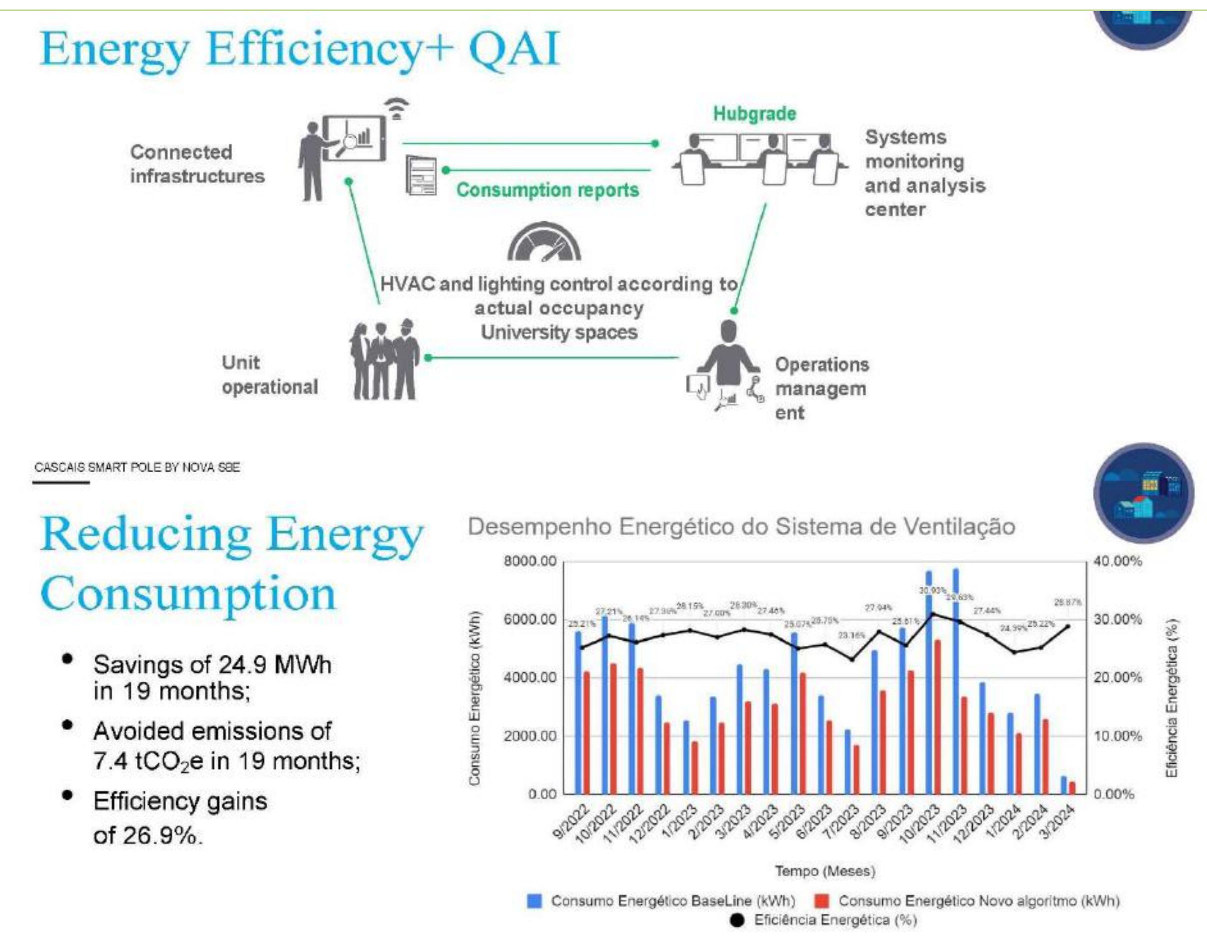


Figure 15: of CSP Energy Efficiency Strategy and Outcomes (CSP Project Final Presentation, 2024)

7.4 Identification of main barriers, needs and priorities

The transition from the CSP Living Lab to a Renewable Energy Community (REC) and potentially a Virtual PED Lab (VPL) at the site faces several key barriers, including:

Main Barriers

- **Regulatory and legal constraints**: Challenges in establishing a REC at the site, alignment with national laws and regulations, especially if REC would be public-private legal entity;
- **Infrastructure limitations**: Insufficient physical and technological infrastructure to support smart and flexible energy grids and management, alongside the site's low smart readiness for VPL implementations.
- **Knowledge and expertise gaps**: A lack of professionals capable of formulating a holistic and integrated VPL concept, incorporating fragmented virtual solutions while addressing defined needs and priorities.
- **Mobility challenges**: The need for a comprehensive mobility strategy, as transport-related emissions represent the largest CO_2 contributor at the site.

Source/Activity	Emissions (tCO2eq)	Weight in inventory (%)
Fuel	2.2	**0.03%**
Electricity	721.6	**9%**
Mobility, Leased Assets, Waste Treatment and liquid effluents	7,474.2	**91.2%**

Figure 16: Cascais Smart Pole (Activity 1.2), CO_2 Inventory: Nova SBE. Treatment of liquid effluents and waste calculated through: Emissions PER CAPITA tCO2e (RNC Cascais 2050), (CSP Project Report, CO_2 Inventory, 2024)

- **Citizen engagement in PEDs:** Identified as the primary challenge by CSP/REC stakeholders, requiring strategies to enhance public participation and behavioral change.

Considering the project goals and the identified barriers**,** the needs and priorities for the future development of the site are outlined below.

Needs and Priorities:

- **Reduction of GHG Emissions and Decarbonization Pathways**
  (local renewable energy use, energy-efficient retrofitting, reducing individual vehicle use)
- **Infrastructure and Technological Development**
  (sustainable mobility infrastructure - public transportation, EV charging stations, cycling networks; Green spaces adaptation to climate change – biodiversity planting, smart irrigation systems; Digital tools development - carbon footprint calculators, mobility information hubs to support decision-making and track progress)
- **Promotion of Circular Economy and Waste Management**
  (biodiesel production from used cooking oil, community composting, home composting, waste sorting systems)
- **Community Engagement and Behavioral Change**
  (renewable energy communities, sustainable/soft mobility practices, waste reduction behaviors, awareness and education, workshops, campaigns, events)

- **Stakeholder Collaboration**
  (strengthen partnerships among local businesses, public authorities, educational institutions, and community members; shared ownership of initiatives through participatory planning and implementation)
- **Policy Integration and Planning**
  (alignment with Cascais 2050 Roadmap, the National Roadmap for Carbon Neutrality, and European decarbonization strategies; share of best practices; set up of a legal framework for REC (Renewable energy Community in the area)
- **Monitoring and Scaling Successful Pilots**
  (establish robust monitoring systems for energy, water, and waste management; Replicate and expand pilot projects like smart irrigation, carbon footprint tools, and renewable energy communities to other areas)

7.5 Standardisation and Upscaling strategies

Standardisation

To enhance upscaling potential and define clear upscaling strategies, the CSP Living Lab engaged in standardization efforts through key indicators, targets, and thresholds, ensuring progress toward sustainability objectives that could be effectively measured.
Examples include monitoring indoor air quality, with CO2 levels capped at 800 ppm as a threshold for acceptable conditions, and setting waste reduction targets through the Pay-as-You-Throw (PAYT) system, which incentivized recycling and reduced waste. In energy and water efficiency, Renewable Energy Community (REC) which is planned at the site should provide measurable improvements in local energy production and consumption and be replicable in other contexts, while smart irrigation systems contributed to water conservation by tracking and optimizing daily usage.
These metrics were integrated into digital tools such as carbon footprint calculators and energy monitoring platforms, enabling real-time measurement, testing, and evaluation of outcomes. The project adopted a systematic and adaptable approach to standardization, ensuring that measurement and evaluation procedures remained iterative and responsive to evolving needs.

Upscaling Strategies

In terms of upscaling potential and strategies, the CSP Project employs a living lab methodology to test, validate, and refine innovative solutions that can be scaled, replicated, and adapted to different contexts. By integrating virtual and digital tools and solutions, such as smart energy monitoring systems, Renewable Energy Community (REC) energy grids, smart mobility strategies, and circular economy tools, the CSP Living Lab establishes a flexible framework for addressing diverse urban challenges.
The methodology for upscaling the CSP Living Lab into REC, an possibly further PED and Virtual PED Lab, identifies additional aspects requiring support from both physical and virtual infrastructure, as outlined i below:

- **Community co-creation** (citizen and stakeholder engagement in design, implementation, and feedback processes to ensure adaptability and social acceptance);

- **Pilot testing** (using Cascais as a real-world laboratory to gather insights under specific social, geographical, and economic conditions);
- **Scalability and replication** (developing flexible and adaptable models like renewable energy communities (recs), replicable technical tools such as carbon footprint calculators, mobility information hubs, energy monitoring systems, smart irrigation systems for efficient water use, and circular strategies for waste management like biodiesel production and composting);
- **Knowledge sharing** (workshops, reports, and digital tools to enhance transparency and encourage replication in other regions);
- **Policy and stakeholder alignment** (integrating solutions with local, national, and European policies while fostering public-private collaborations for broader adaptation).

8. CONCLUSIONS

Positive Energy Districts (PEDs) embody an ambitious vision for sustainable urban living, where integrated urban systems not only meet local energy demands but also contribute surplus energy to the wider grid. Central to achieving this vision are PED Labs, which serve as critical platforms for testing and refining the technologies, strategies, and collaborative frameworks that drive energy-positive urban districts. Virtual PED Labs, as defined earlier in this report, stand out as sophisticated digital environments that enhance and extend the capabilities of Physical PED Labs, addressing key challenges in the development and scaling of PED solutions. The Virtual PED Lab, at its core, is a digital platform designed to simulate and optimize the complex, interconnected systems of PEDs—encompassing energy flows, infrastructure, and socio-economic dynamics. This holistic simulation capability allows stakeholders to model entire urban ecosystems, from individual buildings to sprawling districts, in a way that captures the multifaceted nature of sustainability. Unlike traditional urban simulation tools, Virtual PED Labs are distinguished by their scalability and flexibility, enabling rapid experimentation across diverse urban contexts without the physical or financial constraints that often limit Physical PED Labs. By integrating real-time data—such as energy consumption patterns, weather conditions, and user behaviors—these platforms provide a dynamic, data-driven foundation for testing and refining PED solutions, ensuring that outcomes are both practical and forward-looking.

Collaboration is another hallmark of Virtual PED Labs, as they foster a shared digital workspace where researchers, urban planners, policymakers, and community members can co-create solutions. This interdisciplinary engagement ensures that PED designs are not only technically sound but also socially equitable and economically feasible—critical factors for widespread adoption. Moreover, the educational and public engagement features embedded within Virtual PED Labs democratize access to sustainable urban planning. By offering interactive tools and visualizations, they empower a broader audience to understand and contribute to the PED vision, cultivating a culture of innovation and environmental stewardship.

A defining focus of Virtual PED Labs is their commitment to energy positivity and sustainability. These platforms prioritize achieving net-positive energy balances while tracking essential metrics like carbon emissions and resource efficiency, aligning every simulation with the overarching goals of PEDs. The advanced computational tools that power Virtual PED Labs enable precise modeling and optimization, allowing stakeholders to iterate designs swiftly and identify pathways to energy surplus before physical implementation begins. This targeted approach sets Virtual PED Labs apart from generic simulation tools and underscores their indispensable role in the PED development process.

The synergy between Virtual and Physical PED Labs amplifies their collective impact. Virtual PED Labs provide a risk-free environment for prototyping and scenario analysis, leveraging their scalability and real-time data integration to explore possibilities that would be impractical or costly in physical settings. These virtual insights directly inform the design and execution of Physical PED Labs, ensuring that real-world experiments are grounded in robust digital analysis. In return, the empirical data collected from physical implementations—such as performance metrics and occupant feedback—feeds back into the virtual models, enhancing their accuracy and predictive power. This iterative feedback loop accelerates the refinement of PED solutions, reduces uncertainties, and lowers the barriers to scaling energy-positive innovations across cities globally.

While Virtual PED Labs offer transformative potential, challenges remain, including the need for seamless data integration, high-fidelity models, and standardized approaches to ensure consistency across simulations. The relatively small number of operational Physical PED Labs further underscores the importance of virtual platforms as a scalable testing ground. As PED initiatives evolve, ongoing research and investment will be vital to overcoming these hurdles and unlocking the full potential of both lab types.

Looking ahead, the integration of emerging technologies—such as artificial intelligence, digital twins, and advanced analytics—will further elevate Virtual PED Labs, enabling even more precise simulations and adaptive solutions. These advancements will strengthen their capacity to address the complexities of urban sustainability, making them essential tools for cities striving to meet ambitious climate and energy targets. By harnessing their unique capabilities—holistic simulation, real-time data integration, collaborative frameworks, and a focus on energy positivity—Virtual PED Labs not only complement Physical Labs but also drive the broader PED ecosystem forward.

In summary, Virtual PED Labs, as articulated in their definition, are far more than supplementary tools; they are integral to the realization of energy-positive urban districts. Their ability to simulate integrated urban systems, foster collaboration, and prioritize sustainability ensures that they address the limitations of physical testing while paving the way for scalable, replicable solutions. As the global push for sustainable urbanization intensifies, Virtual PED Labs will play a pivotal role in transforming the PED vision into a tangible, widespread reality, bridging the gap between digital innovation and physical impact.

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