PEDvolution

Interoperable solutions to streamline
PED evolution and cross-sectoral integration

Deliverable 8.1

PEDs Monitoring and Verification Plan and Co-developer demos preparation

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1 According to Project's Quality Assurance Process

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Glossary of terms and abbreviations used

ABBREVIATION / TERM	DESCRIPTION
BEMS	Building Energy Management Systems
BMI	Business Model Innovation
CAPEX	Capital Expenditure
CHP	Combined Heat and Power
CIM	Common Information Model
DDSG	Dynamic Decision Support Guideline
DGNB	German Sustainable Building Council
DH	District Heating
DHC	District Heating and Cooling
DSO	Distribution System Operator
DT	Digital Twin
EMS	Energy Management Systems
EPB	Energy Performance of Building(s)
ESC	Energy Sharing Community
EV	Electric Vehicle
GDPR	General Data Protection Regulation
IEQ	Indoor Environmental Quality
IP	Interoperability Platform
KPI	Key Performance Indicator
LEC	Local Energy Community
M&V Plan	Monitoring and Verification Plan

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OPEX	Operational Expenditure
PED	Positive Energy Districts
RA	Readiness Assessment
RES	Renewable Energy Sources
SAT	Site Acceptance Testing
UI	User Interface
WP	Work Package

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1 EXECUTIVE SUMMARY

This deliverable details the development of the Monitoring and Verification Plan (M&V Plan) and the preparation of the co-developer PEDs demonstrations in Germany, Switzerland, and Slovenia for the implementation of the PEDvolution solutions in live settings.

The baseline settings of each PED capture the current technical, infrastructural, regulatory, and socio-economic conditions, addressing four dimensions: energy, environment, economic, and social. To this aim, the M&V Plan was developed to track and assess the performance of the seven PEDvolution tools: 1) PED Design and Planning Toolset, 2) PED Readiness Assessment, 3) Dynamic Decision Support Guideline for PED Development, 4) PED Energy Manager, 5) Data Exchange, Integration and Interoperability Platform, 6) PED Business Models, 7) Social Innovation tool. In this plan, the performance indicators were highlighted, and evaluation methodologies were defined, aligning with applicable standards and policies. Each of the pilot sites was defined according to the baseline data as to how the demonstration will be conducted.

The deliverable serves as a technical and strategic measure to connect between the completed preparation phase and the upcoming demonstration phase. It provides an operational framework for demonstration and replication, whereas defined KPIs and carry-out procedures enable multi-dimensional performance assessment, ensuring the comparability and transparency of the results. For this purpose, feedback-driven mechanisms were created to iteratively refine and adjust the tools' performance and site configurations based on the testing outcomes.

The preparation phase has successfully established the necessary technical, organisational, and methodological foundations to proceed with the demonstration phase across all co-developer PEDs. Each PED has achieved demonstration readiness through the comprehensive definition of baseline conditions, the implementation of the PEDvolution tools, and the alignment of site-specific infrastructures, and evaluation criteria. Furthermore, all seven solutions have reached a level of maturity that enables their effective deployment and performance assessment in real-life environments, supported by clearly defined KPIs, standardized methodologies, and feedback-driven refinement mechanisms. Together, this ensures that both the PEDs and the integrated solutions are fully prepared for transparent, and comparable demonstration activities in the next project phase.

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2 INTRODUCTION

This deliverable supports the demonstration of the PEDvolution solutions in the three co-developer PEDs and provides the foundation for validating their overall performance and effectiveness through periodic assessment cycles.

The main objectives of the deliverable are:

1. define a robust monitoring and verification plan for PEDs, covering energy, environmental, economic, social, and smartness performance.

2. prepare co-developer demonstrations, including site analysis, scenario development, solution deployment, business model integration, and stakeholder engagement.

3. integrate tools and methods from previous work packages, ensuring alignment of KPI, data collection, and verification procedures.

4. provide a solid foundation for subsequent deliverables, including D9.1 (Demonstrator solution testing), D9.2 (PEDs performance assessment report), D9.3 (Report on PED business plan), and D12.2 (PEDvolution replication and market analysis & exploitation strategy), ensuring continuity across the project.

5. ensure replicability and alignment with PEDvolution objectives, so that the monitoring and verification framework can be applied to future PED and similar demonstration projects.

2.1 Mapping Project's Outputs

This section maps PEDvolution's Grant Agreement commitments, both within the formal Deliverable and Task description, against the project's respective outputs and work performed. The official deliverable title and task descriptions are provided in the «GA Component Title» and the «GA Component Outline» columns in Table 1 below. The chapters where these outputs are detailed are indicated in the «Respective Document Chapter(s)» column, while the «Justification» column presents a brief overview of the activities reported.

Table 1: Adherence to Project's GA Deliverable & Tasks Descriptions.

PROJECT GA COMPONENT TITLE	PROJECT GA COMPONENT OUTLINE	RESPECTIVE DOCUMENT CHAPTER(S)	JUSTIFICATION
DELIVERABLE			
D8.1 PEDs M&V Plan and Co-developer demos preparation.	M&V Plan of the PEDs covering energy, environmental, economic and social aspects. Detailed report on preparation	Deliverable 8.1 covers the entire T8.1 and T8.2	The deliverable is structured into three main chapters: Chapter 3 (overall information on Tasks T8.1 and T8.2), Chapter 4 (detailed M&V Plan), and Chapter 5 (preparation activities for the pilots and solutions, i.e. co-development).

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	and modification process of co-developer demonstration sites.		
TASKS			
Task 8.1 M&V Plan	This task defines the M&V Plan of the PEDs covering energy, environmental, economic and social aspects. This Plan is based on the identified requirements and KPIs, the partners' experience in these fields and existing evaluation methodologies, such as the one from IEA Annex 83 and is aligned with corresponding regulations, policy, standards and initiatives identified through T2.2 and T4.1.	Chapter 3, 4, 6	Chapter 3 explains the scope and methodological basis for the M&V Plan, relating the requirements, KPIs, and inputs from the previous tasks to the monitoring and verification framework. Chapter 4 explains the concept of the M&V Plan in detail, including the monitoring and data collection framework, the definition of the KPIs, the verification methodologies, the reporting framework, and the relationship to relevant regulations, policies, standards, and evaluation approaches, including the energy, environmental, economic, and social dimensions. Chapter 6 summarises the results from the process and verifies that the results match the objectives for Task T8.1 and the PEDvolution project.
Task 8.2 Co-developer PEDs preparation and deployment of tools	This task is based on the definition of all details related to the PEDvolution demonstration in the Co-developer pilots. The initial demo set-up from the proposal phase will be improved and optimised in the WPs 2-7, the scenarios and use cases defined will be executed and the findings documented. This elaboration from the proposal to the project execution phase is necessary in order to accommodate fine grained aspects related to local PEDs factors, applicable policy and regulatory context, environmental factors to be named among others. The	Chapter 3, 5, 6	Chapter 3 outlines the context of the scope of the demonstrations, reflects the optimisation of the initial demo set-up from the proposal phase, and relates the activities to the overall WP8 structure together with WPs 2-7. Chapter 5 presents the preparation of the co-developer PEDs, including infrastructure mapping, definition and execution of scenarios/use cases, solution deployment, integration of energy, environment, economy, social, and regulation aspects, as well as business model and social innovation processes. Chapter 6 presents the summary of the documented findings, confirming their relation to the objectives of Task T8.2 and the overall PEDvolution project.

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	definition of the demonstrators' specific scenarios will be supplemented by the mapping of available infrastructure at the demonstrator site and the necessary additional assets, tools and equipment for becoming a PEDvolution demonstrator. PEDs will actively participate to the business model innovation and social innovation processes, leading to the definition of suitable business models and stakeholder engagement roadmaps as part of the deployment of the tools.		

2.2 Deliverable Overview and Report Structure

Deliverable D8.1 provides a structured overview of WP8 activities, aiming to define a robust monitoring and verification framework for PED (PEDs) and to prepare co-developer demonstrations. It serves as a bridge between previous design and planning work and practical implementation, ensuring systematic performance assessment and evaluation. It contributes directly to the project's objective to showcase the interoperable PEDvolution solutions and tools across three co-developer PEDs and assess their overall performance and effectiveness through regular evaluation cycles and focuses on expanding, replicating, and mainstreaming the PEDvolution interoperability enablers within three follower demonstrator PEDs. Furthermore social innovation activities in the pilot sites shall be implemented to ensure that the solutions developed meet end-user needs and can be extended to the broader population.

The deliverable addresses WP8 tasks T8.1 (Monitoring & Verification Plan) and T8.2 (Co-developer Demonstrations Preparation),

- Under T8.1 the comprehensive M&V Plan has been developed to assess the energy, environmental, economic, and social performance of the PEDs. This plan draws on identified KPIs, partners' expertise, and established evaluation methodologies, ensuring alignment with relevant regulations, policies, standards, and initiatives defined in earlier project tasks.
- T8.2 operationalises these frameworks within the co-developer pilot sites. It refines the initial demonstration setups from the proposal stage, defines specific scenarios and use cases, and documents results. This includes mapping site infrastructure, identifying additional assets and tools, and integrating local, regulatory, and environmental considerations. The PEDs also engage

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in business model and social innovation processes, contributing to stakeholder engagement strategies and the development of sustainable business models.

In addition to the three original PEDs that were integrated into the project from the start, three newcomer PEDs selected through an Open Call for demonstrators (detailed in D8.2 Demonstrator acquisition process) will be onboarded for further demonstration of tools. The M&V Plan includes a clear support plan and a specific deployment process in order to facilitate this onboarding process.

The deliverable is structured according to the following chapters:

- Chapter 1 presents an executive summary, outlining the purpose, scope, and key outcomes.
- Chapter 2 introduces the objectives, links to other project outputs, and definitions relevant to PEDvolution.
- Chapter 3 explains the scope of the deliverable, highlighting how it builds on WPs 2–7 and prepares for subsequent project activities.
- Chapter 4 defines the M&V framework, specifying procedures to assess energy, environmental, economic, social, and smartness performance, as well as detailing the methodology, data collection, verification and reporting.
- Chapter 5 describes the PED pilot sites in Germany, Switzerland, and Slovenia, including implemented solutions and associated KPIs. In addition, chapter 5 focuses on co-developer demonstration preparation, covering site analysis, scenario development, solution deployment, business model integration, stakeholder engagement, and expected outcomes.
- Chapter 6 summarises the conclusions, highlighting outcomes and next steps
- The Annexes contain:
    I. a comprehensive list of KPIs used in the project;
    II. a structured reporting template for documenting tests, standards compliance, KPIs, SAT procedures, deviations, and sign-off; and
    III. detailed descriptions of the PEDvolution solutions, including their purpose, functionalities, and roles within PED development and operation.

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3 SCOPE

This chapter describes the structural framework of tasks T8.1 and T8.2, considering the technical development work undertaken in completed Work Packages, the preparation activities for the demonstration, and the baseline that guides this preparatory work. It illustrates how the outputs from this earlier work converge into the foundation of performance evaluation of the PEDs and the seven PEDvolution tools.

3.1 Work Done in WP2-7

This subchapter summarises the progress achieved in WP 2-7, forming the basis for WP8. The outcomes and interdependencies of each WP have progressively enabled the development of a robust monitoring, verification and validation framework for PED performance, which forms the core of WP8. Figure 1 describes how the work in previous WPs is used in the different tasks in WP8.

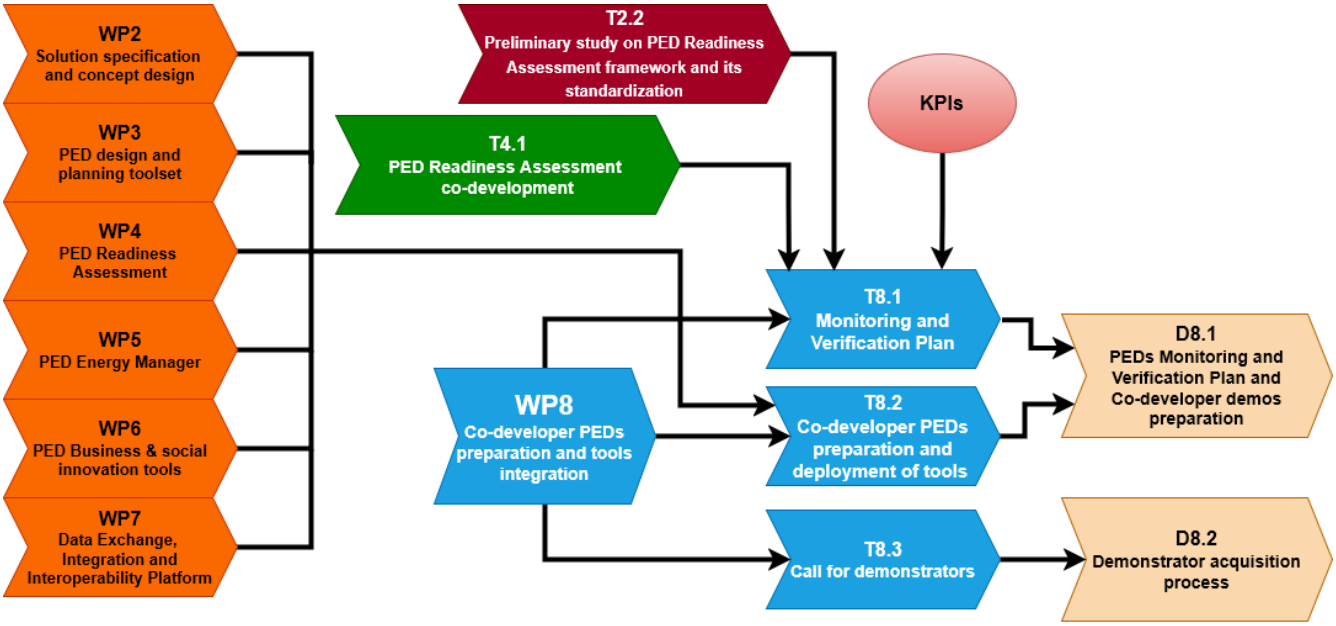


Figure 1: Interdependencies of the tasks and WPs for WP8.

WP 2 - Solution specification and concept design

The objective of this WP is to specify, ideate and plan the solutions for the PEDs. It sets the foundation for the solutions' architecture and provides a plan for the remaining process and conclusion on the true system development of the three related PEDvolution solutions. This includes the definition of The PED design and planning toolset with the development of a Digital Twin-based toolchain. Any data requirements related to existing building stock, current energy performance and renovation history will be defined. A *Preliminary study on the PED Readiness Assessment framework and its standardisation follows with the user and problem definition for the dynamic decision support guideline, focused on* specific problems or opportunities identified under WP1 (User-centered system analysis). The research and analysis of existing KPI-frameworks and assessment approaches in PEDs will lead to an inventory

of PED KPIs and categorisation. In addition, a *Solution specification and ideation for the PED energy manager* is designed for the following use-cases:

1) Demand Response Management (DRM) optimisation, energy, and flexibility management
2) Sector-coupled operation, optimising different energy vectors within PED, and
3) PED architecture and flexibility exchange

The business model and social innovation solution design adaptation for PED is composed of two intertwined tools and activities:

1) The business model innovation (BMI) tool adaptation and
2)The social innovation tool adaptation.

WP3 – PED Design and Planning Toolset

The activities undertaken in WP3 regarding the PED design and planning toolset are incorporated into the M&V Plan and the Co-developer PEDs preparation and deployment of tools through the following steps:

1. Development of algorithm-based optimised renovation packages for buildings and districts according to the PED energy and decarbonisation goals, including measures for:
    - Building envelope improvements
    - PV
    - Heat pump
    - Storage
    - E-Mobility

    These measures of the renovation packages serve as KPIs in the M&V Plan and provide a clear structure for each PED to show cost-effective renovation pathways and enable comparison among PEDs.
2. Advancement of the DHC assessment methods by expanding the optimisation models to evaluate the feasibility of low temperature-district cooling- and heating systems, including locational renewable energy- or excess heat-sources. This expands the design and planning toolset to a broader approach for each PED's energy and decarbonisation goals and strengthens the M&V Plan with another measurement to be applied.
3. Deployment of uncertainty and robustness optimisation routines to enhance decision making and its reliability to ensure resilient PED design. This includes:
    - Definition of uncertainty framework
    - Generating future climate scenario-databases for each pilot site
    - Preparation of methods to evaluate the performance of the renovation and DHC strategies under varying techno-economic conditions.

    Similar to the above-mentioned step no.2, the uncertainty and robustness optimisation routine extends the reach of the M&V Plan and the Co-developer PEDs preparation and deployment of tools.

Those three mentioned steps focus on interoperability and expanding existing open-source tools to create for each PEDs situation an integrated digital-twin-based planning framework, which matches the core purpose of the M&V Plan and the Co-developer PEDs preparation and deployment of tools. Further, the new toolsets, developed in WP3, introduce enhanced functionalities to ensure comprehensive support for district-scale energy analysis and decision-making.

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WP4 – PED Readiness Assessment

This WP assesses the potential of market-, social-, technology-, and interoperability- readiness for each PED and defines potential scenarios according to the KPIs defined in D2.2 (Understanding the PED Readiness Assessment framework). In the M&V Plan, the results of WP4 are aligned for each PED with the PED design and planning toolset (WP3). For that reason, each PED must provide the data according to the catalogue of criteria, with on-site assessment and working sessions ensuring the data alignment.

WP5 – PED Energy Manager

Many of the tools developed in other Work Packages need to be implemented in the participant's IT infrastructure and fulfil certain requirements to reach the PED's energy and decarbonisation goals, and especially to make the M&V Plan applicable. The PED Energy Manager is a holistic platform - close to real-time operation - with its associated tools :

1. AURORA is a decentralised energy-system optimisation platform for:
    - Holistic optimisation of complex, multi-vector and multi-level energy systems
    - Real-time flexibility management via FlexOffer
    - Automated trading of energy flexibility
    - System monitoring, analysis, and decision-support
    - Secure and scalable operational data storage
2. ANODE is an advanced Energy Management System for:
    - Integrating diverse assets into the AURORA platform
    - Collecting and sharing operational data in real time
    - Estimating and aggregating asset flexibility
    - Generating and sending FlexOffers
    - Executing optimal schedules on connected assets
3. DERMOT Is an algorithm-based DRM optimisation tool for:
    - Load scheduling
    - Thermal Building Management
    - Learning based battery- & EV-control
    - Behaviour modelling

Those three tools are the core IT-infrastructure feeding the M&V Plan in:

1. a sector coupled operation, including:
    - the extended "FlexOffer"-protocol
    - the extended MILP-based optimisation algorithm
2. multilevel PED architecture regarding and including
    - flexibility exchange and aggregation
    - a reliability index for performance evaluation
    - hierarchical exchange and possible market participation

    The PEDs various assets and the multilevel architecture is also transferred to the M&V Plan to ensure proper alignment, technical functionality and secure operation within the PED's assets and its surrounding energetical environment.

3. User-friendly interfaces with UI mock-ups for the WP3 results.

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To establish the PED Energy Manager, hardware requirements such as smart meters, smart plugs, control- and Moxa-boxes need to be met and installed at the demonstrator's sites. It is an essential step to secure proper functioning of the M&V Plan. Without those hardware instalments, neither the M&V Plan can receive any Data, nor the Co-developer can start the PEDs preparation and deployment of tools.

WP6 – PED business and social innovation tools

The requirements of stakeholder-analysis, -engagement and -participation need to be met via interviews, workshops and participant-recruitment to develop scenarios and feasible solutions in each PED. As a result, blueprints of business-cases and social innovation tools are carried out to adapt to each PED's local requirements and social acceptance. In the context of the M&V Plan, the stakeholders and participants of a PED can be seen as the surveyed subject.

WP7 – Data Exchange, Integration and Interoperability Platform

Similar to WP5, the results of WP7 are not just fundamental to ensure synchronised and harmonised operation of the PED's energy infrastructure, but also to apply the M&V Plan and the Co-developer PEDs preparation and deployment of tools. The M&V Plan gathers its information out of the Data Exchange, Integration and Interoperability Platform and uses it as one of the main inputs.

Thus, a Common Information Model (CIM) has been designed and implemented, integrating multiple characteristic ontologies to ensure semantic alignment across Pilots and Solution Providers, and to establish a shared and consistent understanding of the meaning, structure, and relationships of data generated within the PEDs. The CIM acts as a unifying semantic layer that bridges heterogeneous data sources and domain models, enabling coherent interpretation and standardised data exchange across the PEDvolution's ecosystem.

3.2 Relation to WP9 – PEDvolution demonstration, tool refinement and technical support

The WP8 tasks T8.1 (Monitoring & Verification Plan) and T8.2 (Co-developer Demonstrations Preparation), contribute directly to the WP9 tasks T9.1 (PEDvolution demonstration) and T9.2. (PEDvolution tool refinement and technical support) by preparing the on-site implementation. Thus, the tasks mentioned in WP8 need to be successfully completed and implemented at each PEDvolution demonstrator site. The M&V Plan as well as the Co-developer Demonstration Preparation also help to detect first difficulties, which may occur at the implementation phase and the possibility for decision makers for pre-intervention.

3.3 Baseline Approach

The baseline approach in this deliverable follows general principles of international energy management and M&V standards (ISO 50006, ISO 50015 and the International Performance Measurement and Verification Protocol, IPMVP), further detailed in Table 3. In line with these standards, a pre-intervention baseline is established for each co-developer PED, including clearly defined system boundaries and initial values of key performance indicators. Building on current PED frameworks (e.g. JPI Urban Europe PED Reference Framework and IEA EBC Annex 83), the baseline is characterised across four

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dimensions, energy, environment, economy and social aspects, which serve as the reference point for subsequent monitoring, verification and validation activities in WP9.

This baseline approach is documented in chapter 5 throughout the demonstration descriptions and tool deployment.

The baseline approach is built on the following six elements:

1 - Definition of system boundaries. For each PED, the physical, functional and organisational boundaries are defined. This includes the spatial extent of the district, the assets relevant for local generation, storage, flexibility and consumption, and the relevant actors (municipal actors, Distribution System Operator (DSOs), building owners, residents, operators). The boundary definition is necessary to ensure that monitoring of generation, consumption, emissions, socio-economic activity and stakeholder engagement is comparable over time and across sites. This system definition is consistent with the PEDvolution concept that PEDs are embedded in and interacting with local ecosystems (energy, mobility, ICT, industry) and continuously evolve under changing environmental, social and market conditions. These boundaries are used consistently by the PEDvolution planning and assessment solutions (WP2–WP4), the flexibility and operational solutions (WP5) and the interoperability platform (WP7) so that design, operation and monitoring of all seven solutions refer to the same PED system.

The “Pilot and Dimensions” column in Annex I: List of KPIs specifies for each indicator the relevant PED(s) and domain(s). During the demonstration phase, updated KPI values and verified changes with respect to this baseline will be reported by the solution providers using the WP9 reporting template provided in Annex II (Site Acceptance Testing) and consolidated in the subsequent WP9 reporting deliverables.
For each PED, baseline KPI values are defined before large-scale deployment of the PEDvolution solutions. The KPI set is derived from T2.2 and from the PED RA in WP4, which covers all four genotype dimensions: market, social, technology, and interoperability. These dimensions reflect PED maturity in terms of planning, implementation readiness, governance, and scalability. The baseline records the initial PED RA score per dimension and maps these to the energy, environmental, economic, and social pillars required in Task 8.1. This enables WP9 to quantify the PED readiness improvement per dimension. The KPI baseline provides the common reference against which the contribution of all seven PEDvolution solutions to PED readiness in each dimension will be assessed.

2 - Technical-operational characterisation. The baseline documents the current energy infrastructure and operational practices in each PED: on-site renewable generation and performance; flexibility assets and their control strategies (e.g. DERMOT, DRMS, AURORA, ANODE); building stock and renovation status; district heating and cooling where relevant; storage; and the current import/export balance. The data sources are WP2–WP5 (digital twins, renovation pathways, flexibility coordination logic). These data form the quantitative baseline for the energy and environmental pillars in Task 8.1 and are used to assess progress towards the expected outcomes with improved integration of energy (e.g. distributed renewable energy generation, storage) and non-energy sectors (e.g. mobility) within PEDs and improved integration of PEDs in energy systems and improved energy grid robustness regarding dependencies to energy supplies. This element is directly linked to the operation- and flexibility-related solutions developed in WP5, which will modify these technical and operational conditions during deployment.

3 – Community engagement and governance characterisation. The baseline captures stakeholder structures, governance models, and business model configurations at each PED site (WP6). It identifies (i) which actors hold operational, financial, or decision-making authority, (ii) which stakeholder

engagement processes are in place, (iii) which business model patterns exist or are emerging, and (iv) the degree of community participation and social innovation. This forms the quantitative and qualitative baseline for the economic and social pillars in Task 8.1 and is used to assess progress towards the expected outcome of increased social entrepreneurship, citizen participation, and engagement in energy communities. It provides the reference state against which the impact of the WP6 social innovation, engagement and business model solutions on governance structures and participation practices will be evaluated.

4 - Data interoperability and traceability. The baseline uses the data pipelines, semantics, and interfaces defined in WP7, including the CIM and the interoperability platform. This ensures that all baseline indicators are linked to defined sources, units, temporal resolutions, and spatial references, remain available during monitoring and verification, and are auditable in WP9. This supports the increased availability of tools, guides and interoperable solutions for the planning, design, implementation, operation and management of PEDs. This element is directly tied to the interoperability solution developed in WP7, which provides the data backbone for all seven PEDvolution solutions during both baseline establishment and subsequent monitoring.

5 - Temporal reference point. The baseline is fixed at the point at which the PEDvolution solutions are technically ready for deployment, but before the full operational rollout in the co-developer demonstrations. This deliverable marks the transition from integration (WP2–WP7) to demonstration and validation (WP9) in terms of:

- tools, assessment frameworks and interoperability layers are technically specified;
- site-level infrastructure and stakeholder processes are mapped;
- large-scale behavioural, infrastructural, or operational changes from implementation have not yet occurred.

At this reference point, all seven PEDvolution solutions are in a deployable form but have not yet significantly modified the PEDs, enabling their impact to be assessed against this baseline.

6 - Alignment with demonstration preparation. Task 8.2 requires that the demonstration setup be settled and finalised in WP2–WP7 (scenarios, infrastructure mapping, regulatory constraints). The baseline, therefore, also records, for each PED, the agreed pre-deployment scenario, i.e. the planned configuration of tools and use cases for WP9. This links the baseline directly to demonstration planning and enables later comparison between intended and actual deployment. In each PED, the pre-deployment scenario , described in chapter 5, specifies which of the seven PEDvolution solutions will be deployed, in which sequence and with which functional scope, so that WP8 and WP9 can trace how the combined solution portfolio changes the baseline conditions over time.

Operationally, the baseline approach functions can be seen in Table 2.

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Table 2: Baseline Approach Functions.

Operational step	Linked elements of baseline approach	Explanation
Step 1: Collect site-specific technical, organisational, regulatory and socio-economic input from WP2–WP7 for each co-developer PED, using WP7-compliant data structures.	1. Definition of system boundaries; 2. Technical-operational characterisation; 3. Community engagement and governance characterisation; 4. Data interoperability and traceability; 5. Alignment with demonstration preparation.	System boundaries, technical and socio-economic conditions, and interoperability requirements are derived from the inputs provided by WP2–WP7 and are structured according to the WP7 data models for each co-developer PED.
Step 2: Derive initial KPI values per PED across the four domains (energy, environmental, economic, social) and per PEDvolution four-dimension approach (market, social, technology, interoperability), and map these KPI values to the expected outcomes.	1. Definition of system boundaries**;** 2. Technical-operational characterisation; 3. Community engagement and governance characterisation.	The KPI baseline uses the technical and socio-economic characterisation of each PED to quantify the initial state per domain and per PEDvolution dimension and links these values to the expected outcomes (for example system integration, flexibility and grid robustness, citizen participation, availability and uptake of interoperable tools).
Step 3: Document assumptions and data limitations (e.g. incomplete metering data, preliminary stakeholder engagement data still under collection) and record them explicitly so that later changes can be attributed to actual intervention rather than to improved data availability.	1. Definition of system boundaries; 2. Technical-operational characterisation; 3. Community engagement and governance characterisation; 4. Data interoperability and traceability.	Assumptions and data gaps affect all descriptive elements of the baseline and must be made explicit to enable transparent interpretation of KPI changes and to avoid misattributing improvements to better data rather than to PEDvolution interventions.

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Step 4: Freeze these values, assumptions and mappings as the baseline state to be used in WP9 monitoring and validation.	1. Temporal reference point; 2. Definition of system boundaries 3. Alignment with demonstration preparation.	Fixing the baseline at a clearly defined temporal reference point establishes a stable reference for all KPIs and links it to the agreed pre-deployment scenarios for each co-developer PED, enabling systematic comparison between baseline in WP8 and post-deployment performance and WP9.

3.4 Overview of Regulations, Policies, Standards, and Frameworks

The M&V Plan and the preparation for deployment of the demonstration sites comply with European and international regulations, policies, standards, and frameworks to ensure technical consistency, regulatory compliance, and comparability of all activities in the PEDs. These are applied and used as guidance to define the methodological, procedural, and operational conditions for monitoring, verification, assessment, and implementation within all the PEDs (Table 3).

For the **Energy dimension**, the M&V Plan is structured to align with principles described in the International Performance Measurement and Verification Protocol (Interoperability Platform MVP; EVO, 2018) [1], providing a foundation guide for quantifying energy and cost savings through baseline definition, measurement boundaries, and adjustment procedures. ISO 52000-1:2013 [2] and the Energy Performance of Buildings Directive (Directives [EU] 2018/844 and 2024/1275) [3], [4] are used to define the methods for calculating energy-related KPIs (such as efficiency, flexibility, and renewable share) and are applied, for local operators and tool developers, respectively, to plan renovations in an energy- and cost-optimal way, ensuring verification of delivered and exported energy values. SAREF [5] and FLEXoffer [6] provide the framework to integrate energy and flexibility information into the Interoperability Platform, ensuring compatibility of data flows between PED tools. Additionally, the principles of IEA EBC Annex 83 [7]-[8] are followed to establish methodological guidance for multi-vector balancing, scenario evaluation, energy boundary definition within PEDs, and energy performance assessment.

For the **Environmental dimension**, EN ISO 16798-1:2019 [7], EN ISO 7730 [10], and ASHRAE 55:2013 [11] define the standardised measurement procedures for temperature, humidity, CO_2 concentration, and illuminance, establishing the comfort classes and sensor-placement protocols that structure indoor environmental KPIs. At the district level, CIBSE TM52 (2013) [12], CIBSE TM59 (2017) [13], and CIBSE Guide A [14] provide the procedures for thermal comfort evaluation, ventilation adequacy, and environmental design benchmarks. BREEAM International New Construction (2016) [15], German Sustainable Building Council (DGNB) [16] System for Buildings in Use (2020), LEED [17], and the EU Level(s) Framework [18] define life-cycle and environmental impact assessment methods for cross-PED comparability.

For the **Economic dimension**, cost-optimal methodologies use Directive (EU) 2024/1275 and integrate the Interoperability Platform MVP's cost-adjustment provisions to calculate Capital Expenditure (CAPEX), Operating Expenditure (OPEX), and payback indicators. The DGNB and LEED frameworks are

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applied in verification for life-cycle-cost efficiency, resource management, and investment replicability at the demonstration sites.

Within the **Social dimension**, ISO 21542:2011 (standardising accessibility and usability of the built environment) [19] and the General Data Protection Regulation (GDPR 2016/679) [23] define data-collection, processing, and storage requirements to ensure ethical compliance for all stakeholder and user-oriented processes. The DGNB, BREEAM, and LEED social indicators are used to measure community engagement, health, and comfort regarding the social KPIs.

Table 3: Regulations, Policies, Standards, and Frameworks, and their applications.

Regulation / Policy / Standard / Framework	Dimension	Purpose and How/Where Used	Extent of Application
International Performance Measurement and Verification Protocol (Interoperability Platform MVP): Core Concepts 2018 (Efficiency Valuation Organization)	Energy / Economic	Provides principles for quantifying energy and cost savings through baselines, measurement boundaries, and adjustment procedures.	The M&V Plan uses the principles methodological foundation for defining baselines and verification measures.
ISO 52000-1:2013 – Energy Performance of Buildings: General Framework and Procedures	Energy	Methodological estimation for overall energy performance by balancing delivered and exported energy per carrier for KPI calculation.	Used to calculate and validate energy KPIs.
Energy Performance of Buildings Directive (EPBD) – Directive (EU) 2018/844 and Directive (EU) 2024/1275	Energy / Economic	Specifies procedures for energy and cost-optimal renovation planning and energy performance calculations.	Ensuring energy and economic KPIs compliance with EU building performance and cost-optimality requirements.
SAREF – Smart Applications REFerence Ontology	Energy	Defines data models and interoperability rules for smart-meter and flexibility data.	Guaranteeing consistency and traceability of energy-related data exchange within the interoperability platform.
FLEXoffer Standard	Energy	Standardises communication structures	Enabling collection and validation of

		for flexibility data and events.	flexibility KPIs across systems.
IEA EBC Annex 83 – PED	Energy	Provides methodological guidance for multi-vector energy balancing and scenario evaluation, aligning M&V with PED boundaries.	Used to align PED data models with integrated multi-energy system definitions.
EN ISO 16798-1:2019 – Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings	Environmental	Defines comfort classes and measurement protocols for temperature, humidity, CO_2, and lighting.	Structures environmental indicators.
EN ISO 7730 – Ergonomics of the Thermal Environment	Environmental	Provides ergonomic comfort principles complementing EN ISO 16798-1 and ASHRAE 55.	Assessing of thermal comfort indicators for environmental evaluation.
ANSI/ASHRAE 55:2013 – Thermal Environmental Conditions for Human Occupancy	Environmental	Specifies comfort conditions for human occupancy and complements EN ISO 7730 and EN ISO 16798-1.	Defining and verifying comfort classes in environmental monitoring.
CIBSE TM52 (2013), TM59 (2017), and Guide A – Environmental Design	Environmental	Establish analytical methods for evaluating thermal comfort, ventilation adequacy, and indoor air quality in buildings.	Benchmarking and verifying environmental performance and comfort levels at district scale.
BREEAM International New Construction 2016 Manual	Environmental / Social	Provides life-cycle-based environmental verification and indicators for health, comfort, and community engagement.	Supporting PED comparability and verification of environmental and social indicators.
DGNB System – Criteria for Buildings in Use (2020)	Environmental / Economic / Social	Defines criteria for environmental performance, resource efficiency, life-cycle costs, and social well-being.	Evaluating sustainability, cost-effectiveness, and social factors in demonstrations.

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EU Level(s) Framework	Environmental	Supports life-cycle-based environmental verification across PEDs.	Benchmarking environmental indicators and ensure comparability of the PEDs.
LEED – Leadership in Energy and Environmental Design	Economic / Social	Contributes sustainability indicators for resource efficiency, health, and community engagement.	Support economic and social indicators verification in deployment.
ISO 21542:2011 – Building Construction: Accessibility and Usability of the Built Environment	Social	Standardises accessibility and usability metrics used in stakeholder surveys to evaluate inclusivity.	Ensuring accessibility and usability are consistently measured.
General Data Protection Regulation (GDPR) (Regulation (EU) 2016/679)	Social	Regulates personal-data handling within M&V and deployment, ensuring privacy and ethical compliance.	Processes stakeholder and user data to maintain proper and secure data management.

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4 MONITORING AND VERIFICATION PLAN

The M&V Plan aims to monitor, verify, and assess the solutions developed within the earlier stages of the project and their performance in the demonstration sites, across the four dimensions mentioned earlier. Energy and Environmental performance are assessed by means of simulations and measurements of energy consumption, generation, and RES integration. Indoor Environmental Quality (IEQ) is monitored through environmental parameters, modelling, and occupant feedback. Economic performance is assessed by analysing CAPEX and OPEX at the district level. Social performance is assessed through social indicators, such as community well-being and user engagement levels. The assessment framework on which the M&V Plan is based was defined in D4.1 (PED readiness assessment methodology, calculation sheet and action plan for testing the PED Readiness Assessment) and D4.2 (Readiness Assessment Policy Strategy Roadmap).

This performance will be assessed using KPIs and against baseline data, and results will be reported in D9.2 (PEDs performance assessment report), following the structure of the reporting template in Annex II: Reporting Template (Site Acceptance Testing).

4.1 Process conclusion

The development process of the M&V Plan included the definition of the scope, objectives, performance criteria, and KPIs for each dimension. The baseline data to be simulated and/or measured was determined, whereas monitoring methodologies, time intervals, simulation tools, stakeholder engagement approaches, data sources, responsible actors, and system boundaries were specified. All was done internally by the different solutions. The creation of the plan was built on the work done in WP2 and WP4, specifically the alignment with regulations, policies, standards, and frameworks, shown in Table 3, KPI framework, assessment scheme, and operational integration methodologies.

In addition, in order to enable proper monitoring verification operation, smart meters, EMS, and edge devices were deployed in WP5. The data collected: (i) technical, e.g. via live and offline measurements, and (ii) social, e.g. collection procedures (surveys, participatory mapping, technical screenings), processed within the SI tool, are used for visualising real-world conditions and simulating scenarios, using the Planning tools for testing and validating the different tools implemented (5.2 and ANNEX III: the PEDvolution solutions). Additionally, feasibility and compatibility with the Interoperability Platform are determined to guarantee real-time data exchange, scalability, and data sovereignty (5.2 and ANNEX III: the PEDvolution solutions).

In the operational phase, continuous measurement, simulation, and data collection across the four dimensions will feed the PED Energy Manager, Planning Toolset, Business Models Tool, RA DDSG, and Social Innovation Tool, where energy, IEQ, economic, and social KPIs are calculated, compared against baselines and targets, and analysed for deviations and success of the tests. The results of the verified indicators are reported at appropriate intervals, fed back into the appropriate tool to refine operational strategies, retrofit pathways, business models, and engagement schemes, and used to iteratively update and adjust the M&V outcomes.

Reporting will start taking place in WP9, as the testing of the tools occur, using the template in Annex II: Reporting Template (Site Acceptance Testing). This report is designed to provide a scalability and replicability framework for monitoring and evaluation of PEDs and supports continuous optimisation of

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PED assets and stakeholder acceptance. The template is used to document solution-level performance verification by recording the tests carried out in the relevant test environments, the standards that were applied, the KPIs measured and addressed, the test procedures, the acceptance criteria, and the deviations. It complements the M&V Plan by showing its application in structuring the way monitored and verified results are reported during the implementation and operations phases, while ensuring that the outcomes follow the methodology and are captured in a consistent and traceable manner.

4.2 Energy, Environmental, Economic and Social Aspects

These four dimensions form the core pillars of PEDvolution's PED performance. Their assessment and the overall approach align with international standards as described in chapter 3.4. Existing regulatory frameworks will be integrated and built on the genotype-phenotype model of PEDvolution to ensure adaptability, scalability, and replicability across diverse urban and regulatory contexts. The evaluation will be done using the KPIs found in Annex I: List of KPIs.

4.2.1 Energy

During the design and operational phase, energy needs for all building services, including district heating and cooling, ventilation, lighting, and plug loads, will be measured. These will be simulated using dynamic modelling tools capable of various resolutions and intervals. The simulations will help distinguish between delivered and exported energy per carrier and incorporate stochastic user behaviour profiles, especially in multifamily buildings. Matching factors will be calculated using the same time resolution to assess the alignment between local renewable production and on-site consumption.

Energy performances will be evaluated during the operational phase, in which energy flows will be continuously measured via smart meters, thermal energy meters, and EMS. Measurements will include delivered and exported electricity and thermal energy, sub-metered for EPB and non-EPB uses. These data will be collected at various granulated intervals, going from second levels to 5- or 15-minute, and integrated and factored into the Energy Manager tool for operation of the PEDs. The PED Energy Manager will utilise these data to enable automated, real-time operation of PED assets, flexibility extraction, and demand response, while supporting energy flow optimisation across multiple sectors. Energy KPIs will be monitored to evaluate system efficiency, renewable energy integration, and local flexibility utilisation.

4.2.2 Environmental

Environmental performance will centre on emissions-related indicators (see Annex I: List of KPIs) and IEQ Emissions will be assessed either through direct measurements or via calculations based on metered energy flows and standardised emission factors. IEQ parameters will be monitored in selected buildings through an approach comprising simulation, continuous measurement, survey data, and visual inspections. Key parameters include indoor air temperature, relative humidity, and CO_2 concentration. These will be monitored using equipment installed at standardised measurement positions in accordance with EN 16798-1:2019. The monitoring period will last at least one year to capture seasonal variations. Environmental performance will be assessed and used to adjust operational strategies within the PEDvolution solutions via a feedback mechanism.

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4.2.3 Economic

Business performance will be tracked by systematically approaching PED's CAPEX, OPEX, and developing relevant performance indicators for each PED context. At the district level, business evaluation will consider aggregation savings and shared infrastructure benefits. During the operational phase, relevant data, including investment costs and operational savings, will be collected. This will enable the assessment of energy-related costs and benefits, particularly of the PEDvolution solutions and services. Business KPIs will be used to evaluate the financial viability of PEDs, allowing comparisons across sites and business models.

4.2.4 Social

Social performance will be assessed through a blend of spatial mapping, stakeholder surveys, technical screenings, and audit procedures. Social monitoring includes both physical data, such as access to services, infrastructure quality, and universal design, and human-centric data, such as user satisfaction, perceived comfort, behavioural change, and engagement levels. Data will be collected through surveys, supported by direct engagement with local stakeholders. Technical screenings will follow standardised checklists during both the design and operational phases and include visual inspections to identify issues not captured through quantitative means. Survey results will undergo a data quality assurance process before integration into the PEDvolution social performance framework. Performance will be benchmarked against strategic community goals, and survey insights will inform the PED Social Innovation Tool to foster the co-creation of inclusive, adaptive, and socially resilient energy districts.

The integration of the four dimensions will be driven by the Interoperability Platform. This platform will serve solely as a data manager for data exchange, supporting dynamic visualisation, and scenario modelling. The dimensions mentioned above comply with the regulations, policies, standards and frameworks, described in 3.4 to ensure compatibility with European data spaces and secure, privacy-compliant integration of external data sources. The feedback mechanism embedded within the M&V framework will facilitate continuous learning and adaptation, translating monitoring outcomes into practical adjustments of the PEDvolution solutions. This will promote performance improvement, regulatory compliance, and ongoing alignment of the PED's genotype with its dynamic phenotype.

4.3 Monitoring and Data Collection Framework

The monitoring and data collection framework is structured around project-level KPIs that cover the project's overarching aims and use-case-related aspects, as developed by the solution providers and PEDs. They serve as the operational means for assessing the progress of the operations of the solutions. They are designed to track site-specific developments, as each demonstration PED introduces distinct infrastructures and operational contexts. The KPIs cover building and district-level energy performance, sector integration, flexibility, interoperability, economic feasibility, environmental impact, and social engagement. Each KPI includes a baseline, target value, and defined calculation method based on quantitative or qualitative data inputs. Units vary according to parameter type (e.g., %, kWh, €/MWh, tCO_2e, number of participants). Historical data and comparative analysis are employed to assess deviations and progress against defined baselines.

The KPIs are utilised by solution providers (tools developers) and demonstration sites for the M&V Plan to evaluate the results and ensure that each demonstrator meets the defined project targets. Not all

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KPIs are applied in all of the PEDs, as each site has different configurations and settings, and demonstration objectives.

4.3.1 Data Requirements

Energy data requirements include consumption, production, storage, and flexibility. Measurements cover delivered and exported electricity and heat, collected from PV systems, Combined Heat and Power (CHP) units, batteries, and other distributed assets. The data will be acquired in the appropriate configurable intervals, e.g. one second for electricity and one hour for heat, using smart meters and EMS. The readings are used to provide real-time monitoring, flexibility aggregation, and demand-response optimisation.

Environmental data requirements include parameters crucial for assessing emissions and IEQ, such as temperature, relative humidity, and CO_2 concentration. Emission data are either collected directly by measurement or calculated based on standardised emission factors linked to the energy carrier and technology type.

Economic data requirements include CAPEX, OPEX, market prices, and real-time energy-trading data. These are exchanged through the Interoperability Platform for district heating management, market platforms, and weather or regulatory databases purposes. The data acquired is leveraged to evaluate cost-efficiency, validate the business model, and benchmark performance against relevant regulations, policies, and standards.

Social data involves qualitative inputs on stakeholder behaviour, engagement, and acceptance. These datasets are collected through surveys, interviews, and participatory mapping exercises and processed using the Social Innovation Tool.

Data Processing, acquisition, storage, and processing responsibilities vary between the PEDs, solution providers, and coordinating partners. These are presented in Table 4.

Table 4: Responsibilities of data collection in the PEDs.

PEDvolution Solution / Tool	Germany PED	Swiss PED	Slovenian PED
PED Design and Planning Toolset	DT Tool: collection of building stock data, energy consumption and production, renovation-related technical data (building characteristics, energy performance, topology); Processing of data to model renovation measures, simulate RES	DT Tool: collection of data on solar, hydro, and district heating, including historical building-level consumption; Processing of data into renovation and RES integration scenarios. DHC Planning Tool: collection of data on	DHC Planning Tool only: collection of heat demand profiles, peak loads, and generation unit parameters; models new DHC infrastructure; evaluates industrial waste heat recovery, conversion to biomass, and optimal

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	integration, and determine cost-optimal energy upgrades. DHC Planning Tool: collection of district heating demand and load profiles, generation specs, efficiencies, and costs; produces cost-optimal district heating supply scenarios.	heat demand, storage, generation, and energy prices; evaluates DHC investment pathways, waste heat utilisation, transition to renewable-based operation, and heat storage.	portfolio design based on local resources.
PED Readiness Assessment (RA)	Collection of datasets in technological, market, social, and interoperability dimensions; assesses readiness levels; validates WP4 KPIs; uses SGNI/DGNB certification system for benchmarking; results used to test practicality and feed Dynamic Decision Support Guideline (DDSG).	Same as Germany: collection of technological, market, social, and interoperability data; validates WP4 KPIs; uses SGNI/DGNB system; feeds DDSG.	Same as Germany: collection of technological, market, social, and interoperability data; validates WP4 KPIs; uses SGNI/DGNB system; feeds DDSG.
Dynamic Decision Support Guideline (DDSG)	Processing of datasets from RA and Planning Toolset; analyses data to simulate energy-reduction, CO_2-savings, and RES-increase scenarios; validates usability and logic through stakeholder questionnaires.	Processing of RA data on energy use, socio-economic conditions, and policy assumptions; models multi-energy optimisation scenarios; tests functionality and adaptability via stakeholder feedback and RA integration.	Processing of district heating, storage, and emission datasets; simulates optimisation and decarbonisation scenarios; produces recommendations validated through workshops and structured stakeholder questionnaires.
PED Energy Manager	Collection of real-time and historical power	Collection of real-time data for EV/PV	Collection of real-time data via smart meters

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	and thermal data from PV, CHP, storage, and heating systems via smart meters and edge devices; Processing of for flexibility estimation, activation, and aggregation at household and industrial levels; enables supply optimisation.	coupling and washing-cellar load control; gathers PV generation, EV charging, and consumption data via smart meters and edge devices; Processing of for flexibility estimation, local matching, and optimal portfolio control.	and edge devices; Processing of for portfolio optimisation, flexibility activation, and alignment of renewable generation with industrial demand.
Data Exchange, Integration and Interoperability Platform	Facilitating secure, standardised data exchange between pilots and solution providers; manages datasets (PED and built-environment characteristics, district technical parameters, energy measurements, prices, weather); ensures metadata alignment, schema validation, GDPR-compliant access control.		
PED Business Models (BMI Tool)	Collection of stakeholder data and performance results from deployed solutions; quantifies costs, revenues, and feasibility.	Processing technical validation results and stakeholder feedback; identifies viable business cases and establishes baseline conditions.	Collection of and Processing of performance data, stakeholder feedback, and district-heating parameters; defines site-specific business models.
Social Innovation Tool (SI Tool)	Collection of interview and workshop data from residents; assesses acceptance and interest in shared-battery initiatives; Processing of qualitative data to derive engagement metrics and define participatory activities.	Processing of workshop outcomes and resident feedback; derives stakeholder perspectives for PED planning; co-defines engagement activities with community representatives.	Collection of qualitative data through interviews, questionnaires, and workshops with district-heating operators, municipalities, and end consumers; Processing of data to calibrate social-innovation measures to local requirements and align engagement strategies with PED goals.

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4.3.2 Data Quality Assurance

Data quality is maintained through a combination of automated validation, organised storage, and human observation. The system uses continuous data validation to detect anomalies, missing values, and errors and resolve them. Data exchanges are monitored to ensure traceability, with telemetry services providing auditing and verification, done by the respective solution provider, as stated in Table 4. When data is incomplete or incorrect, the corrective process relies on baseline assumptions or alternative datasets. Manually collected qualitative data is validated and cross-checked for consistency before being integrated into the monitoring framework. These measures help guarantee data integrity and reliability, supporting accurate KPI calculation and the overall robustness of the M&V Plan.

4.3.3 Data Collection Plan

The data collection plan involves a decentralised data-acquisition and coordinated-exchange system. It addresses the mechanisms for collecting and exchanging data necessary for real-time, continuous, and interoperable monitoring across PED demonstration sites and solution components. Additionally, this plan operates within the framework of interoperability, technical standards, stakeholder engagement, and regulations.

Data collection will occur at the PEDs level through the deployment of edge devices, directly connected to pre-existing or newly installed meters and control systems. These devices will interface with energy meters and the building Energy Management Systems (EMS) to measure consumption and production at various intervals.

Energy flows are continuously monitored, and electricity and thermal consumption and production are measured at configurable intervals, typically ranging from 1 minute to 1 hour. Indoor temperature, humidity, CO_2 concentration, and illuminance are collected by sensors installed and operating under EN 16798-1:2019 standards.

The energy-related data collected is retained temporarily in local storage and transmitted to the Interoperability Platform when needed by one of the solution providers. This is accomplished by those local edge devices which are connected to the AURORA Energy Management System (EMS). The AURORA oversees this central repository, storing data in a structured and suitable format that covers information such as households equipped with PV systems or battery storage.

Large PV systems are integrated into AURORA and are controlled. This data storage enables access to both real-time and historical data on consumption, production, and environmental performance. Furthermore, AURORA receives inputs from external systems, including Advanced Metering Infrastructure, District Heating (DH) Management Systems, weather services, and market platforms for electricity.

These sources provide geospatial, regulatory, and financial information, including climate forecasts, market tariffs, emission factors, and characteristics of the built environment.

4.3.4 Data Collection and Exchange System

Data exchange will be facilitated by the Interoperability Platform. This platform does not function as a storage system but rather as an orchestrator of data exchange.

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When a tool or solution provider requires access to specific data, a request will be sent to the Interoperability Platform. The platform will then identify the appropriate data host (number of hosts needed to be specified), retrieve the relevant information via established APIs, and deliver the data to the requesting tool without storing it internally. Each request must be authenticated via the Identity and Access Management service, which issues security tokens and verifies access rights based on predefined policies. This is illustrated in Figure 2. All exchanges are logged and monitored through telemetry services to ensure traceability, auditing, and full compliance with GDPR and other privacy regulations. In this sense, the Interoperability Platform enables secure and targeted data sharing across the ecosystem while preserving the decentralised structure of data ownership and storage.

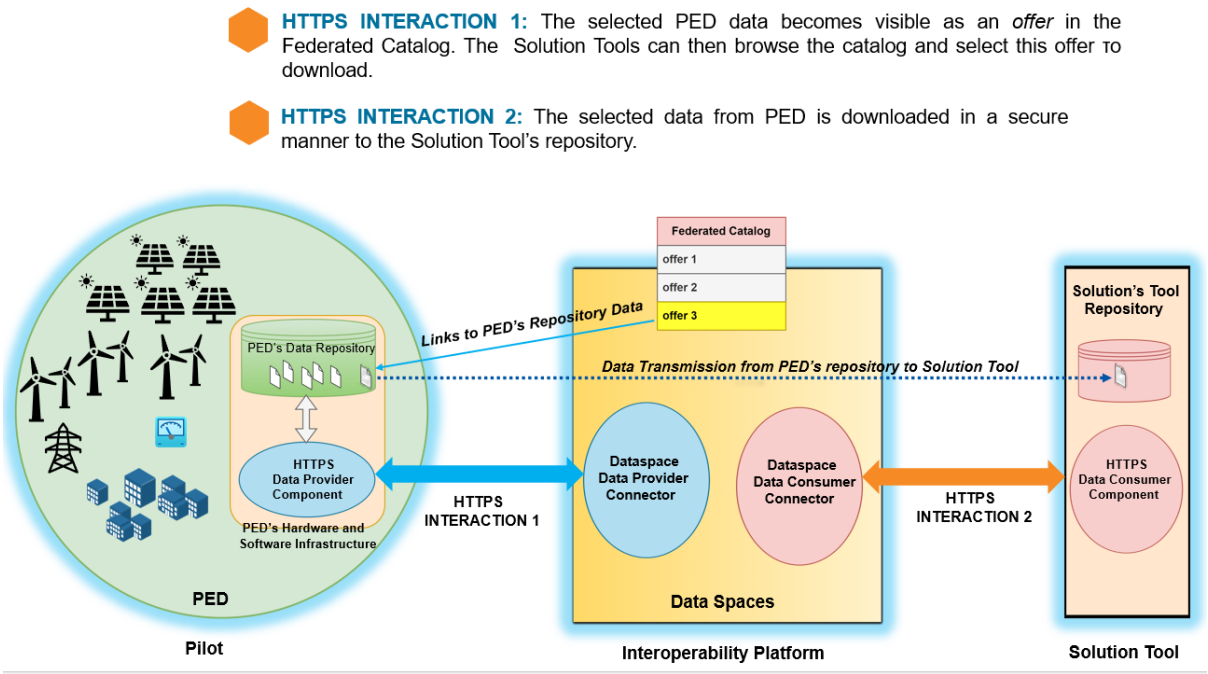


Figure 2: Data Exchange Scheme.

The system is designed to accommodate the following data flows:

1. Technical and quantitative data managed by automated measurement systems and consigned using the interoperability platform.
2. Qualitative and semi-quantitative data that cannot be collected by sensors or automated protocols, including social and behavioural information, which will be collected directly by project partners through interviews, questionnaires, spatial mapping, and observational surveys. This type of data will not interface with the interoperability platform and will be processed separately within the social innovation tool activities.

The energy measurements will be fed into the Energy Manager tool for real-time visualisation and analysis of energy flows, including the matching between on-site renewable production and local consumption.

Environmental data will be collected through sensors installed in accordance with the EN 16798-1:2019 standard, monitoring key parameters such as indoor air temperature, humidity, and CO_2 concentration,

over a period of time capable of capturing seasonal effects. These values will serve both regulatory benchmarking and operational optimisation purposes.

Economic data will be collected through static assessments and dynamic monitoring, including CAPEX and OPEX as benchmarks by the PED Business Models Tool. Real-time data on energy pricing, investment returns, and cost savings will be exchanged through the Interoperability Platform.

Social data collection will be carried out through locally managed engagement processes, including surveys, technical screenings, and participatory mapping exercises by the Social Innovation Tool. The data collected will undergo quality assurance protocols.

The DT and the Interoperability Platform enable the integration of data streams, supporting cross-sectoral analysis, KPI tracking, and the adaptation and refinement scheme. The interactions between energy, environmental, economic, and social factors will be visualised in real-time, utilised to support scenario-based evaluation and allow system adjustment and feedback loops.

The PED Energy Manager Tool collects and manages real-time energy and environmental data from meters, sensors, and controllable assets at the PEDs. This is done by processing datasets to monitor operational performance, optimise local generation and flexibility, and provide real-time coordination of energy assets. The EMS implemented, i.e., AURORA, provides a structured repository for operational and historical datasets.

The data exchange between the tools is coordinated by the Interoperability Platform, establishing secure, decentralised communication between data providers and consumers as illustrated in Figure 2.

Flexibility aggregation and market participation are also regarded within the platform, which enables the PED Energy Manager to acquire all needed consumption and generation data, calculate the available flexibility, and dispatch control signals to participating assets. Post-dispatch data is used to validate event execution and calculate financial remuneration.

4.4 Verification and Reporting Process

The verification and reporting process serves to ensure that the implemented solutions perform as intended and contribute effectively and efficiently to the project's objective across the four dimensions. The purpose is to validate that the measured outcomes correspond with the targets, assumptions and defined KPIs through systematic evaluation and transparent documentation. The verification functions as an integrated, continuous mechanism and as an analytical means to assess the efficacy and accuracy of the deployed solutions. In addition, the verification aims to compare measured outcomes with the baseline data provided earlier in the project and performance targets, while focusing on accurate, transparent, and credible results. Moreover, this process aims to transform verified data into structured and interpretable outputs, enabling evidence-based decision-making and adaptive management throughout the demonstration lifecycle. The reporting translates the verified results into traceable data that support evidence-based decision-making, continuous improvement of solutions, and overall project accountability.

The verification process is necessarily linked to the monitoring and data collection framework. Data and results acquired serve as the main input for the verification. The obtained data is being fed directly into the verification process, guaranteeing alignment, whereas tracked parameters are evaluated for comparison with the baseline data and targets.

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4.4.1 Verification Methodologies

The verification methodology is designed to systematically assess the actual performance of the PEDvolution solutions during their operational phase by comparing observed results with intended outcomes across all dimensions. These methodologies rely on a structured approach that combines real-world data collection, model-based comparison, stakeholder engagement, and iterative analysis. The methodology is directly aligned with the genotype-phenotype model and supports the continuous improvement of the PEDs through validated insights.

The approach is based on three core actions:

(i) structured collection of measured data during the implementation and operation phases;
(ii) processing and analysis of that data to verify whether performance aligns with expectations set during the design phase (3.3); and
(iii) utilisation of verification results to support adaptation, refinement, and optimisation of the deployed solutions in WP9, specifically in T9.1 (PEDvolution demonstration) and T9.2 (PEDvolution tool refinement and technical support), which will be reported in D9.1. The methodology incorporates both quantitative data, such as energy consumption, cost flows, and emission estimates, and qualitative data, such as stakeholder acceptance, comfort perceptions, and behavioural patterns.

The collection of operational data from each PED site is the first step of the verification process. This step uses the infrastructure installed by solution providers. Data is structured according to agreed formats. The verification system does not rely on centralised data storage but on distributed access mechanisms that preserve data sovereignty at each PED level.

The collected data is structured into indicator-specific datasets that are used for performance evaluation and validation:

- For energy and environmental indicators, the analysis involves time series comparison, cross-carrier aggregation, and matching factor computation between local generation and consumption.
- For economic indicators, cost items are aggregated per PED and normalised to reference units for comparability.
- For social indicators, survey responses are analysed statistically and cross-checked with engagement metrics from digital platforms or local activities.

The use of real-time, high-resolution data enables the verification process to spot both long-term trends and short-term deviations. It also helps identify correlations between system behaviour and contextual variables such as weather conditions, occupancy levels, or control strategies. When measured data diverges from design expectations, verification analysis determines whether deviations are caused by modelling assumptions, user behaviour, or system constraints. This supports focused refinement of solution settings, control algorithms, or user communication practices.

These methods are chosen to reflect the complexity and diversity of PED environments. By combining quantitative and qualitative verification approaches, the method captures both technical performance and user-centred outcomes. Distributed data collection and validation frameworks respect the independence of local systems while providing consolidated project insights. Thus, the results are not just static reports but actionable inputs that can influence system operation near real-time.

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The baseline data was established during the earlier stages of the project. **Energy and environmental performance**, using dynamic simulations with suitable modelling tools at hourly or sub-hourly resolution, provide values for energy needs as well as delivered and exported energy per carrier, while matching factors between on-site generation and loads. The verification of these simulations complies with guideline requirements that specify the use of stochastic user behaviour profiles to capture occupant diversity, especially in multifamily buildings. For IEQ, simulations are complemented by modelling indoor air temperature, relative humidity, CO_2 concentration, and illuminance, thus establishing a reference during the design phase before operational monitoring.

As data collection progresses, verification will be based on measured data flows. Delivered and exported energy are measured at the building level, ideally with the capability to distinguish between EPB and non-EPB uses. The source of energy and the energy contribution are quantified whether renewable or not.

The verification of **economic performance** considers CAPEX, OPEX, and derived cost-efficiency indicators. At the building level, costs are benchmarked using nZEB reference costs or relevant national cost codes. Ideally, these reference costs are expressed annually per square metre to align with CAPEX and OPEX assessments. At the district level, cost evaluations account for aggregated savings from multiple buildings, shared infrastructure, and increased operational flexibility. The collected data includes pricing, ROI, and operating costs.

Social performance verification focuses on data collection divided into physical and human-centric data. Physical data involves mapping and screening points of interest, accessibility features, and buildings and neighbourhoods using a PED-specific Cartesian reference system. Human-centric data involves surveys conducted to assess stakeholder satisfaction and engagement levels.

4.4.2 Execution

Verification activities are executed through automated and manual procedures.

Verification and reporting aims and activities differ within the planning, implementation, and operation phases. The overarching goal is to validate the solutions' readiness and performance in the demonstration settings. This is achieved by comparison against defined KPIs (see Annex I: List of KPIs), baseline conditions, and performance targets. Verification is integrated and used as a continuous analytical mechanism, whereas reporting is performed only when systems and data flows are operational to obtain meaningful results, based on actual input.

As the planning phase is limited to preparatory activities, covering the definition of system boundaries and baseline references established earlier in the project, the outputs generated in this stage are primarily used for internal documentation. During the implementation phase, verification focuses on confirmations that monitoring infrastructure, data acquisition, and interoperability mechanisms are correctly deployed and functional. This results in a reporting output, solely documented internally, to oversee the implementation progress. During the operational phase, verification is done by continuously monitoring the solutions' performances within the PEDs to produce reports (see Annex II: Reporting Template (Site Acceptance Testing)). This covers KPIs, performance assessment, and deviation identification, resulting in refinement measures.

The different aspects in each of the phases are illustrated in Table 5.

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Table 5: Verification and Reporting Execution.

Aspect	Planning Phase	Implementation Phase	Operational Phase
Primary objective	Preparation activities, covering scope definition, assumptions, KPIs, requirements, and baseline references; no verification or reporting is executed	Verification of deployment of monitoring infrastructure, data acquisition, and interoperability; internal progress reporting	Performance verification of deployed solutions against KPIs, baseline data, and targets; Reporting is executed – output feeds into the refinement process
Reporting scope	Not applicable	Deployment and integration readiness of the tools within PEDs, and availability and accuracy of required datasets	Energy, environmental, economic, and social performance of PEDvolution solutions under real operating conditions
Reporting content	Not applicable	Internal documentation of installed meters, sensors, EMS components, data interfaces, and platform connectivity; confirmation of data accessibility	KPI results, test results and deviation analyses, testing model result comparisons, economic and social performance summaries
Reporting modality	Not applicable	Manual and semi-automated reporting based on internal deployment checks and integration tests	Automated and manual reporting for energy and environmental indicators; manual reporting for economic and social indicators
Responsible actors	PEDs with inputs from solution providers	Solution providers responsible for tool deployment and integration, with PED collaboration	Solution providers responsible for data provision and reporting, with PED collaboration
Supporting systems and tools	Internal documentation and collection of data as per the requirements	Monitoring infrastructure, systems, tools, data exchange, and integration	Continuous monitoring infrastructure, systems, tools, and data exchange
Reporting timing	Not applicable	During installation, deployment, and commissioning of	Periodic and continuous, driven by characteristics of the data stream, sub-hourly

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		monitoring and data collections	metrics, and scheduled stakeholder engagement activities
Reporting outputs	Not applicable	Deployment and integration verified; readiness confirmation of operations	Performance reports based on KPIs, formatted according to the ANNEX II Reporting Template, including deviation overview and summary, sent to solution providers and PED operators

4.4.3 Feedback Loop and Data Flow

The results from the collected data and tests are processed and validated by the solution providers and the relevant testing environment (i.e. PED). They serve as actionable feedback for refinement measures, e.g. control algorithms and operational strategies, enhancing data accuracy and the significance of the improvement actions. The information obtained supports the dynamic learning mechanism, in which continuous adaptation to real operating conditions. If deviations occur, they can be analysed to determine if they can be traced back to modelling assumptions, user behaviour, or system constraints. The outcomes of this analysis are utilised by the solution providers, and if needed with the PED managers, to optimise configuration settings, operational adjustments, and stakeholder engagement strategies. The verified datasets, distributed through the data-exchange framework, maintain local data sovereignty while enabling aggregated evaluation at the project level. Consequently, the data flow from measurement to verification and back to implementation ensures continuous alignment between genotype and phenotype representations of each PED.

4.4.4 Responsibility, Reporting, and Communication

As mentioned in section 4.3, data is collected by the solution providers, whereas necessary data for several solutions is exchanged via the Interoperability Platform, as shown in Table 6. As an extension to section 4.4.2, the different solution providers must translate and utilise the data obtained into meaningful reports, essential for the refinement process of the tools' operations.

Potential obstacles include missing or incomplete data due to sensor failures, low user participation in surveys, or delays in interface configuration. To manage these risks, verification planning includes redundancy in data sources where possible, early validation of measurement infrastructure, and involving local actors in data provision. Additionally, a fallback method is used when direct measurement is unavailable, relying on simulation or standard assumptions to estimate performance and keep the evaluation process continuous.

Therefore, the verification methods are not just tools for performance monitoring but a vital part of the PEDvolution process. They ensure each solution is implemented transparently, tested in its actual context, and continually improved based on verified results. This lays the foundation for a repeatable

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and adaptable PED deployment model capable of responding to technical, social, and environmental challenges.

The responsibilities of the different solution providers in each of the PEDs are presented in Table 6.

Table 4 and Table 6 represent the responsibilities of the solution providers for monitoring and verification, respectively. They are interlinked as the monitoring responsibilities must correspond with the verification ones.

Table 6: Responsibilities of Solution Providers for Verification and Reporting.

PEDvolution Tool / solution provider	German PED	Swiss PED	Slovenian PED
PED Design and Planning Toolset (VITO, TUW)	DT: Verification of building stock renovation scenarios, RES integration, and cost-optimal improvement pathways using building-level data, and energy consumption and production. DHC Planning Tool: Validation of cost-optimal DH supply options using real-time heat demand, generation capacities, and RES utilisation. Datasets of PV, CHP, and storage are processed and cross-checked with measured energy profiles. Results are compiled into deviation analyses between simulated and observed performance.	DT: Validation of renovation and RES integration scenarios using measured data on solar, hydro, and DHC production. DHC Planning Tool: Verification of heat demand, generation efficiency, and storage operation against simulated scenarios. Datasets are processed to evaluate investment pathways, waste heat recovery, and RES transition. Reports summarise verified results and scenario consistency.	DHC Planning Tool: verification of district heating demand profiles, generation unit parameters, and heat recovery options. It validates the conversion of heat systems to biomass and optimises supply scenarios. Collected datasets of heat demand, peak loads, and fuel characteristics are checked against model outputs.
PED RA Framework (ZHAW)	Verification covers the practicality of the RA of technology, market, social, and interoperability. KPIs developed in WP4 are tested and validated	Verification of practicality of technology, market, social, and interoperability. The KPIs are validated and ensure usability for replication. Results benchmark the	Verification of data completeness and indicator applicability. The KPIs related to technology, market, and social readiness are calculated and compared

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	using pilot data. The framework benchmarks measured results and supports certification alignment with SGNI/DGNB criteria. Reports summarise readiness status per dimension and are shared with DDSG.	Swiss PED status in technology, market, social, and interoperability and are shared with DDSG for correlation with improvement scenarios.	to other PEDs. Results confirm compliance with project objectives and integration potential and shared with DDSG.
Dynamic Decision Support Guideline (NTNU)	Verification scenario accuracy and data consistency using results from the RA. Datasets include historical energy consumption, RES generation, and flexibility data. Verification checks alignment between projected and measured results in energy reduction, CO_2 savings, and RES share. Reports summarise verified scenarios.	Processing RA datasets to simulate and verify scenarios to ensure proper utilisation of RA data and logical flow between input and recommendations. Reports include validated scenarios and comparison metrics.	Verification of scenario logic by comparing simulated results of industrial waste heat recovery and biomass conversion with measured system data. Reports validate CO_2 reduction, RES increase, and economic feasibility for integration into PED planning.
PED Energy Manager (OFFSET)	Verification to assess the correct operation of the PED Energy Manager under real-world conditions. This includes its capability for real-time monitoring of both industrial and household energy assets and the ability to perform portfolio optimisation using flexible energy resources. Specifically, it will be tested whether the PED EM can provide realistic estimations of flexibility potential, activate the available	Verification of efficiency, stability, reliability of operation, and data integrity relying on data from PV and EV charging station. Deviations between measured and expected energy output are reported and used to validate model accuracy. Reports summarise verified flexibility potential, activation success, and energy savings for the ANODE and DERMOT tools.	Verification to assess the correct operation of the PED Energy Manager under real-world conditions. This includes its capability for real-time monitoring of industrial energy assets and the ability to perform portfolio optimisation (AURORA) using flexible energy resources. Specifically, it will be tested whether the ANODE can provide realistic estimations of flexibility potential, activate the available

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	energy resources when needed, and fulfil energy demands. Anode will provide flexibility estimates and activate them for the industrial sector, DERMOT for the residential sector, while AURORA will monitor the overall operation and provide optimal schedules. Verification will assess whether the AURORA can aggregate flexible energy resources (retrieved from ANODEs and DERMOT), provide the aggregated flexibility to external systems (e.g., Super-PED, markets), and handle household-level resources as well. On a technical level, verification will ensure that the PED Energy Manager (ANODE and DERMOT) operates within defined process limits and constraints. The reliability of real-time data acquisition, external controllability, and communication capabilities will also be assessed. This includes both internal communication within the PED EM tools and external interactions with other PED systems and PEDvolution solutions. Relevant for ANODE and		energy resources when needed, and fulfil energy demands received from the AURORA. Optimal schedules created by the Aurora will be verified (if the system really performs optimally). On a technical level, verification will ensure that the PED Energy Manager (ANODE and AURORA) operates within defined process limits and constraints. The reliability of real-time data acquisition, external controllability, and communication capabilities will also be assessed. This includes both internal communication within the PED EM solutions (ANODE and assets) and external interactions with other PED systems and PEDvolution solutions.

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	DERMOT on the assets level and for the AURORA for communication with other PEDvolution solutions and external systems.		
Data Exchange, Integration, and Interoperability Platform (ICOM)	Verification of secure exchange of pilot data (asset characteristics, heat and power measurements, KPIs), confirmation of dataset accessibility, ontology conformity, and traceable updates and solution outputs. Reports document validation status and interoperability consistency.	Verification of secure exchange of pilot data (asset characteristics, heat and power measurements, KPIs), confirmation of dataset accessibility, ontology conformity, and traceable updates and solution outputs. Reports document validation status and interoperability consistency.	Verification of secure exchange of pilot data (asset characteristics, heat and power measurements, KPIs), confirmation of dataset accessibility, ontology conformity, and traceable updates and solution outputs. Reports document validation status and interoperability consistency.
PED Business Models Tool (SIN)	Verify the business model framework toward delivering value for residents and grid operator through the operation of the pilot's Energy Sharing Community (ESC) “WUNergy” first, then expansion into Super-PED level. This is done through validation of feasibility of the technical solution, financial stability, and social value created. Verification will build on collaboration with project partners and SWW/ZENOB as the pilot leader. SIN will coordinate and ensure	Verification of cost and economic parameters based on validated energy and operational data by cross-checking operational results with calculated ROI and CAPEX/OPEX structures to ensure consistency. Reporting includes validated financial KPIs, economic viability summaries, and structured datasets.	Assess and verify the cost-effectiveness of Kranj's district-heating transition and pathways, focusing on industrial waste-heat integration first, and alternative options such as biomass or renewable retrofitting. The goal is to determine which route offers the best balance of cost, emission reduction, and long-term feasibility. Verification will be coordinated by the BM tool using technical and financial data shared by project partners and the district heating operator. PED design and planning tool plays an integral role

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	consistency when it comes to measurable indicators pertinent to the business model such as participation, battery utilisation, revenues and costs. The pilot managers cooperate with data and inputs. Outputs should contribute to linking technical, economic, and social indicators in both projections vs actual performance. A cost-benefit validation of profitability and value creation will be demonstrated focusing on the viability of the WUNergy model and Super-PED implementation serving as potential replication and blueprint for other locations.		in providing techno-economic results. Outputs will include a validated business model framework comparing economic and environmental performance of the implemented option with clear investment and cost-benefit indicators. Furthermore, a concise blueprint that captures the transition in the Slovenian pilot site would be documented towards replication in other cities.
Social Innovation Tool (SIN)	Verification of that the tool strengthens understanding and participation in the shared battery and energy community initiative. Verification is supported by monitoring participation rates and implementation of recommendations. Reports include pilot-level summaries prepared by SWW on participation levels, engagement outcomes and lessons learned.	Validation of social participation in co-creation workshops and energy-behavioural surveys. Verification analyses engagement metrics, satisfaction levels, and participation consistency. Reports summarise verified stakeholder acceptance to create a social-performance evaluation.	Verification of that the tool supports stakeholder collaboration and engagement in the waste heat integration and renewables integration projects. Verification relies on monitoring stakeholder involvement and actions following engagement recommendations. Reports include site documentation provided by EG and GEK on collaboration progress and engagement results.

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5 CO-DEVELOPER PEDS PREPARATION AND DEPLOYMENT OF TOOLS

The Co-developer PEDs preparation and deployment of tools covers the operational readiness of the three co-developer PEDs and the validation of all seven PEDvolution solutions. Each site establishes an executable testing environment, allowing the integrating of the tools developed in WPs 2–7, while ensuring alignment with regulatory, infrastructural, and environmental conditions. This process has resulted in asset and system mapping, set-up of continuous data flows, and verification of interoperability among all PEDvolution tools.

Across all co-developer PEDs, the expected outcomes are:

- Verified integration of planning, decision-support, and operational management tools into functioning local energy systems.
- Established data exchange and interoperability mechanisms ensuring secure and standardised information flow between all PEDvolution tools.
- Quantified improvements in renewable utilisation, flexibility activation, and energy efficiency at district scale.
- Demonstrated applicability of business models that reflect local market, regulatory, and stakeholder conditions.
- Validated stakeholder engagement approaches leading to increased community participation, awareness, and acceptance.
- Proven scalability and replicability of the PEDvolution framework for adoption in additional demonstration sites.

These outcomes shall validate the effectiveness of the PEDvolution solutions as an integrated system combining planning, management, data exchange, business modelling, and social innovation. The findings will serve as the foundation for replication and upscaling in future PED implementations.

5.1 Co-developer PEDs settings and operational basis

This section provides an overview of the three Co-Developer PEDs and their settings as to how they were prepared for deployment and testing of the PEDvolution solutions. It describes the relevant assets, systems, configurations, and infrastructure preparation of each site. Furthermore, this section outlines the operational basis for the demonstration phase and verification activities to come.

5.1.1 Wunsiedel, Germany

The German PED is practically comprised of two PEDs, the Schönbrunn PED, focused on combined heat and power with heat customers as active participants, and the WUNergy PED, an Energy Sharing Community (ESC), structured around electricity sharing across the broader Wunsiedel area. The ZENOB Super PED will be overarching and comprises the assets of the two previously described PEDs — such as generation units, EMS, and related components.

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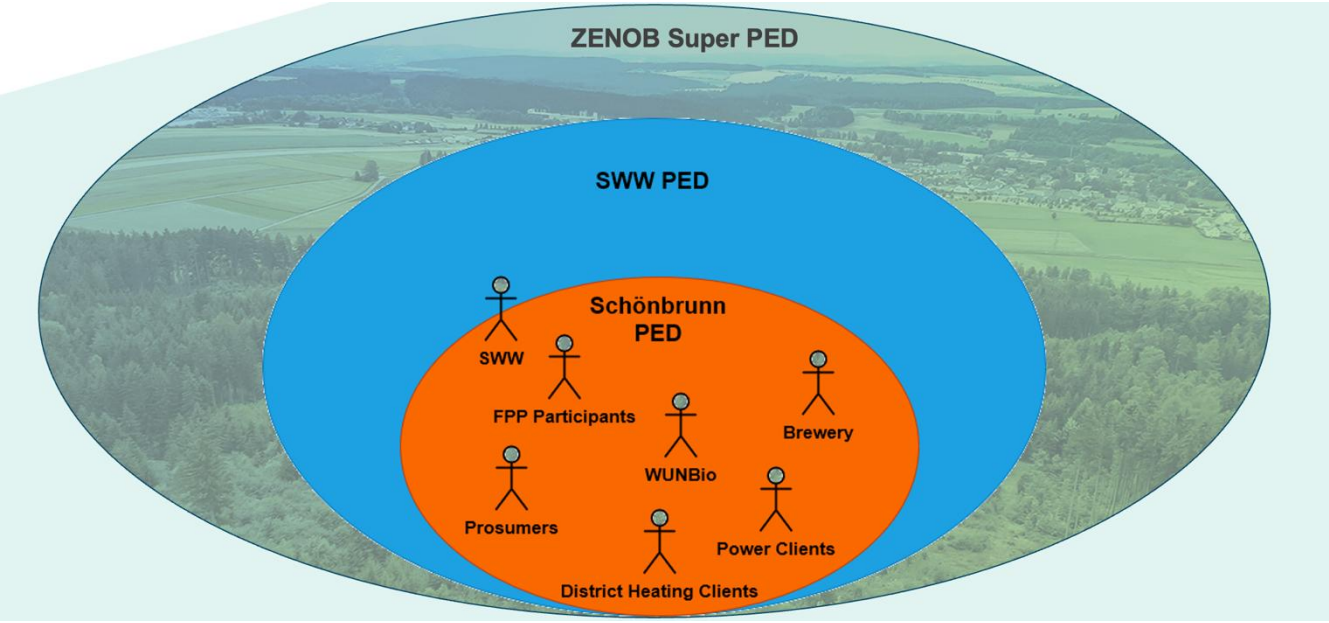


Figure 3: Presentation of the three PEDs in Wunsiedel.

The Citizens in the area shall be deeply involved: prosumers, prostormers, and energy communities, who form the backbone of PEDs. While 180 involved households were assumed, so far there are 154 participating entities, while one goal would be to achieve full capacity with 400 households. Consumers shall be transformed into active prosumers or prostomers. Many households have their own PV systems installed and other assets like seasonal thermal storage, wood gasifiers and a heating rod for sector coupling are available. It is envisioned that each building will generate, store and digitally control the needed energy on-site, while overall aiming for a net-positive energy balance as the Schönbrunn PED.

The system aims for full cross-sector integration (energy, mobility, industry), leveraging local renewables like biomass and solar, and using real-time optimisation to reduce energy waste and infrastructure costs. Complex users are supposed to benefit from stable, efficient operations.

The regulatory landscape in Germany offers a supportive yet complex context for PED deployment. While high-level climate goals and support mechanisms enable action, real-world implementation must navigate detailed compliance requirements, evolving heat planning mandates, and sector-specific barriers. Strategic workarounds include early stakeholder coordination, staged compliance aligned with future policy rollouts, and leveraging public funding to bridge investment gaps and therefore ensuring contextual and regulatory alignment throughout the PED lifecycle.

5.1.1.1Schönbrunn PED

5.1.1.1.1.1 Definition of system boundaries

The Schönbrunn PED is located within the jurisdictional area of Wunsiedel in Upper Franconia. The physical boundaries comprise 154 residential and industrial buildings connected to the local distribution grid, with metering infrastructure and distributed energy resources (DER), as well as to the district heating system, powered by a CHP plant, which also contributes to the power supply. The plant includes

two pellet-based gasification units (230 kWel / 220 kWth each), a 950 kW pellet boiler, a 1 MW power-to-heat unit, an 82 kWp PV installation, and an 80,000-litre thermal storage unit. These were delimited within WP2, where system scope, data requirements, and system architecture are defined. In WP3, the digital twin tool and DHC planning tools are applied to model assets and to develop renovation pathways, and later on scenario analyses. In WP5, the basis for the instrumented infrastructure was defined, including edge devices and EMS configurations.

Functionally, this PED covers energy generation and consumption, residential and SWW-owned storage, sector coupling capabilities, and flexibility operations. The functional layer is linked with WP3 to construct testing scenarios for system optimisation, with WP4 to assess PED readiness in terms of technology, market, social and interoperability, with WP5 for utilising real-time system operation optimisation, flexibility aggregation, and asset control, and in WP7 to construct data exchange.

At the organisational level, the PED includes residential consumers, prosumers, and industrial customers, all managed by SWW Wunsiedel GmbH, which acts as the DSO and district heating provider. In WP2, stakeholder requirements and existing engagement schemes were defined. In WP6, stakeholder analysis, engagement initiatives, and participation processes were carried out, linked to the development of business models and user acceptance schemes.

In this PED, energy, flexibility, system operations, and economic aspects are monitored and tested by the solutions, as shown in section 5.2 and addressed by relevant KPIs, as shown in Annex I: List of KPIs.



Figure 4: Schönbrunn Village (left), Satellite CHP in Schönbrunn (right).

5.1.1.1.1.2 Operational characterisation

The Schönbrunn PED is characterised by sector-coupled hybrid energy systems with strong emphasis on flexibility aggregation, load optimisation, and renewables integration. The CHP supplies heat and is supported by a backup pellet boiler and a P2H heating rod, allowing sector electrification. This configuration supplies the local district heating network, meeting an annual thermal demand of approximately 3,000 MWh. The thermal buffer tank allows for temporal decoupling of heat generation

and demand, enabling optimised dispatch of thermal assets. On the electricity side, a distributed PV capacity of around 1,355 kWp is installed across various households and communal rooftops, collectively generating approximately 1,490 MWh annually. Electricity consumption within the district totals approximately 2,429 MWh per annum.

The baseline operating strategy comprises grid operation monitoring via 550 nodes in eight substations, six of which are equipped with PQ measurement systems for real-time monitoring. About 75 of the 550 grid nodes are equipped with remote meter reading capabilities, feeding real-time data into the system. The existing operation already includes load management and aggregation of flexible resources, allowing the PED to deploy a centralised control mechanism through which aggregated assets are traded as market products, enabling a smooth operational framework and interaction with energy markets.

In Q1/2026, a 500 kVA Battery Energy Storage System (BESS) was commissioned. This will serve as an extension and as a planned addition for future operational enhancement, enabling synchronised dispatch of power generation, electric loads, and district-wide energy demand patterns. Ultimately, this configuration will increase the PED's ability to respond to grid constraints, align with market signals, and enhance the penetration of variable renewable generation.

In WP2, the foundations for the specifications of PED configurations and stakeholder requirements were created, including energy systems layout and modelling of consumption and generation capacities. In WP4, Schönbrunn's operational readiness was assessed by collecting site-specific baseline metrics. In WP5, AURORA functionalities were tailored to the Schönbrunn PED within the scope of PEDvolution. In WP6, stakeholder engagement strategies were weighted to develop strategies for optimised engagement and further recruitment, as well as assessing current business models.

5.1.1.1.1.3 Socio-economic and governance characterisation

Schönbrunn has a contractually integrated service model managed by SWW. Households have bilateral agreements for connection to the district heating and low-voltage power networks. Stakeholders include residential consumers, prosumers with rooftop PV systems, and prosumers with PV and private storage units. SWW maintains operational control over energy assets, data infrastructure, and flexibility coordination. Governance responsibilities are organised around system operation, maintenance, data management, and regulatory compliance. The socio-economic model focuses on reliable energy service delivery, tariff-based participation, and targeted engagement through information sessions and technical consultations. No peer-to-peer energy transactions occur within this PED. However, flexibility is aggregated and traded centrally under operational monitoring and management.

5.1.1.1.1.4 Data interoperability and traceability

In Schönbrunn, AURORA, as an EMS, facilitates energy management. The EMS connects to the Interoperability Platform, which federates a data space architecture that follows the Common Information Model (CIM) for semantic alignment. Operational data streams from CHP units, PV systems, heating networks, and grid nodes are securely transferred and catalogued. The platform ensures that all participating tools and actors can access consistent datasets for analysis, visualisation, and control. The system supports both real-time and non-real-time data exchange, with strict protocols for encryption, timestamping, and role-based access. Substations equipped with PQ metering enable high-resolution monitoring of power flows, voltage profiles, and frequency stability. The DSO acts as the

local data custodian, ensuring data integrity is maintained and records are archived in compliance with European data governance frameworks.

The linkage between KPIs and their respective data sources, temporal resolution, and units follows the monitoring and data collection framework defined in Section 4.3 and Annex I: List of KPIs, where each KPI is explicitly mapped to its underlying dataset, calculation method, and measurement characteristics. Energy-related KPIs (e.g. consumption, generation, flexibility utilisation) are derived from smart meters, EMS data streams, and substation measurements, typically at sub-hourly resolution (seconds to 5–15 minutes) and expressed in units such as kWh, kW, or %. Environmental KPIs are based on sensor data and calculated emission factors, with defined measurement intervals and units such as tCO_2e, °C, or ppm. Economic KPIs are linked to cost and market data exchanged, expressed in €/MWh, CAPEX/OPEX values, or payback periods, while social KPIs rely on survey and engagement data with qualitative or quantitative indicators (e.g. participation rates, satisfaction levels).

High-resolution PQ metering at substations enables the calculation of grid-related KPIs (e.g. voltage stability, power quality, frequency deviations) based on continuous or near real-time data streams, ensuring that each KPI is consistently linked to a defined data source, temporal granularity, and unit as specified in the M&V framework and corresponding KPI tables.

5.1.1.1.1.5 Temporal reference point

For the Schönbrunn PED, the reference point is positioned before the deployment of PEDvolution tools and the operationalisation of the integration framework. It is defined at the point of deployment readiness as the tools and supporting infrastructure are technically operational and represent the transition from the preparation phase to the demonstration and validation activities planned for WP9. At this point, the tools are considered technically ready for deployment, but they are not influencing operations, such as load management or flexibility allocations, in Schönbrunn. The reference period is established using 2023 operational data and early 2024 measurements, providing an overview of energy flows and asset performance before the integration of the PEDvolution solutions. Annual metrics, including electricity consumption (2,429 MWh), PV generation (1,490 MWh), thermal energy demand (3,000 MWh), and heating network throughput, form the basis for KPI benchmarking.

5.1.1.1.1.6 Alignment with demonstration preparation

In Schönbrunn, the pre-deployment includes the finalised prerequisites and configurations of the technical infrastructure, data streams, and stakeholder roles, as set in WP2-7. At this stage, the tools and solutions to be tested are not yet active. These activities cover the mapping of building characteristics, metering devices, consumption, generation, storage, and load assets, as well as market components and relevant stakeholders.

Descriptions of the solutions involved, their scope and how they operate are listed in sections 5.2 and ANNEX III: the PEDvolution solutions.

Once the tools are deployed, they will be tested and validated under real-world conditions. This will be done by comparing real-time data, control systems, technical compatibility and readiness, business model viability and feasibility, and stakeholder alignment through workshops against the baseline data using KPIs delineated in Annex I: List of KPIs.

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5.1.1.1.1.7 Achieving this PED

Achieving the PED relies on an integrated, adaptive energy management approach. State-of-the-art EMS continuously monitor generation and consumption patterns, dynamically reallocating energy based on real-time conditions. This will predominantly be achieved by introducing sector coupling capabilities and leveraging flexibilities. By flexibly switching between energy vectors, the PED ensures uninterrupted service, reduced reliance on external resources, and optimal utilization of available energy. As the Schönbrunn PED matures, it aims to integrate with existing energy-sharing structures in Wunsiedel, forming a Super-PED that spans approximately 9,000 inhabitants. This larger energy ecosystem coordinates multiple decentralized units, expands flexibility services, and better manages both fast and slow dynamic changes in supply and demand. By tapping into a broader pool of prosumers, industrial flexibility assets, and storage solutions (such as large batteries in Wunsiedel), the Super-PED can optimise regional energy flows more efficiently. It will enhance local energy resilience, support the regional grid's stabilisation, and promote scalable solutions that can be replicated across Europe. Ultimately, the integration advances the broader vision: transforming a small, rural community into a pioneering example of how sector coupling, dynamic local markets, and intelligent controls can accelerate the transition toward sustainable, net-PED.

5.1.1.2 WUNergy Energy Sharing Community

5.1.1.2.1.1 Definition of system boundaries

The WUNergy ESC is located and operated within the jurisdiction of SWW. The physical boundary comprises of a range of stakeholders, including consumers who primarily draw energy from the community, prosumers who generate and consume electricity, owners of Battery Energy Storage Systems, and smaller companies contributing to local economic stability. Moreover, this ESC is equipped with PV and residential battery systems.

Functionally, the PED, besides consumption, decentralised renewable energy generation, and storage, includes flexibility aggregation and exchange that support balancing and energy sharing within the community and are guided by surplus-deficit-driven resource allocation and collective optimisation of self-consumption. This enables energy sharing among multiple users connected to the same physical grid and supply points.

At the organisational level, this PED is structured around consumers, prosumers, and storage asset owners. SWW acts as the utility and infrastructure provider, physical and billing coordinator. This ESC operates under regulatory compliance with §42c EnWG (German Industrial Act). Within the community, contractual roles are clearly delineated between all stakeholders. The demonstration comprises 76 households participating in a coordinated ecosystem model, whereas the ESC is seen and treated as a single unit.

5.1.1.2.1.2 Operational characterisation

The baseline operational configuration comprises of real-time monitoring of consumption and generation. The annual consumption within the ESC is approximately 83,000 kWh/á. Whereas power supply systems, i.e., PV and storage, have the capacity of 60.23 kWp, generating approximately 50,227 kWh/á, and battery systems with a capacity of 13.6 kW, providing 26.3 kWh. Residential consumers and prosumers contribute either by offering flexible consumption patterns or providing controllable generation and/or storage assets. Real-time energy flows and balancing are coordinated by AURORA,

which allocates and matches production with demand. When local demand is met and exceeded, surplus electricity is fed into the grid and potentially monetised on energy markets, whereas demand deficits are imported from the DSO (SWW). Further community recruitment and integration of optimisation measures, such as demand forecasting and additional flexibility mechanisms, are planned.

In WP2, the foundations for the specifications of PED configurations and stakeholder requirements were created, including energy system layout and modelling of consumption and generation capacities. In WP4, the ESC's operational readiness was assessed by collecting site-specific baseline metrics. In WP5, AURORA functionalities were tailored to the ESC within the scope of PEDvolution. In WP6, stakeholder engagement strategies were weighted to develop strategies for optimised engagement and further recruitment, as well as assessing current business models.

5.1.1.2.1.3 Socio-economic and governance characterisation

Authority and roles: While SWW serves as the local DSO by offering the infrastructure and services, governance takes place on the basis of collective participation within the ESC. Coordinating activities take place through the contractual registration of the participants of the cooperative WUNergy ESC, as well as digital management of the system. There are no hierarchies present within the ESC, and everyone enjoys equal rights.

Engagement processes: Participation. It is voluntary, organised in a specific way, in which users must give their consent to share energy, information, and costs through the recruitment process. To ensure participation and full knowledge about everything that happens, community meetings, workshops, and other forms of communication are used.

Business models: A cost-sharing scheme based on the joint use of a PV system serves as the economic framework for the ESC. The savings in grid charges, optimised energy usage, and energy distribution within the ESC make members realise their benefits. Flexibility monetisation will be considered in subsequent stages.

Participation level: Engagement is promoted and desired. Through feedback mechanisms, dynamic pricing signals, and community representation structures, engagement can be maximised. The initial data are the number of participants, the amount of energy exchanged, and household savings.

5.1.1.2.1.4 Data interoperability and traceability

In the ESC, remotely readable meters and AURORA continuously collect consumption and generation data. This data is prepared to be aligned with CIM, as specified in WP7, to ensure they match with all dataset requirements from the different PEDvolution tools and the interoperability platform. In addition, the collected data is stored in local repositories and AURORA, allowing historical and real-time access, all data is timestamped and secured with access control protocols.

The linkage between KPIs and their respective data sources, temporal resolution, and units follows the monitoring and data collection framework defined in Section 4.3 and Annex I: List of KPIs. Energy-related KPIs (e.g. consumption, generation, flexibility utilisation) are derived from remotely readable meters and data streams in AURORA with 15 minutes resolution, measured in kWh, kW, or %. Environmental KPIs are based on calculated emission factors, measured in tCO_2e, °C, or ppm. Economic KPIs are linked to cost and market data expressed in €/MWh. Social KPIs rely on survey and engagement data with qualitative or quantitative indicators (e.g. participation rates, satisfaction levels).

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5.1.1.2.1.5 Temporal reference point

For the ESC, the reference point is the period before deployment of the PEDvolution tools and is defined as ready for demonstration within the planned WP9 activities. The tools for this PED are technically operational, and the stakeholders are ready for the active demonstration. Though the tools are technically ready, they are not yet operational.

The reference baseline data is established by using operational data from 2023 until early 2025, providing an overview of power flows and system performances within the ESC before the integration of PEDvolution's tools and solutions.

The deployment readiness was reached by the end of the WP8 activities, whereas all tools, HW, SW, and qualitative aspects (social and business) were available for demonstration in WP9.

5.1.1.2.1.6 Alignment with demonstration preparation

In the ESC PED, pre-deployment scenario includes the finalised prerequisites and configurations of the technical infrastructure, data streams, and stakeholder roles, as set in WP2-7. As mentioned above, the tools are not yet active. The activities involve validating the metering and data collection infrastructure, and mapping consumption, generation, storage, and flexibility potentials, as well as market components and stakeholders.

Descriptions of the solutions involved, their scope and how they operate are listed in sections 5.2 and ANNEX III: the PEDvolution solutions.

Once the tools are deployed, they will be tested and validated under real-world conditions. This will be done by comparing real-time data, control systems, technical compatibility and readiness, business model viability and feasibility, and stakeholder alignment through workshops against the baseline data using KPIs delineated in Annex I: List of KPIs.

5.1.1.2.1.7 Achieving this PED

Establishing and maintaining the ESC PED's electricity-positive status depends on careful coordination of technology, market mechanisms, and stakeholder involvement. The PED Energy Manager, supported by AI-enabled tools, balances real-time supply and demand, prioritising local use of renewable electricity before allowing surpluses to be fed into external grids and traded on external markets. In times of elevated solar generation, surplus electricity is sold on the energy markets (e.g., EPEX spot market). Conversely, if local generation falls short, the PED draws on residual renewable energy from the energy supplier, maintaining stable service even during periods of low solar input. The ESC PED's cooperative structure ensures that all transactions occur transparently and comply with market regulations. Dynamic tariffs and innovative billing methods incentivise participants to shift consumption to periods of high renewable availability. This approach enhances cost-effectiveness and encourages engagement in flexibility services.

Once fully operational and consistently producing a surplus of renewable electricity, the ESC PED intends to integrate with the ZENOB Super PED framework. In this broader construct, multiple PEDs across the region share resources, exchange surpluses, and collectively contribute to a more resilient and flexible energy landscape. By pooling generation, storage, and flexibility capacities, the ESC PED and other interconnected communities can address more complex supply-demand fluctuations, offering ancillary services to the local distribution system operator and supporting the stability of wider

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energy networks. This integration enables a two-way flow of energy and value between neighbouring PEDs, ensuring that local surpluses do not go to waste and that shortages can be quickly addressed. Ultimately, the ESC PED's successful participation in the Super-PED will exemplify how localised, cooperative-based energy communities can scale up, driving broader societal benefits and serving as a blueprint for other regions seeking to implement and expand similar energy-sharing frameworks.

5.1.1.3 ZENOB Super PED

The ZENOB Super PED, as an overarching PED, consists of the assets, including generation units, EMS, etc. of the two PEDs described above, namely the Schönbrunn PED, focused on combined heat and power with heat customers as active participants, and the WUNergy PED (ESC), structured around electricity sharing across the broader Wunsiedel area.

Each PED maintains its own operational model and entry mechanism. Participants are required to sign in under PED-specific procedures, contractual integration for Schönbrunn and community-based enrolment for ESC, with associated responsibilities and rights under the energy service framework. The participation of various actor types are essential and are defined within each of the PEDs: consumers, prosumers, and prosumers with storage, with supporting roles fulfilled by the service provider, heat provider, and the DSO.

In accordance with the project's definition, a PED is recognised as such if it maintains a net-positive energy balance over a specified time interval. For the ZENOB Super PED, this condition is assessed on a yearly basis. Seasonal discrepancies, such as reduced solar production in ESC during winter, are managed through sector coupling and energy storage in Schönbrunn, ensuring that the integrated system remains positive over the annual timeframe.

5.1.2 Winterthur, Switzerland

5.1.2.1 Definition of system boundaries

The Hard area is located on the outer boundary of the city of Winterthur in the canton of Zurich and consists of a cluster of historical and newer buildings. The physical boundaries cover 80,000 m² and include 10 buildings with 45 residential units and 40 office spaces, connected through a local district heating network (Figure 5). This network is currently centrally supplied by a gas heating system with a capacity of 450 kW. Additionally, heat is provided by a local solar thermal installation with an annual generation of approximately 55 MWh and a total thermal storage capacity of 10,000 litres, contributing further to the energy supply. The total annual heat demand of the area is about 860 MWh. Furthermore, energy is generated from the nearby Töss River via a small-scale hydropower turbine with a capacity of 575 kW and an annual yield of approximately 2550 MWh. Electricity generation is complemented by a photovoltaic system with a capacity of 48 kWp, producing around 43 MWh annually.

These system elements were defined within WP2, where the system scope, data requirements, and system architecture were established. In WP3, the digital twin tool and DHC planning tools are applied to model assets and, in particular, to develop renovation pathways for replacing the gas-based heat supply. In WP5, the foundations for the interconnected infrastructure were defined, including the collection of residential and industrial consumer data. Functionally, this PED provides energy generation, sector coupling capabilities, and flexibility solutions. The functional layer is linked with WP3 to develop testing scenarios for system optimisation, with WP4 to assess PED readiness in terms of

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technology, market, social aspects, and interoperability, with WP5 to enable real-time system operation optimisation, flexibility aggregation, and control of EV charging infrastructure, and with WP7 to implement data exchange.

At the organisational level, the PED includes both private and commercial consumers, managed by the Hard community (GeHa AG), while electricity is supplied by the municipal utility Stadtwerke Winterthur. In WP2, stakeholder requirements and existing engagement measures were defined. In WP6, stakeholder analysis, engagement initiatives, and participation processes were carried out, linked to the development of business models and user acceptance strategies. Within this PED, energy generation, economic aspects, and flexibility potentials are monitored and evaluated through the implemented solutions.



Figure 5: Hard Community PED.

5.1.2.2 Operational characterisation

The Hard PED is characterised by a very strong electricity production from hydropower, which significantly exceeds local demand. In addition, a district heating network thermally connects the buildings and provides strong potential for sector coupling through the planned replacement of the gas heating system with heat pumps.

The electricity consumption of the Hard area amounted to approximately 666 MWh in 2025, while gas demand was around 880 MWh. During the same period, approximately 2,600 MWh of electricity was generated, of which 2,550 MWh originated from hydropower and 50 MWh from the photovoltaic system. On the thermal side, an additional 55 MWh was generated from the solar thermal installation.

Based on the results from WP3, WP4, WP5, and WP7, several measures will be implemented at the site. These include dynamic load management for electric vehicle charging, smart plugs to increase household flexibility, and the replacement of the gas-based heating system with renewable district

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heating or heat pumps. Currently, it is being evaluated whether a centralised or decentralised heating supply system will be implemented.

5.1.2.3 Socio-economic and governance characterisation

The Hard PED is supplied with electricity by the municipal utility Stadtwerk Winterthur; therefore, GeHa AG does not have operational control over the electricity supply to residents. Heat supply is managed through the local district heating network, with billing carried out individually by GeHa AG. Engagement processes are possible at multiple levels, as the shareholders of GeHa AG consist of residents and local businesses. This ensures that ownership and decision-making authority remain within the local community. Major decisions are taken democratically during three to four general assemblies per year. The Board of Directors manages GeHa AG, while the administrative office acts as its executive body. Together with five department heads, it ensures daily operations and is responsible for ongoing projects. The finance, audit, and design committees provide advisory support to both the general assembly and the Board of Directors. The nine housing communities hold building rights (heritable building rights) from Hard Community AG, typically under 100-year usage contracts, and are autonomous in their internal organisation. Some housing groups are structured as condominium associations, while others are organised as cooperatives or joint-stock companies.

Hard Community AG requires substantial financial resources to maintain its extensive infrastructure and shared assets. This includes the upkeep of the surrounding environment (parks, canal, gardens, tree maintenance), infrastructure maintenance (hydropower plant, utility networks, roads), community spaces, events, cultural activities, and personnel. Approximately half of the expenditures are financed through electricity revenues from the hydropower plant, while the other half is covered by building lease fees paid by the housing groups (fixed charges per square metre of residential or commercial space).

5.1.2.4 Data interoperability and traceability

In the Hard PED, a measurement, control, and regulation system (MSRL) is installed for the district heating network. This system manages the supply of heat and domestic hot water to the buildings. However, due to its age, it does not provide real-time data access. PV production is monitored via a WhatWatt device, which reads data from the smart meter at a 5-second resolution and transmits it via a Moxa box to both the AURORA platform and the Interoperability Platform (IP). Six electric vehicle charging stations are monitored and controlled throughouta device from CLEMAP, enabling flexibility services that can be activated by the AURORA platform depending on solar power availability. The corresponding data is also transmitted to the IP. EV users are intended to have the option to override the charging control via an app using a booster function.

Electricity generation from hydropower as well as total electricity consumption are transmitted once per day to the IP at a 15-minute resolution. In three households, a total of 12 electrical appliances are monitored via smart plugs from Shelly, providing data at second-level resolution to DERMOT and the Interoperability Platform. Each KPI follows the monitoring and data collection framework defined in Section 4.3.

The linkage between KPIs and their respective data sources, temporal resolution, and units follows the monitoring and data collection framework defined in Section 4.3 and Annex I, where each KPI is explicitly mapped to its underlying dataset, calculation method, and measurement characteristics. Energy-related KPIs (e.g. consumption, generation, flexibility utilisation) are derived from smart meters and end-user measurements, typically at sub-hourly resolution (seconds to 5–15 minutes) and

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expressed in units such as kWh, kW, or %. Environmental KPIs are based on sensor data and calculated emission factors, with defined measurement intervals and units such as tCO_2e, °C, or ppm. Economic KPIs are linked to cost and market data exchanged via the Interoperability Platform and are expressed in either CHF/MWH or €/MWh, CAPEX/OPEX values, or payback periods, while social KPIs rely on survey and participation data with qualitative or quantitative indicators (e.g. participation rates, satisfaction levels).

5.1.2.5 Temporal reference point

For the Hard PED, the reference point is defined prior to the deployment of the PEDvolution tools and the commissioning of the Interoperability Platform. It is positioned at the stage of deployment readiness, where the tools and the supporting infrastructure are technically operational and mark the transition from the preparation phase to the demonstration and validation activities planned in WP9. At this stage, the tools are considered theoretically and/or technically ready but do not yet influence system operations, such as flexibility allocation for EV charging stations.

The reference period is established based on operational data from 2024 and measurements from 2025, providing an overview of energy flows and asset performance prior to the integration of the PEDvolution solutions. Annual key figures form the basis for KPI benchmarking, including electricity consumption (666 MWh), thermal energy demand (860 MWh), hydropower generation (2,550 MWh), PV generation (50 MWh), and solar thermal energy production (55 MWh).

5.1.2.6 Alignment with demonstration preparation

In the Hard PED, the pre-deployment phase includes the final definition of prerequisites and configurations of the technical infrastructure, data streams, and stakeholder roles, as established in WP2–WP7. At this stage, the tools and solutions to be tested are not yet active. These activities include the mapping of building characteristics, metering devices, consumption, generation, and load components, as well as market components and relevant stakeholders.

Descriptions of the solutions involved, their scope and how they operate are listed in section 5.2 and ANNEX III: the PEDvolution solutions.

Once the tools are deployed, they will be tested and validated under real-world conditions. This will be carried out by comparing real-time data, technical compatibility and readiness, business model viability and feasibility, and stakeholder alignment through workshops against the baseline data, using the KPIs defined.

5.1.2.7 Achieving this PED

To achieve a PED for the Swiss site, several key things need to be achieved: First, it is important to clarify the situation with regard to the hydro power plant: Currently, there is measurement undertaken regarding monitoring the real time production data by installing smart meters. As there is a long-term contract to sell all the energy produced to the utility at a good price, there is no direct self-consumption at the site. Since there is a new federal energy law since 2025/2026, the national focus is getting to be laid on building up the so called ‘Local Energy Communities’ (LECs or LEGs). Discussions and strategical planning about including the Hard community in such a LEC are ongoing. Second, the other renewable energy option to be explored is the installation of more PV panels. In that case, a private investor shows interest in supporting the Hard community by offering some of his financial, technical and political resources. Discussions and bridge building approaches are currently ongoing.

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Another key issue is the heat production: The current biogas heating will not be able to continue as the DSO is closing the pipe network. It is very important to find the most suitable and sustainable solution for heat distribution and production. Measurements regarding this are undertaken, also via e.g. student case studies from ZHAW.

Investments and Modifications:

- Hydropower Optimisation: Enhance the automation and control systems to better align with community energy needs.

- PV Expansion: Add more PV systems on available rooftops to increase local renewable energy production.

- EV Charging Expansion: Expand the number of EV charging stations and integrate them into the community energy management system.

- Heat production: Replace the central gas heating system with a more efficient system.

- Inclusion of services from DSO and from local community

All of the above is only possible if the members of the pilot site are on board. In the Hard area, each building is self-governed, and the residents decide together what they want to do and what they do not want to do. It is therefore crucial to address them, to involve them and to convince them to implement the recommendations of this project.

5.1.3 Kranj, Slovenia

5.1.3.1 Definition of system boundaries

The Slovenian PED is situated in the Municipality of Kranj and comprises two functionally interconnected areas, namely the residential district of Planina and the adjacent industrial zone of Labore. The defined spatial boundary encompasses a mixed-use urban environment with residential, commercial, and industrial functions, covering approximately 740,000 m² and including around 16,000 inhabitants and 4,300 apartments. This dual structure enables the integration of different demand profiles and energy flows, which is a defining characteristic of the PED concept in this context .

From a technical perspective, the system boundary includes both the electricity and district heating infrastructures. The existing baseline configuration is centred on the district heating system in Planina (Figure 7), which is currently supplied by a 17 MW natural gas boiler with an annual heat production of approximately 36,000 MWh. This installation defines the initial operational and environmental reference point for the PED. The future system boundary expands beyond this conventional configuration by integrating multiple decentralised and renewable energy sources, including waste heat recovery from industrial processes in Labore, photovoltaic systems installed on rooftops, hydropower generation assets, electric boilers, and combined heat and power units.

The inclusion of waste heat recovery represents a critical extension of the system boundary, with an estimated potential of up to 20,000 MWh per year, allowing the utilisation of otherwise unused thermal energy from industrial processes. In parallel, photovoltaic installations with a planned capacity of approximately 2.5 MW and hydropower plants with an expected expansion to 2 MW will contribute to local electricity generation. The integration of combined heat and power units with a total installed capacity of 4.3 MW and electric boilers with a capacity of 1 MW introduces additional flexibility and

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sector coupling between electricity and heat. Furthermore, the potential future deployment of a biomass steam boiler with a capacity of up to 20 MW represents an optional extension of the system boundary, enabling the provision of renewable heat not only to the residential district but also to industrial consumers.

At the organisational level, the system boundary encompasses all relevant stakeholders involved in the planning, operation, and use of the energy system. These include the Municipality of Kranj as the local authority, the distribution system operator Elektro Gorenjska, the district heating operator Domplan, renewable energy producer Gorenjske Elektrarne, industrial stakeholders in the Labore zone, and end users in the residential and commercial sectors.

In this PED, energy, flexibility, system operations, and economic aspects are monitored and tested by the solutions, as shown in section 5.2, and addressed by relevant KPIs, as shown in Annex I: List of KPIs.

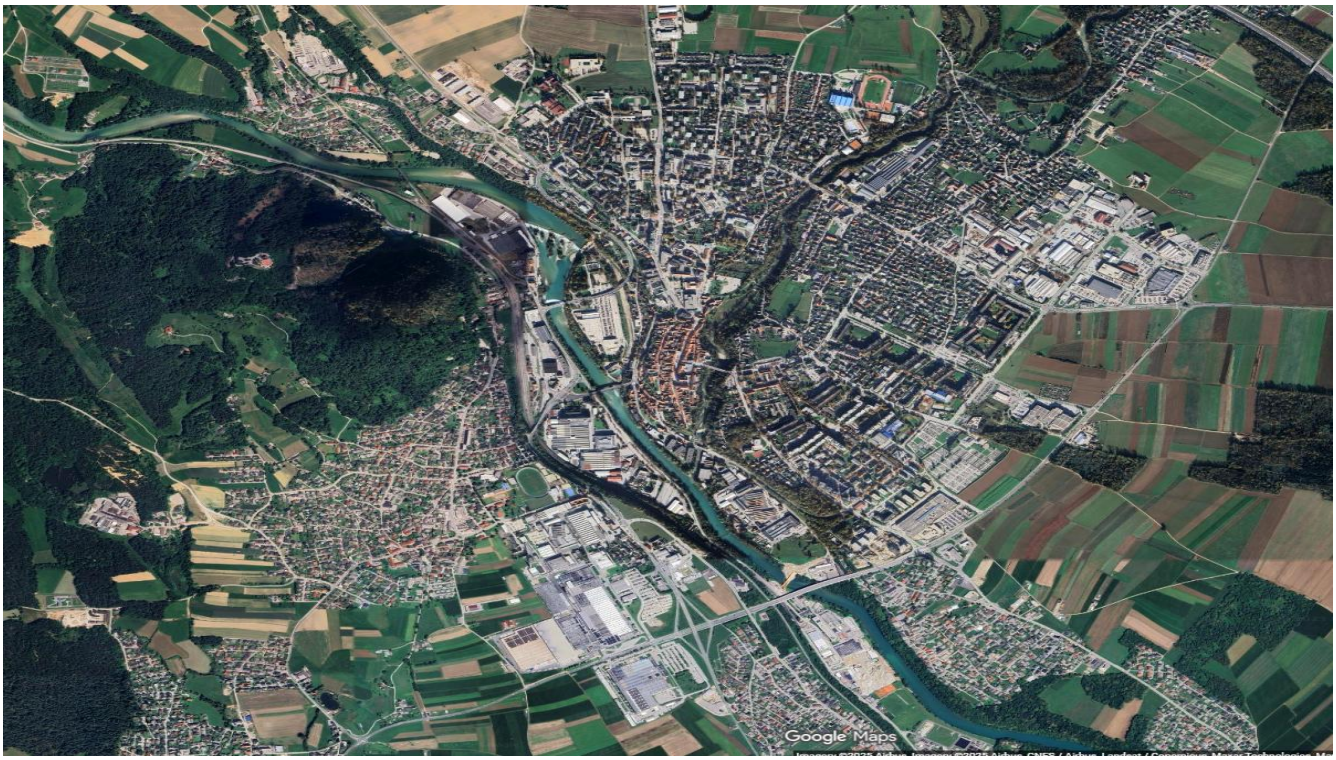


Figure 6: Planina PED area overview.

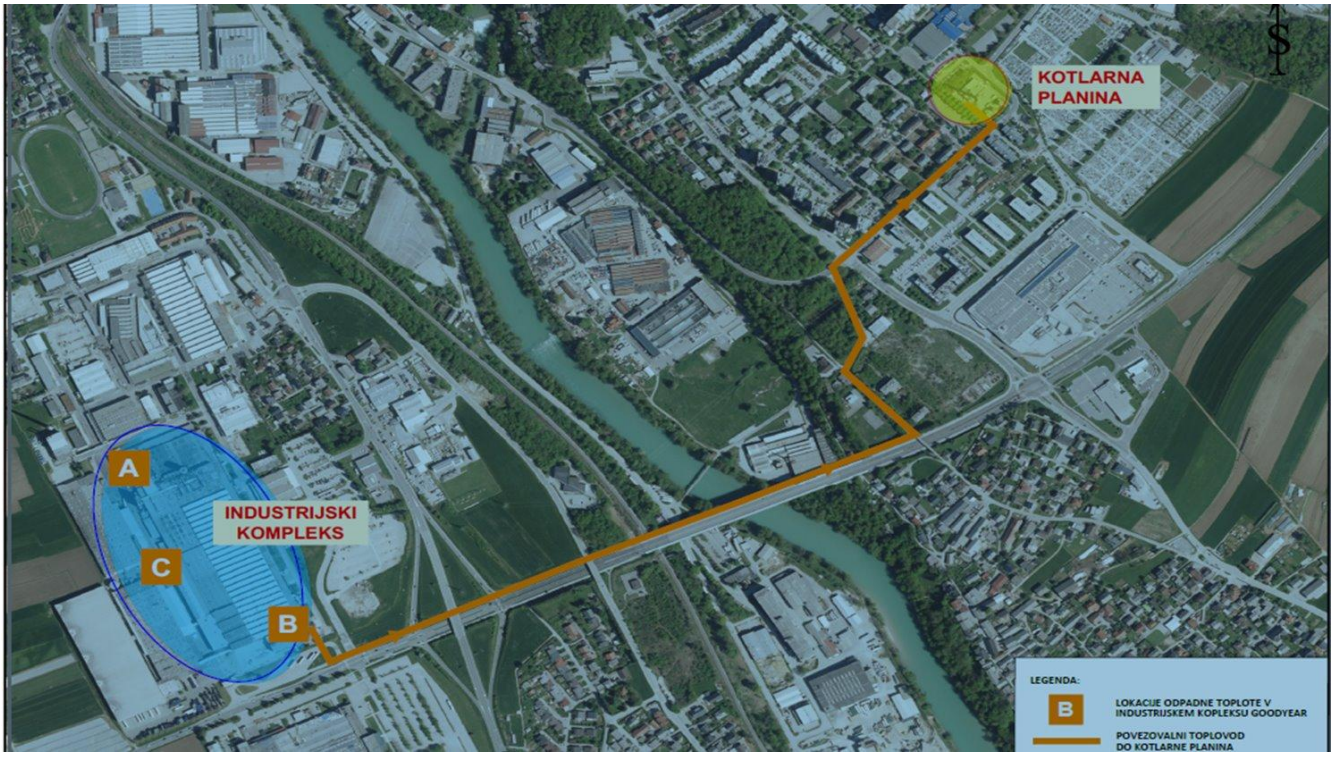


Figure 7: Planina PED.

5.1.3.2 Operational characterisation

The operational characterisation of the Slovenian PED reflects a transition from a predominantly centralised and fossil-based energy supply system towards an integrated, multi-source, and sector-coupled energy system. In the current baseline configuration, the operation of the district heating network is largely dependent on a single natural gas boiler, while electricity is mainly supplied from the external grid with limited local generation.

The target operational concept introduces a diversified portfolio of energy sources and technologies, combining waste heat recovery, renewable electricity generation, and high-efficiency cogeneration. Waste heat from the Labore industrial zone is expected to provide a substantial share of the base thermal load, thereby reducing the reliance on fossil fuels. Photovoltaic systems and hydropower plants will contribute to local electricity generation, while combined heat and power units will simultaneously produce electricity and heat with a focus on economic optimisation.

A key feature of the operational strategy is the market-oriented operation of the CHP units, which are designed to run during periods of high electricity prices, typically between 2,000 and 2,500 hours per year, thereby maximising revenue generation. Electric boilers are introduced as flexible assets capable of converting electricity into heat, providing both operational stability and the possibility to deliver grid-balancing services. This combination of technologies enables a high degree of sector coupling, linking electricity and heat systems in a coordinated manner.

The overall operation of the PED is expected to be coordinated through an Energy Manager, which will serve as the central control and optimisation layer. This system will enable forecast-based dispatch,

coordination of distributed energy resources, and optimisation of energy flows across sectors. It is also expected to support participation in energy markets and facilitate the provision of flexibility services.

5.1.3.3 Socio-economic and governance characterisation

The Slovenian PED is characterised by a multi-level governance structure involving public authorities, infrastructure operators, private companies, and end users. The Municipality of Kranj plays a central role in coordinating the initiative and ensuring alignment with local sustainability objectives, while operational responsibilities are distributed among specialised entities such as the electricity distribution system operator Elektro Gorenjska, the district heating operator Domplan, and the renewable energy company Gorenjske Elektrarne. Industrial stakeholders in the Labore zone and local residents and businesses constitute the primary user base of the system.

The socio-economic model of the PED is based on the gradual transition towards a more integrated and participatory energy system. The business model incorporates multiple revenue streams derived from electricity and heat sales, the utilisation of waste heat, the operation of combined heat and power units, and the provision of flexibility services. Additional revenue is expected from electric vehicle charging infrastructure and, potentially, from future biomass-based heat production. The strategic operation of CHP units during peak electricity price periods represents a key element of the economic optimisation strategy.

Stakeholder engagement activities have been initiated through workshops, surveys, and other participatory processes aimed at increasing awareness and acceptance among local users. In the longer term, the PED aims to evolve towards an energy community model in which users actively participate in energy production, consumption, and decision-making processes.

5.1.3.4 Data interoperability and traceability

Data interoperability and traceability within the Slovenian PED are addressed through the planned implementation of the Interoperability Platform, which will enable structured data exchange between different system components and stakeholders. The architecture foresees the integration of the Energy Manager, based on Moxa's and the AURORA platform as a central element responsible for collecting, processing, and utilising data for operational optimisation and monitoring purposes, especially concerning real-time data. Operational data streams from CHP units, PV systems, heating networks, and grid nodes are securely transferred and catalogued. The platform ensures that all participating tools and actors can access consistent datasets for analysis, visualisation, and control. The system supports both real-time and non-real-time data exchange, with strict protocols for encryption, timestamping, and role-based access. Static and infrastructure data has been provided in GeoJSON and JSON format based on a structure defined within PEDvolution project.

The platform is expected to rely on secure communication protocols, such as HTTPS-based APIs, to facilitate the exchange of data between energy generation units, consumption points, and control systems. Data inputs will include information from combined heat and power units, photovoltaic systems, hydropower plants, electric boilers, the district heating network, and electric vehicle charging infrastructure. This integrated data environment will support real-time monitoring, performance assessment, forecasting, and decision-making processes.

The linkage between KPIs and their respective data sources, temporal resolution, and units follows the monitoring and data collection framework defined in Section 4.3 and Annex I, where each KPI is

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explicitly mapped to its underlying dataset, calculation method, and measurement characteristics. Energy-related KPIs (e.g. consumption, generation, flexibility utilisation) are derived from smart meters, EMS data streams, and substation measurements, typically at sub-hourly resolution (seconds to 5–15 minutes) and expressed in units such as kWh, kW, or %. Environmental KPIs are based on sensor data and calculated emission factors, with defined measurement intervals and units such as tCO_2e, °C, or ppm. Economic KPIs are linked to cost and market data exchanged via the Interoperability Platform, expressed in €/MWh, CAPEX/OPEX values, or payback periods, while social KPIs rely on survey and engagement data with qualitative or quantitative indicators (e.g. participation rates, satisfaction levels).

5.1.3.5 Temporal reference point

For the Kranj PED, the reference point is positioned before the deployment of PEDvolution tools and the operationalisation of the integration framework. It is defined at the point of deployment readiness as the tools and supporting infrastructure are technically operational and represent the transition from the preparation phase to the demonstration and validation activities planned for WP9. At this point, the tools are considered technically ready for deployment, but they are not influencing operations, such as load management or flexibility allocations, in Kranj.

The reference period is established using 2023 operational data and early 2024 measurements, providing an overview of energy flows and asset performance before the integration of the PEDvolution solutions. The temporal reference point for the Slovenian PED is defined by the current operational state of the energy system prior to the implementation of the planned interventions. This baseline is characterised by the dominant role of the natural gas-based district heating system in Planina, with an annual heat production of approximately 36,000 MWh, and a relatively low level of integration of renewable and decentralised energy sources.

This reference state serves as the benchmark against which the performance of the PED will be evaluated in terms of energy efficiency, renewable energy share, greenhouse gas emissions, and economic performance. At present, the baseline definition is primarily based on available system-level data and infrastructure characteristics, as comprehensive historical datasets covering all relevant key performance indicators are not yet available.

5.1.3.6 Alignment with demonstration preparation

The Slovenian PED is currently in an advanced stage of preparation, with a clearly defined roadmap for the deployment of key technologies and system components. The installation of calorimeters in the Labore industrial zone has already been carried out, as well as installation of additional equipment to collect both static and real-time data from various assets within the Kranj PED in order to quantify waste heat potential, the deployment of electric boilers, the initial integration of hydropower generation into the PED framework, and the installation of combined heat and power units for market-based operation.

In the medium term, the focus will shift mostly towards the expansion of photovoltaic systems, the development of electric vehicle charging infrastructure, and the increased integration of waste heat into the district heating network. The potential implementation of a biomass steam boiler will also be assessed as part of the system expansion strategy. In the long term, the objective is to establish a fully integrated energy community in which residents and businesses actively participate in shared energy production and consumption, with the ultimate goal of achieving carbon neutrality.

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Descriptions of the solutions involved, their scope and how they operate are listed in sections 5.2 and ANNEX III: the PEDvolution solutions.

Once the tools are deployed, they will be tested and validated under real-world conditions. This will be done by comparing real-time data, control systems, technical compatibility and readiness, business model viability and feasibility, and stakeholder alignment through workshops against the baseline data using KPIs delineated in Annex I: List of KPIs.

5.1.3.7 Achieving this PED

Achieving the Planina PED goals will require integrated technical and governance innovations:

- The integration of industrial waste heat into the district heating network is pivotal. If sufficient long-term heat availability from Labore cannot be secured, a 5 MW biomass boiler will be installed to ensure energy security.
- Smart coupling of electricity and heat using electric boilers, hydropower, and PV installations will optimise use of local renewables and enhance flexibility.
- Through the PEDvolution tools, especially the PED Energy Manager, energy production, storage, and consumption will be dynamically managed and optimised.
- Establishing a local energy community model with fixed-price contracts is planned, aiming to reduce exposure to market volatility and encourage broader community participation.

The overarching aim is a net-positive energy balance (heat + electricity), long-term CO_2 reduction, and a resilient, economically stable PED, serving as a replicable example for similar urban districts in Slovenia and beyond..

5.2 Deployment and Testing of Tools in the Co-Developer PEDs

This section illustrates the deployment processes and testing plans of the seven PEDvolution tools. The transition from deployment to operational testing and KPI validation occurs through a staged implementation framework for M&V, which continues tool operation, cross-solution integration, and site-specific verification through the piloting stages and finally consolidates verification and reporting within the project timeframe.

A more detailed description of the PEDvolution Tools is provided in ANNEX III: the PEDvolution solutions.

5.2.1 PED Design and Planning Toolset

The PED Design and Planning Toolset is comprised of the Digital Twin Planning Tool and the PED District Heating and Cooling Planning Tool. It aims at executing scenario testing for renovation strategies and energy system and district heating optimisation.

Deployment:

In the demonstration phase, the toolset will be deployed to analyse current district conditions, identify renovation priorities, and assess energy transition pathways under different future scenarios. The workflow integrates data collection, energy demand and supply modelling, DHC scenario analysis, and renovation advisory generation at building and district levels. the toolset will produce renovation

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advisory dashboards and DHC scenario, providing transparent and comparable results on energy demand reduction, renewable integration potential, waste heat utilisation and investment needs.

The toolset will be applied and demonstrated through a dedicated user interface, enabling planners, and developers to interactively explore renovation scenarios, test DHC configurations, and visualise the resulting KPIs at both building and district levels. The web-based UI provides access to core functionalities including building-level renovation recommendations based on energy performance, typology, and retrofit potential and district heating and cooling expansion or decarbonisation options, including the integration of local renewable and waste heat sources.

Deployment status:

The tools are ready, technically, for deployment. However, the tools require an operable UI, which is developed within the scope of WP7 and is expected to be ready in July 2026.

Testing:

The Digital Twin Planning Tool will be tested in the German and Swiss PEDs.

The PED District Heating and Cooling Planning Tool will be tested in all three PEDs.

Both tools will also be tested in at least one of the Follower PEDs selected through the Open Call for Demonstrators.

The testing scope in each PED is described below (Table 7). The relevant KPIs to be validated can be found in Annex I: List of KPIs.

Testing duration:

The testing and refinement period will be between 6 to 9 months.

Table 7: Testing scope of the PED Design and Planning Toolset.

PED	Testing scope	Testing commencement
German PED	The Digital Twin Planning Tool will simulate building-level simulations and renewable energy integration to validate energy and emission reductions. The District Heating and Cooling Planning Tool will test cost-optimal configurations for district heating, evaluating flexibility of model parameters and significance of the results under varying conditions.	July 2026
Swiss PED	The Digital Twin Planning Tool process monitored data from the local platform to assess the alignment between measured simulated values for renovation scenarios for the building stock in PEDs and renewable integration. The District Heating and Cooling Planning Tool will test the shift from fossil-based to biomass-based heating operation and	July 2026

	waste heat integration, whereas the results will be used for system and regulatory compliance.	
Slovenian PED	The District Heating and Cooling Planning Tool will model a shift from natural gas to biomass and the utilisation of industrial waste heat. This will be done by simulations, using local datasets, for the verification of energy balance and the feasibility of the results.	July 2026

5.2.2 PED Readiness Assessment (PED RA)

The PED RA Framework gathers data on demos current status and various PEDvolution solutions. This includes information four dimensions concerning market, social, technology, and interoperability (the PEDvolution phenotypes). It is set to assess the readiness of PEDs on four planes, namely technological, market, social, and interoperability.

Deployment:

The PED RA Framework will be deployed in all PEDs (Wunsiedel, Kranj, Winterthur and the three follower PEDs selected through the Open Call for Demonstrators) to evaluate the readiness of each PED across four dimensions: market, social, technology, and interoperability. The framework provides a clear picture of the status and identifies gaps to be addressed, based on appr. 40 performance indicators. Deployment will include a review of consolidated KPIs, an initial assessment to establish baseline readiness, and the consolidation of target values for further development of the framework. The process will also evaluate data availability, specific PED assumptions and integrate the SGNI/DGNB certification level as a benchmark for sustainability performance. Stakeholder feedback (from SGNI as certifier) will be integrated in the final exploitable results.

Deployment status:

The PED RA computational logic, data structures, and overall framework has been developed and validated internally, and initial datasets are being collected in collaboration with the co-developer PEDs. The tool has so far been applied through structured data inputs and offline processing to define baselines values and preliminary outputs in four dimensions.

For the follower PEDs, deployment is currently at an earlier stage, as specifically social KPI data collection and preparation are still ongoing. However, PED RA deployment has begun in the other dimensions.

Testing:

This PED RA will be tested in all co-developer PEDs and will be extended to all three Follower PEDs selected through the Open Call for Demonstrators.

The testing scope can be found in Table 8 and the relevant KPIs to be validated can be found in Annex I: List of KPIs.

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Testing duration:

The testing will be performed in April 2026. Feedback will be collected by the end of April 2026 and the results will be used to review the consolidated KPIs, an initial assessment to establish baseline readiness, and the consolidation of target values and weighting factors for finalisation of the framework development. The deployment will also evaluate data availability, specific PED assumptions and integrate the SGNI/DGNB certification level as a benchmark where applicable.

Table 8: Testing scope of the PED Readiness Assessment Tool.

PED	Testing scope	Testing commencement
German PED	The KPIs developed for the PED RA will be used to assess and rate the PED for DGNB certification, framework usability verification, replicability, and significance for connecting with the DDSG.	April 2026
Swiss PED	The PED RA will focus on ensuring usability and replicability, as well as connection to the DDSG using the KPIs and DGNB.	April 2026
Slovenian PED	The PED RA will focus on ensuring usability and replicability, as well as connection to the DDSG using the KPIs and DGNB.	April 2026

5.2.3 Dynamic Decision Support Guideline (DDSG) for PED Development

The DDSG for PED Development enhances and refines PEDvolution solutions by analysing real-time data on energy demand, costs, geospatial factors, and legislative frameworks. It enables PED planners to generate scenarios that integrate various technologies, energy requirements, and financial constraints, while simultaneously assessing their social, economic, and environmental impacts.

Deployment:

The DDSG will be deployed following a structured action plan that identifies PED planners as the main users. The deployment process focuses on validating three core dimensions to ensure the tool's reliability, usability, and scalability.

1. First, the functionality and logic structure will be evaluated by examining how effectively the DDSG processes baseline performance data from the PED RA (PED RA) and other context-specific inputs. These inputs will be analysed through calibrated formulas and scenario multipliers to simulate future development pathways and identify suitable PED improvement options. The tool will generate a series of strategy recommendations that are selected, scored, and assessed by each demonstration site to determine their impact. This process will be supported by individual workshops with each demo, enabling direct interaction, validation, and refinement of results.
2. Second, usability will be assessed by analysing how easily users can navigate the tool, input data, and set preferences through the graphical user interface where the DDSG is hosted. The

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interface apart from the set of strategies will include visualisation features, dashboards, and impact charts, to enhance clarity and user engagement during the decision-making process.

3. Third, adaptability will be tested to evaluate how well the DDSG performs across different PED contexts and local conditions, ensuring that the logic and outputs remain relevant across diverse frameworks, systems, and stakeholder settings. User feedback will be collected through a single dedicated questionnaire and will be complemented by continuous feedback loops throughout the deployment phase.

Deployment status:

The DDSG computational logic, data structures, and scenario framework have been developed and validated internally, and initial datasets have been prepared in collaboration with the co-developer PEDs. The tool has so far been applied through structured data inputs and offline processing to define baselines, strategy portfolios, and preliminary outputs. The main component pending deployment is the graphical user interface (UI), which will enable interactive use, scenario selection, and visualisation of results. The UI is expected to be completed and operational at the start of the testing phase in May.

For the follower PEDs, deployment is currently at an earlier stage, as data collection and preparation are still ongoing. These PEDs will begin their deployment process once the required baseline and contextual data have been gathered and validated according to the DDSG data templates.

Testing:

This Dynamic Decision Support Guideline will be tested in all co-developer PEDs and will be extended to all three Follower PEDs selected through the Open Call for Demonstrators.

The testing scope can be found in Table 9 and the relevant KPIs to be validated can be found in Annex I: List of KPIs.

Testing duration:

The DDSG testing phase is planned over approximately 10 months, following an iterative and workshop-based validation process. Testing begins with the Swiss PED as the initial reference case, followed closely by the German and Slovenian PEDs, and the follower PEDs as well when deployment is finished with them. The process includes multiple testing rounds, feedback collection, and refinement cycles, concluding with final validation and replicability assessment by January 2027.

Table 9: Testing scope of the Dynamic Decision Support Guideline.

PED	Testing scope	Testing commencement
German PED	Testing will assess the full integration of the 10 KPI formulas included in the DDSG, including cross-domain consistency between energy, economic, governance, and smartness strategies. Particular attention will be given to how priority selection reshapes outcomes and	**May 2026 (Start of testing for all co-developer PEDs)** **Workshop 1 (Apr-May):** Baseline validation and dataset confirmation **Workshop 2 (May):** Scenario

	how scenario divergence evolves over time.	walkthroughs and execution of computational chain **Workshop 3 (Early June):** UI testing (navigation, filtering, interpretation) **Workshop 4 (September):** Preliminary testing + first structured testing round (UI + data integration) **Questionnaire 1 (September):** Feedback on usability, clarity, and reliability **Iteration phase (October–November, NTNU):** Logic and UI improvements **Second testing round (November):** Independent validation including PED RA integration **Workshop 5 (January 2027):** Final testing (refinement, scalability, replicability) **Questionnaire 2 (January 2027):** Final feedback and validation **Finish February 2027** **August – September 2026 (Start of testing for all follower PEDs)** Similar structure to co-developer PEDs. To finalise in February 2027 **Finish March 2027**
Swiss PED	Testing will examine how the DDSG behaves under already high baseline conditions, especially saturation effects, diminishing returns, and readiness scaling. The scope will verify that improvements remain realistic, that scenario sensitivity is credible, and that governance and smartness indicators meaningfully influence long-term resilience trajectories.	
Slovenian PED	Testing will focus on validating the robustness of the energy-production-driven logic, particularly RES increase and system reduction under different scenarios. Since some social and governance aspects are less structurally embedded, the scope will also assess how the DDSG handles partial domain maturity.	

5.2.4 PED Energy Manager

The PED Energy Manager is an advanced tool that optimises energy performance across PED through real-time monitoring, sector coupling, flexibility aggregation, multi-district coordination, and market interaction to enhance renewable self-consumption, reduce curtailment, and enable strategic energy use and trading. It is comprised of AURORA, ANODE and DERMOT.

The PED Energy Manager will test optimisation measures for local flexibility portfolios.

Deployment:

The PED Energy Manager will be deployed across all three Co-Developer PEDs and one additional newcomer PED onboarded during the open call. In total, more than 30 assets will be integrated, including both household and industrial assets. All WP5 tools will be deployed on the appropriate servers, except for the Anodes, which will be installed directly at the industrial asset locations. In particular, AURORA will be deployed on cloud server infrastructure, with one AURORA environment per PED (logically separated to ensure independent operation). A total of nine or more Anodes are expected to be deployed, although the exact number cannot yet be determined as the open call is still ongoing. The ANODEs will be deployed as edge devices on industrial Moxa PCs. A more detailed description of the technical hardware configuration is provided in D2.3.

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In total, three AURORA environments and three DERMOT cloud-based environments are planned to be deployed, aligned with the participating Co-Developers. DERMOT will be hosted as a cloud tool. More than nine ANODE edge devices are expected to be installed at industrial asset locations.

The deployment will include a diverse range of industrial and household assets with different power capacities and levels of controllability. On the industrial side, the PED Energy Manager will integrate assets such as photovoltaic systems, battery storage units, CHP plants, hydro power plants, EV charging stations, and heat rods. These assets cover a wide range of scales, from smaller distributed systems to large industrial units exceeding several hundred kilowatts. Household deployments will include smaller assets such as EV chargers, washing machines, and small battery systems, contributing to local flexibility and demand response.

Due to the limited availability of suitable household assets in the Slovenian PED, only the industrial components of the PED Energy Manager (Aurora and Anodes) will be deployed there, while the other two Co-Developers will implement the full PED Energy Manager, covering both industrial and household sectors.

Deployment status:

PED Energy Manager tools (AURORA, ANODE, DERMOT) have been deployed at all the Co-Developers. While the tools are operational and collecting the relevant data, the following refinements are currently being finalized to reach full system integration:

- German PED: Battery needs to be integrated, allowance and exact control procedure of the heat rod is being discussed. Household assets are being integrated.
- Swiss PED: Household assets are being integrated. EV charging station is being integrated.
- Slovenian PED: The V2G charger and the hydro power plant are being integrated to complete the asset portfolio. Ongoing work focuses on validating data streams and addressing some errors in communications with the assets to ensure accurate real-time monitoring and consistent asset control.

Testing:

The PED Energy Manager will be tested in all co-developer PEDs and will be extended to at least one of the Follower PEDs selected through the Open Call for Demonstrators.

The testing scope can be found in Table 10 and the relevant KPIs to be validated can be found in Annex I: List of KPIs.

Testing duration:

Mentoring already commenced. Active control from summer 2026 (ongoing discussion with the PED on exact time windows). Test duration all WP9.

Table 10: Testing scope of the PED Energy Manager.

PED	Testing scope	Testing commencement
German PED	Two implementations will take place: (i) Industrial and (ii) household assets operational optimisation. This will	June 2026

	include measuring the extent to which the tool can schedule and activate steerable assets. Flexibility and dispatch estimations will be compared against baseline datasets. All tools will be tested.	
Swiss PED	The tools will optimise operation of PV, EV charging station and assets available at households. All tools will be tested.	June 2026
Slovenian PED	The tools will examine optimisation of PV and EV data. Possibly also EV data. AURORA and ANODE will be tested.	June 2026

5.2.5 Data Exchange, Integration and Interoperability Platform

The Data Exchange, Integration and Interoperability Platform is a secure, decentralised Data Space that enables semantic and syntactic interoperability across PEDvolution solutions, IoT platforms, and devices by facilitating trusted data exchange, discovery, and access control among diverse stakeholders. The platform constitutes the core digital backbone of the PEDvolution project, enabling secure, trusted, and policy-controlled data sharing across Positive Energy Districts (PEDs) and Solution Tools. The platform is implemented as a decentralised Data Sharing solution, aligned with European Data Spaces principles (e.g., Gaia-X and IDSA), and leverages Eclipse Dataspace Components[2] to support federated secure data exchange and policy enforcement.

The Data Exchange, Integration and Interoperability Platform will be tested to validate its data exchange and integration capabilities within the PEDvolution ecosystem.

Deployment:

The Data Exchange, Integration, and Interoperability Platform has been deployed within a Kubernetes production cluster environment, enabling secure, and standardised data exchange between the participating PED (PEDs) and Solution Tools.

The deployment is hosted on a dedicated Virtual Machine (VM) under the domain name *.pedvolution.intracom-telecom.com, which serves as the central development and integration environment of the PEDvolution project.

The platform follows a cloud-native architecture, leveraging:

- Kubernetes for container orchestration

[2] https://github.com/eclipse-edc

- Docker for containerisation.

Each core component is deployed as an independent and scalable service (Kubernetes pod), including:

- Dataspace Connectors (Provider & Consumer)
- Federated Catalogue Service
- Identity and Trust Management Components (Identity Hub)
- Data Plane and Control Plane Services
- API Server, exposing secure HTTPS interfaces that facilitate the seamless integration of data providers (PEDs) and data consumers (Solution Providers) with the platform

A Nginx Ingress Controller Kubernetes pod is used to:

- Provide secure HTTPS endpoints
- Enable load balancing and traffic routing
- Handle TLS connections

TLS certificates are managed as Kubernetes secrets with yearly renewal via DigiCert security organization, ensuring continuous and trusted encrypted communication.

Additional deployment characteristics include:

- Network isolation and security zoning, separating internal platform components from externally exposed services
- Secure exposure via HTTPS (secure port 443), ensuring that all external communication is encrypted and standardised
- Proxy and firewall configurations ensuring secure communication with external data providers (PEDs) and consumers (Solution Providers).
- Whitelisting mechanisms for Data Providers (PEDs) and Data Consumers (Solution Providers):
  - Only pre-authorised IP addresses, domains, or endpoints are permitted to interact with the platform
  - This ensures protection against unauthorised access and aligns with data sovereignty and trust requirements of Data Spaces.

This deployment approach ensures that the platform is secure-by-design, scalable, and compliant with Data Space principles of trust, sovereignty, and federation.

Deployment status:

The platform is fully deployed and operational at central level, serving all relevant PEDs. PEDs act as data providers, exposing their datasets through secure HTTPS endpoints made available via the platform. Solution Providers act as data consumers, accessing data through the same shared infrastructure.

The Data Exchange, Integration and Interoperability Platform follow a centralised cloud-based deployment model, and therefore no separate deployment instance is required per PED.A single, shared platform instance is deployed under the domain *.pedvolution.intracom-telecom.com, which serves all

participating PEDs and Solution Providers. Each PED is integrated into this common Data Space through secure onboarding procedures, rather than through independent local deployments.

The testing scope can be found in Table 11 and the relevant KPIs to be validated can be found in Annex I: List of KPIs. The testing scope is uniformly applied to all data providers (PEDs) and data consumers (Solution Providers), establishing a harmonised validation framework that ensures consistent assessment of interoperability and secure data exchange across the entire PEDvolution Data Space.

Testing duration:

The testing activities will be conducted throughout the full lifecycle of the WP9 demonstration phase, spanning from May 2026 until June 2027.

Table 11: Testing scope of the Data Exchange, Integration, and Interoperability Platform.

PED	Testing scope	Testing commencement
German PED	The Data Exchange, Integration and Interoperability Platform will be tested to validate its data exchange and integration capabilities within the PEDvolution ecosystem. During this phase, pilot data originating from the participating PED (PEDs) will be published as offers in a shared Data Space catalogue, in accordance with data sovereignty principles inspired by the Gaia-X and IDSA frameworks. Authorised Solution Providers will be able to discover and retrieve the required data from PEDs listed in the shared catalogue, through developed APIs and secure data exchange protocols (HTTPS, Hypertext Transfer Protocol Secure). The shared data space catalogue supports advanced search and filtering functionalities, allowing Solution Tools to discover relevant data from PEDs, based on various search criteria, such as: • Time range and temporal resolution, • Data category (e.g., energy, building, grid), • Name or location of the PED, • Data type (e.g., real-time or non-real time). The exchanged datasets will comprise mapped and harmonised pilot data, including but not limited to: • Building stock characteristics, • Grid infrastructure and electrical characteristics, • Energy assets and consumption/production profiles, • Energy prices,	June 2026
Swiss PED		June 2026
Slovenian PED		June 2026

	• Photovoltaic Systems This validation activity aims to demonstrate the data exchange platform's ability to ensure semantic interoperability, and data integrity, while enabling secure, discoverable, and standardised data sharing between PEDs and Solution Tools across the PEDvolution ecosystem.	

5.2.6 PED Business Model Innovation (BMI) Tool

The PED Business Model Innovation tool (BMI Tool) builds business model approaches which are relevant for community-based energy systems. Its primary objective is to create a typology of various business model options or building blocks for PED (PEDs), tailored to the PEDvolution context while also being adaptable for other PEDs in general.

The Business Model Innovation Tool will be tested by configuring and validating adaptable business model patterns through three key phases: Adaptation, Implementation, and Validation.

1. Adaptation Phase:

This phase focuses on adapting the E-LAND community-based business model innovation tool to meet the specific needs of PEDs. The tool will provide a set of building blocks, known as 'business model patterns,' that have been proven effective in community-based business solutions. These patterns will be customised using additional tools such as the Value Proposition Tool, Force Field Analysis, and SWOT Analysis to understand the pains and gains, as well as the driving and restraining forces for individual PEDs and their integrations. The aim is to formulate the first set of business model patterns tailored to the PEDvolution context while ensuring flexibility for wider application.

2. Implementation Phase:

During this phase, the co-development process actively involves PEDvolution demonstration sites, leverage the outcome from the integration of various tools, and technology developers. The business model patterns will be fine-tuned through a series of workshops aimed at co-developing tailored business models for each site. This process follows a step-by-step approach, starting with the initiation phase, which focuses on identifying and understanding local challenges and opportunities. This is followed by the ideation phase, where innovative business model options are generated, and the integration phase, which combines and adapts business model patterns to fit local contexts. Finally, the implementation phase applies the tailored business models to PEDs with active stakeholder (focusing on business model) involvement. Feedback gathered throughout this process will be used to enhance the design of the BMI Tool, ensuring it effectively addresses the specific needs and opportunities within local contexts.

3. Validation Phase:

In the final phase, the developed business models will be co-validated by actively engaging PED managers and relevant stakeholders and gather quantifiable project consequences from the use cases tested and measured KPIs. This phase also involves assessing economic viability, assess users-acceptance, investigating barriers including regulations, and investigate the potential for the involvement of social entrepreneurs. In line with the PEDvolution business model process, the co-

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validated business models will be adaptable which will promote various sustainable PED tools and solutions.

Deployment:

The deployment of the PED BMI tool enables each pilot PED to define at least one business model addressing real contextual challenges, and to validate and evolve these models into practical, site-specific cases, supporting their planning, implementation, or operation.

Co-development first constitutes adapting the typologies of business model patterns to the unique technical, economic, social, or governance contexts of each PED. A first draft of the tool was co-developed by M18. Deployment then focused on agile testing, feedback collection, and iterative refinement of the tool and its deployment methodology.

Deployment of the BMI tool started in M19 (July 2025) with all three Co-Developer PEDs focusing on their highest priority challenges and will be extended to all newcomer PEDs from the open call for demonstrators.

For the three Co-Developer PEDS, deployment follows the same co-development methodology used up to M18 (June 2025) but applies it in greater depth to address their specific challenges. A series of workshops, analyses, and feedback sessions are conducted to build a holistic understanding of each case and support each PED in translating its priority into a concrete business model by the end of M24 (December 2025). Each PED will also define an initial set of business indicators to track progress and prepare a piloting plan for implementation within WP9. These outcomes have been documented in Deliverable D6.1 “Implementation of business model innovation tools”.

Deployment status:

The PED BMI tool has been deployed in each co-developer PED (German, Switzerland and Slovenia).

Testing:

The Business Model Innovation Tool will be tested in all co-developer PEDs and will be extended to all three Follower PEDs selected through the Open Call for Demonstrators.

The testing scope can be found in Table 12 and the relevant KPIs to be validated can be found in Annex I: List of KPIs.

Testing duration:

This is co-validation phase for the PED BMI and aligns with WP9 timeline until M42 (June 2027). Indeed, it depends on the progress of the testing of the technical tools in the PEDs.

Table 12: Testing scope of the PED Business Model Innovation tool.

PED	Testing scope	Testing commencement
German PED	The BMI tool will utilise input created by the different tools and stakeholder workshops to identify viable use cases, in which revenue and cost stream metrics will be verified against literature data.	June 2026 onwards till the end of the project. This also depends on the testing progress of the technical tools deployed for the PED.

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Swiss PED	Participatory validation of business cases will be carried out, leveraging local stakeholders to help define and assess the use cases. In addition, the tool will perform feasibility analyses for the specific Swiss market conditions.	June 2026 onwards till the end of the project. This also depends on the testing progress of the technical tools deployed for the PED.
Slovenian PED	The utilised data from all technical solutions to establish a business-as-usual baseline, against innovative scenarios, will be developed and compared.	June 2026 onwards till the end of the project. This also depends on the testing progress of the technical tools deployed for the PED.

5.2.7 Social Innovation (SI) Tool

The PED Social Innovation Tool is a four-phase methodology designed to support stakeholder alignment, engagement, and decision-making in PED by guiding the identification, analysis, and incorporation of diverse stakeholder needs to foster social acceptance and effective project implementation.

The Social Innovation Tool will be deployed to engage stakeholders in order to assess and enhance local acceptability of selected project interventions.

Deployment:

The Social Innovation tool guides assessing stakeholder and community needs, values and priorities in order to understand how to enhance local acceptance and encourage stakeholder participation. This methodology involves four phases including community scoping, analysis, development of action plans and evolvement. The community scoping and development of action plans will be conducted through WP6 during 2025, and further implementation will continue during the piloting phase.

During the deployment and piloting phase, PEDs will implement agreed engagement activities and follow corresponding KPIs to ensure continuous involvement of relevant stakeholders. At a later stage, the approaches will be assessed to ensure their continued relevance as PEDs evolve.

Deployment status:

Deployment started in co-developer PEDs as described above. Deployment of the process will start in Follower PEDs mid-2026.

Testing:

The Social Innovation Tool will be tested in all co-developer PEDs and will be extended to all three Follower PEDs selected through the Open Call for Demonstrators.

The testing scope can be found in Table 13 and the relevant KPIs to be validated can be found in Annex I: List of KPIs.

Testing duration:

The testing is divided in four phases or steps out of which the two first ones corresponding to PED scoping and analysis were conducted during the preparation period, and implementation will be

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conducted during the testing and piloting period. For Follower PEDs, the estimated duration of the whole process is one year.

Table 13: Testing scope of the PED Social Innovation tool.

PED	Testing scope	Testing commencement
German PED	Interviews and a workshop have been conducted, focusing on a shared battery initiative as a future component of the local ESC. The results will be leveraged to define the user engagement potential.	Steps 1-2 conducted during 2025. Finalise action plans in May 26, and implement during the testing period.
Swiss PED	On-site workshops will be carried out to define next steps for the project to replace the heating system, and to inform development engagement plans.	
Slovenian PED	Interviews will be carried out to understand stakeholder perspectives on the integration of waste heat in the district heating system, and to inform engagement plans.	

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6 CONCLUSIONS

This deliverable aims to prepare the demonstration phase by establishing clear baselines for testing and monitoring and verification frameworks.

The M&V Plan was developed to assess the performance of the tools and PEDs by incorporating KPIs, data requirements, monitoring methodologies, verification procedures, and feedback mechanisms, to ensure an evaluation throughout the demonstration phase with alignment with a set of regulations, policies, standards, and other frameworks.

Preparation and co-development activities were carried out to configure and deploy the seven PEDvolution tools in the three co-developer PEDs within WP8. This was done in compliance with site-specific infrastructures, regulatory conditions, and stakeholder contexts in the co-developer PEDs in Germany, Switzerland, and Slovenia. These activities include infrastructure mapping, deployment of metering, monitoring, and control equipment, validation of data-exchange pathways, and integration of business model and social innovation processes to ensure operational readiness. The preparations also clarify responsibilities for data provision and tool operation while ensuring that regulatory and stakeholder considerations are embedded in the deployment strategy. For the Follower PEDs the preparation and deployment activities will be documented in dedicated Follower PED reports in June 2026.

The frameworks developed in WP2-7 for tool development, specifications, and assessment provide the groundwork for the necessary baseline conditions for each PED by documenting their existing technical, infrastructural, regulatory, and socio-economic characteristics in the energy, environmental, economic, and social dimensions, which define the scope and parameters for solution testing and performance monitoring and verification.

In the German PED, the Schönbrunn and Energy Sharing Community (ESC) PEDs are expected to demonstrate a net-positive annual energy balance for heat and electricity through coordinated operation of generation and storage assets, supported by sector coupling. The PEDs will confirm scalability to enable integration into the ZENOB Super-PED framework. The results are expected to address system-level optimisation, household participation, and cross-sector flexibility management.

In the Swiss PED, multi-energy integration and participatory governance in a cooperative environment will be validated. In addition, operational verification of smart metering, flexibility optimisation of renewable and controllable assets, and a measurable decrease in fossil energy use and CO_2 emissions. The PED will demonstrate the functionality of local data exchange, adaptive planning, and user involvement in a real living-lab context.

In the Slovenian PED, the PED will demonstrate the power use optimisation, integration of industrial waste heat within an urban-industrial setting, and CO2 reduction by shifting fossil-based to renewable-based heating. In addition, the operation of integrated renewable assets (PV, CHP, hydropower, biomass, electric boilers), improved energy self-sufficiency, and readiness for legal activation of energy sharing once national regulation allows will be validated.

The results of the testing and verification will be collated into solution-specific and PED reports, detailing the performance achieved, corrections made, and alignment to the objectives set, and will be documented as part of the M&V reporting structure developed for the project, i.e., Site Acceptance Testing (Annex II: Reporting Template). The SAT will function as an instrument for documentation of

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the tracking of the tools' operations in the ecosystems of the PED sites. SATs for all PEDs will be consolidated in the subsequent WP9 reporting deliverables due close to the end of the project.

The PEDvolution tools will operate in both the co-developer and the Follower PEDs selected through an Open Call for Demonstrators. The extension of the solutions to the newcomer PEDs will be selective depending on the needs of each site and their relevance to the testing, as shown in Table 14.

Table 14: Mapping of the PEDvolution solutions' testing within the PEDs.

PEDvolution Tool		German PED	Swiss PED	Slovenian PED	Newcomer PEDs
PED Design and Planning Toolset	Digital Twin Planning Tool	X	X		In at least one
	PED District Heating and Cooling Planning (DHC) Tool	X	X	X	In at least one
PED Readiness Assessment (PED RA)		X	X	X	In all three
Dynamic Decision Support Guideline (DDSG)		X	X	X	In all three
PED Energy Manager	AURORA	X	X	X	In at least one
	ANODE	X	X	X	In at least one
	DERMOT	X	X		In at least one
Data Exchange, Integration and Interoperability Platform (IP)		X	X	X	In at least one
Business Model Innovation (BMI) Tool		X	X	X	In all three
Social Innovation (SI) Tool		X	X	X	In all three

The preparation activities to enter the demonstration phase, in terms of infrastructure mapping, metering and control equipment rollout, and scope of data exchange were completed. However, not all solutions are fully developed and deployed. Though the PED Design and Planning Toolset is technically ready, it requires a finalised use interface, developed within WP7 (Data Exchange, Integration and Interoperability Platform), expected to be utilised in July 2026. The PED RA is ready for deployment and testing, including refinement, in all of the PEDs within the scope of WP9 (PEDvolution demonstrators and performance assessment). The DDSG is technically ready for deployment but requires a finalised use interface, developed within WP7, expected to be utilised in May 2026. The PED Energy Manager is technically developed and will be ready for full deployment within the scope of WP9. The BMI tool was developed, but not yet fully deployed, as its operation depends on the progress of the technical tools

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and their testing, expected to start validation in June 2026 as part of the WP9 activities. The Social Innovation tool has completed its initial phases, whereas full implementation and further validation and will be carried out within the scope of WP9.

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ANNEX I: LIST OF KPIS

KPI ID	KPI description and baseline / assumptions	Target Value at Project End	Baseline	Assumption	Owner(s) / Associated solution	Pilot and Dimensions
1,1	Increased number of individual energy measures and solutions to make every building reach required energy performance and flexibility	100% coverage of demo sites	Currently demonstration PEDs partially cover some of the individual building measures.	PEDvolution will develop a pathway for each individual building to reach their energy goal and increase their flexibility with the gird through renovation packages such as building envelope, PV, heat pump, e-mobility, storage, smart meters, etc.	PED Design and Planning Toolset	DE, CH Energy
1,2	Increased nº of district energy measures, high/low (H/L) temperature district heating network in combination with individual measures.	H+L (pilot)	Real-time measurements are mostly available at generation, while primary and secondary side only measure consumed energy.	PEDvolution will monitor primary cycle through calorimeters and secondary cycle (4/5gen) through integration with assets. District heating production grows with about 3% per year and the new installations will be based on 4th and 5th generation	PED Design and Planning Toolset	DE, CH, SL Energy

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				(measured assets – heat pumps).		
1,3	Higher model accuracy, closing the performance gap in final annual energy balance.	90%	Mean absolute percentage error (MAPE). Accuracy = 1 – MAPE.	Model is based on combination of interrelations and forecasts. Using deep learning and neural networks, the model accuracy will improve on average.	PED Design and Planning Toolset	DE, CH, SL Energy
1,4	Reduction of design and engineering time	30%	According to E4TC study from RWTH Aachen, Engineering 4.0, under which the PEDvolution technologies fall, assumes 20% savings due to better exchange, 25% for schematic creation and additional 25% through automation of processes.	PEDvolution will employ gradual approach, exploiting on average 50% of each potential.	PED Design and Planning Toolset	DE, CH, SL Economic
1,5	Reduction of design and engineering cost	20%	Same as KPI1.4	Discounted for the required specialisations, costs of implementation and other transformations.	PED Design and Planning Toolset	DE, CH, SL Economic

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1,6	Number of supported PED planning processes	21	We include the demo cases from previous projects where the non-dynamic Decision Support Guideline was used as well as the demo cases of the PEDvolution project: syn.ikia, ARV, openLAB.	PEDvolution will include 8 additional processes (8 – including all demo developer and demonstrator candidates).	PED Design and Planning Toolset	DE, CH, SL Energy / Economic
1,7	Nº of different Dynamic Decision Support Guidelines	12	Number of context-climate definitions for a methodological implementation of the Dynamic Decision Support Guideline	PEDvolution project mentioned for the KPI above, results in 12 different guidelines. >6 applications of Decision support guidelines	Dynamic Decision Support Guideline	DE, CH, SL Energy / Economic
2,1	Use of identified waste heat to cover PED heat demand (normalised by PED heat demand)	20-30%	The heat is not used (waste heat).	PED design and planning tools will generate plans for waste heat recuperation, starting with high-impact sources. The planning will continue throughout implementation, generating additional recuperation designs.	PED Design and Planning Toolset	SL Energy / Environmental

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2,2	Increased interoperability of PED solutions, specifically integration of district heating and cooling grids with renovation scenarios and renewables	3 vectors	Individual planning scenarios for heating, cooling and renewable investments.	Interoperable planning tools will support holistic planning of different energy vectors and stakeholders.	PED Planning Toolset Dynamic Decision Support Guideline Data Exchange, Integration and Interoperability Platform	DE, SL Energy / Environmental
2,3	Decreased dependency on natural gas import, normalised by the PED energy requirement	0,05	83% of the natural gas is imported to EU. The ratio between heat and electricity in the local production is 60:40. Waste heat potential in industrial environment alone, without residential and tertiary buildings, ranges from 5% to 30% of the demand. Estimated potential for residential sector is estimated at 50% of industrial.	For every recuperated unit of heat, the dependency on natural gas for local CHPs is reduced by factor 2 (provided that surplus electricity is generated locally from RES).	PED Design and Planning Toolset	CH, SL Energy / Environmental / Economic
2,4	Non-exploited energy: Amount of energy (from different sectors)	0,1	Waste heat potential in industrial environment ranges from 5%	PEDvolution will approach the challenge from both fronts, identifying and	PED Design and Planning Toolset	DE, CH, SL Energy / Environmental

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	currently not recuperated – available for future investment		to 30% of the demand. Additionally, between 5% and 15% of energy can be saved through efficient management.	recuperating wasted energy in combination with advanced EMS.		
2,5	Cross-sector diffusion: Degree of optimisation results that influence more than 2 energy vectors. Normalised by overall dispatched energy.	0,05	Predominant sector-coupled assets are the cogeneration plants (CHP), where the usual ratio is 60% heat and 40% electricity. Those units are driven by one of the vectors – primary vector.	Through sector-coupled operation and advanced management, 5% - 15% of improvement can be achieved (e.g. storing excess in complementary process / storage).	PED Energy Manager	DE, CH Energy / Environmental
2,6	Improved accuracy of determining actual waste-heat potential	0,15	Current estimations based on temperature.	Improved estimations based on several factors (such as flow, multi-point temperature measurement, real-time collection, etc.) will greatly increase the estimation accuracy.	PED Design and Planning Toolset	SL Energy / Environmental
3,1	Reduction of PED peak demand: Highest peak in observed period before	10%	Experience from peak-shaving systems in industrial environment, reaching 10%	PED environment with local RES production can be comparable to installed power of medium	PED Energy Manager	DE, CH,SL Energy / Economic

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	and after PEDvolution		reduction of the peak demand.	industry. With growth of controllable assets and storage systems, the potential for peak reduction will increase.		
3,2	Share of flexibility offered for outside-PED services	10%	PEDvolution PEDs currently don't offer outbound services.	it is expected that 75% of the flexibility will be utilised internally (participation in energy community, peer-to-peer, portfolio optimisation) and 25% will be offered to outside buyers.	PED Energy Manager	DE, CH, SL Energy / Economic
3,3	No. of outside (grid, market) platforms integrated for service provision	12 (3x4)	No interoperability platform exists in the demonstrator PEDs.	Expected integration with 2-3 weather providers, 3x local flexibility market, 6x data provision systems (e.g. SCADA, local EMS) in the project. Expecting similar topology for each follower PED.	Data Exchange, Integration and Interoperability Platform	DE, SL Energy / Economic
3,4	Share of controllable assets within PED	20%	Based on Redispatch 2.0 data from Germany/SWW, the percentage	The initial assessment of demo sites shows possibilities to	PED Energy Manager	DE, CH, SL Energy / Economic

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			in power of controllable assets (above 100kW) in the pool of local PV production is 15%. In case of SWW, the total installed power of local PV is 16MW, out of which 2.5MW is integrated into control system.	integrate both sector-coupled units and local PV generation. The integrated assets will increase the KPI for 5 percentage points. It is expected that at least 50% of new assets in PEDs will be controllable and therefore available for value stacking, whereas the growth rate will be correlated to overall PV growth rate of 25%.		
3,5	No. of standard ontologies/data models supported	3	Data in PEDs is unstructured and in most cases not collected – available only at the process level.	Data will be transcribed and stored in standard data models, such as SAREF, CIM and FlexOffer within the project. These models are expected to gain importance in the future; therefore, the KPI value is expected to stabilise.	Data Exchange, Integration and Interoperability Platform	DE, CH, SL Energy / Economic
3,6	No. of different communication protocols supported	10	Protocols at the process level (e.g. MODBUS), protocols at the	Field-level assets will require dedicated	Data Exchange, Integration and	DE, SL Energy / Economic

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			IoT level (e.g. MQTT, Wifi, Zigbee), protocols at the platform level (e.g. HTTP REST, SOAP, Interoperability PlatformSec).	integration with supported protocols; PEDvolution tools will be integrated using standard and open protocols. Future assumption is harmonisation through standardised protocols (e.g. FlexOffer) and standards (e.g. SAREF), therefore, the KPI value is expected to normalise.	Interoperability Platform	
4,1	Average PED readiness improvement, per dimension	1 dim.	PED RA methodology will be developed during the PEDvolution project and will contain several categories (dimensions) for benchmarking PED.	All co-developer PEDs will improve at least 1 dimension of the KPI until the end of the project. In 3 years, 50% of the dimensions will be improved, in 7 years contribution on all dimensions is expected.	PED RA	DE, CH, SL Energy / Environmental / Economic / Social
4,2	Capability of each PEDvolution Co-developer demo area to produce energy necessary for	110%	Existing surplus (both utilised and not-utilised) available in local environments.	Increased local production based on the present growth rate of PV installations in the EU (25%	PED Managers	DE, CH, SL Energy / Environmental

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	one year by itself.			from 2021 to 2022); increased storage systems capable of long-term/seasonal storage (Hydrogen, biomass); additional export capabilities through waste energy utilisation.		
4,3	No. of PEDs actively implementing stakeholder engagement activities based on joint planning through the social innovation tool	3	Assumed to be zero as tool not available yet.	Minimum of 2 implemented activities per year will comply with the requirement for actively implementing. The baseline does not consider the possible already existing engagement methods, which will be assessed in the T1.1 community analysis. Increase is estimated based on the increasing expected number of PEDs in Europe for 2030 and the replication and exploitation plan	Social Innovation Tool	DE, CH, SL Social

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				to be implemented.		
4,4	No. people participating in engagement activities (consultations, co-creation, etc.) implemented by local actors as PEDs evolve.	Affected communities	Assumed to be zero.	As this figure depends strongly on the type and needs of each PED, the target will be set once we have developed the engagement plans at local level. The number should be increasing each year during and after the project.	Social Innovation Tool	DE, CH, SL Social
4,5	No. Social entrepreneurs interested and engaged in PED activities	8 (3+5)	Assumed to be zero.	The assumption is: there exists at least 1 interested social entrepreneur per each PED and assumes there is a linear growth in the engagement of the social entrepreneurs i.e., 8 (3+5).	Social Innovation Tool	CH Social / Economic
5,1	No. of trades (offers) performed within PED during observed period	24/d	Data from the UK IntraFlex market with 241 trades during 2-month period = 4 trades per day.	Due to automation and lower thresholds, the number of offers will be significantly higher – 1 offer per hour. The interval will be shorter in the future, expected	PED Energy Manager	DE, CH, SL Energy / Economic

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				15-min and then 1-min intervals.		
5,2	Energy and flexibility service provision - No. of different exploitation channels for PED assets / aggregates for the demonstrator PEDs	5	Currently, demo PEDs do not participate in any flexibility exploitation scheme.	Expected is participation in 3 local flexibility markets (intra-LEC market or congestion service for DSO) (1 per co-developer PED) + 1 energy / ancillary market (e.g. intra-day, Super-PED flexibility market) + internal PED exploitation. Expected is increased participation in established and new markets after the project.	PED Energy Manager	DE, CH, SL Energy / Economic
5,3	Number of business models per demonstration pilots	6	Currently there are no energy/flexibility business models in demonstration PEDs.	Each PED will construct 1 primary business model during the project. After the project, each replicator will create an additional model, while co-developers will assemble secondary business model. Further increase is estimated based on the	PED Business Models	DE, CH, SL Economic

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				increasing expected number of PEDs in Europe for 2030 and the replication and exploitation plans to be implemented.		
5,4	No. of market mechanisms integrated	4	Currently demo PEDs do not participate in any market.	Integration with 1 local flexibility market per PED and 1 established market (e.g. intraday). Later, integrating with ancillary markets and wholesale markets.	PED Energy Manager	DE, CH, SL Energy / Economic
5,5	Number of PED Readiness assessed PEDs	6	Currently no PED RA available.	All demos will be assessed and thus increase their participation in the value chain in the energy system. After the project, many PED RA will be done. In the beginning appr. 2 assessments per year, later 10 assessments per year.	PED RA	DE, CH, SL Energy / Economic / Social

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ANNEX II: REPORTING TEMPLATE

Revision history (including peer reviewing & quality control)

[Project** Solution **Test Report]	
Solution Name**:**	*[Name of Solution [and included tools]]*
Test	*[Very brief description of the test. E.g. Adaptation test]*
Version	*[Unique name. Maybe smt like toolID_version#]*
Date:	*[DD/MM/YYYY]*
Prepared by:	*[Author Name & Role]*
Performing Partner	*[Partner's name performing the test]*
Reviewed by:	*[Reviewer Name & Role]*

Overview

1. ***Site/Test environment description** [Where and how the tool is used (e.g., pilot site location, end-user context, operational environment)] (deployed tools, included HW&SW, architecture of the deployed solution, included/connected assets, external systems, etc. Some prerequisites).*
2. **Description:** *[Brief description of the testing (e.g., a tool, system, or service) and its functionality. And what functionality exactly are tested. Reference to other tests already executed, corrections, etc].*

Standards and Regulatory Alignment

Ensure the alignment with all applicable standards, guidelines, and regulations. Below is a table, serving as a checklist of relevant standards/protocols, with space to note how each is addressed:

Standard / Regulation	**Compliance Notes *(Relevance & how requirements are met)***
e.g. **ISO 52000-1:2013 (Energy performance framework)**	*[e.g., methodology for building energy performance applied in design]*

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e.g. **EN 16798-1:2019 (Indoor environmental criteria)**	*[e.g., indoor climate parameters (thermal, IAQ, lighting) set as per categories]*
e.g. **nZEB (Nearly Zero Energy Building standards)**	*[e.g., building meets nZEB energy performance target]*
e.g. **FlexOffer protocol (Energy flexibility)**	*[e.g., integrates FlexOffer format for demand-response]*

Relevant KPI

KPI ID	Description
KPI 1	*[Description of KPI]*
KPI 2	*[Description of KPI]*

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SAT (Site Acceptance Testing)

Site Acceptance Test (SAT) to validate that *[Tool's name]* operates correctly in the real environment and integrates with other systems. The testing aims to record the actual outcomes of each test, compare them against expected criteria, and note whether the acceptance criteria were met.

For each test conducted, document the results and evaluate them: all measured data and observations are recorded, and a pass/fail (with interpretations) status is assigned based on whether the acceptance criteria were satisfied. If any test outcome does not meet the expected criteria, note the deviation for follow-up.

1. **Test name/ID:** (provide detailed tests descriptions in multiple sections)
1. **Test description/plan:** [How a solution/tool, service, functionality will be tested. Complete procedure/steps. For example, a table with one or multiple tests-what exactly was tested and how. And relevant outputs of the tests.]. Could be something like this:
2. **Key Objectives:** *[List the main goals or performance targets of this tool]* (e.g., energy savings of X%, maintain thermal comfort per standard, ensure accessibility, etc.)
3. **Results**: [Provide results (visualisations, reports, tables, pictures, etc.)]

Test ID	**Test case**	**Objective**	**Test Procedure**	**Acceptance criteria**	**Actual result**	Pass/Fail
T1	e.g. User interface	e.g. The forms works properly to monitor & manage the loads	• Open operation form	Visual check according to the manual		
			• Open adaptation form			
			• Open settings form			
			• Open FAT test form			
T2	e.g. Load operation	e.g. Operation of load control commands	Use FAT test form: • Put each load out/into operation and check status	Visual check of statuses on GUI		

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Test ID	Test case	Objective	Test Procedure	Acceptance criteria	Actual result	Pass/Fail
T3	e.g. Flexibility generation	e.g. Flexibilities generation correctness	Use FAT test form: • Start the flexibility generation test. The control periodically puts the loads in and out of operation with the period 15 secs.	Visual check the change of flexibility capacity on GUI		
	e.g. Adaptation execution	e.g. Load adaptation correctness	Use FAT test form • Start partial adaptation test. The test triggers FOA to send adaptation request.	• Load goes into adaptation state		
				• Operation power is changed according to the test specification		
				• Adapted energy is within the prescribed tolerance		
			Use FAT test form • Start total adaptation test. The test triggers FOA to send adaptation request.	• Load goes into adaptation state		
				• Operation power is changed according to the test specification		
				• Adapted energy is within the prescribed tolerance		
	e.g. Adaptation	e.g. Put the load out of	Use FAT test form	• Load returns to normal operation		

Test ID	Test case	Objective	Test Procedure	Acceptance criteria	Actual result	Pass/Fail
	rejection test	adaptation by force	• Start Total adaptation test. • Press the adaptation abort on load settings form	• Operation power is changed to the level prior the adaptation		
				• the FAT test form confirms the sending of abort adaptation info to FOA		
	e.g. Stop Adaptation test	e.g. Error handling communication	Use FAT test form • Start total adaptation test. The test triggers FOA to send adaptation request. • Start adaptation cancellation test. The test triggers FOA to send adaptation cancellation info.	• Load returns to normal operation		
				• Operation power is changed to the level prior the adaptation		
Tx						
Ty						
Tz						

Deviations and Corrective Actions

If a test could not be executed as planned or if the **acceptance criteria were not met**, provide a clear description of the issue and how it was resolved (or how can be resolved). For each deviation, note the impact, the corrective measures, and the outcome of re-testing (if applicable).

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Deviation ID	Description of Deviation	Impact (Requirements affected)	Corrective Action (and Timeline)	Resolution Status
D1	*[Describe the deviation or test failure: which test, what went wrong]*	*[Impact on performance or compliance]*	*[Action taken to correct (e.g., software patch, component adjustment) and timeframe]*	*[Resolved after re-test / Pending]*
D2	*[Another deviation]*	*[...] *	*[...] *	*[...] *

Approval and Sign-off

All stakeholders should confirm that the testing produced results meeting the aims and objectives of the intended testing. The following checklist is to be completed before final sign-off:

- All **SAT (on-site)** tests have been performed and produced results
- All **SAT (on-site)** tests have been performed and addressed refinement measures (for second round testing)
- All noted deviations or deficiencies have been noted, re-tested, and closed out.
- The testing meets all defined performance metrics and key objectives (as specified in the **Overview**).
- Compliance with all relevant standards and regulations (listed in **Standards and Regulatory Alignment** has been confirmed.
- The report is accepted for use in the project environment and is ready for operation (initial and iteration).

Final Signoff: (Each responsible party to sign, indicating review and acceptance)

Role	Name	Signature	Date
[Role 1] **(e.g., Tool Owner)**	*[Name]*		
[Role 2] **(e.g., PED Manager)**	*[Name]*		
[Role 3] **(e.g., WP Leader)**	*[Name]*		
[Additional signoffs if needed]	*[Name]*		

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ANNEX III: THE PEDVOLUTION SOLUTIONS

1. PED Design and Planning Toolset

PED Design and Planning Toolset is a solution designed to support informed decision-making for PED planners. These tools empower developers and managers of PEDs to expedite the development process towards achieving or enhancing a PED:

- Utilise precise energy models to create renovation pathways for District Heating and Cooling (DHC) grids tailored to local conditions.
- Propagate uncertainty to minimise planning risks and enhance the robustness of PEDs.
- Facilitate informed decision-making by providing evidence-based insights to PED developers and managers.

The PED Design and Planning Toolset provides dual functionality, offering a comprehensive assessment of the current state while charting a detailed roadmap for future development. It delivers insights into the breakdown of final energy consumption, evaluates emissions, and conducts economic analyses of the existing conditions, including fuel types, energy costs, and Operational Expenditure (OPEX). The tool also visualises buildings and district assets, highlighting their energy performance and exchange capabilities, alongside structured data on their current status. Building on this foundation, the toolset guides users through a step-by-step roadmap for development, offering renovation advice, phased implementation strategies, and scenario planning for DHC systems, including grid expansion and optimisation of future supply portfolios. It evaluates potential assets and technologies, such as renewable energy generation and Electric Vehicle (EV) integration, alongside their impacts. Additionally, the tool provides financial analyses, covering both CAPEX and OPEX, and incorporates uncertainty analysis to ensure robust planning and effective risk mitigation across various scenarios, supporting sustainable and evidence-based PED development.

1.1 Digital Twin Planning Tool

The DT planning tool is aimed to facilitate PED planners and managers by providing a detailed overview of both the current state and future energy scenarios of the buildings. It helps planners evaluate various renovation strategies and energy transition pathways, ensuring that they make informed decisions about the district's overall energy, environmental, and economic performance. Simultaneously, the tool also serves building users and owners by offering specific insights into their building's current energy performance and recommending tailored renovation measures. These insights include detailed projections of energy savings, environmental benefits, and cost impacts for each building. This dual functionality ensures that both district-wide objectives and individual building improvements are aligned to maximise the overall energy efficiency and sustainability of the PED.

1.2 PED District Heating and Cooling Planning Tool

The PED District Heating and Cooling (DHC) Planning Tool developed in this project will enable comprehensive assessment and optimisation of DHC systems within PEDs. It will assess the potential for DHC infrastructure by analysing current conditions and future development pathways, including building renovation plans – which are devised by the PED Renovation Planning Tool – and demand densities. The tool will optimise implementation and investment pathways, integrating locally available Renewable Energy Sources (RES), excess heat, and storage options, while determining the optimal grid

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temperature levels for PEDs' low-energy demand profiles. It will also account for uncertainties such as energy price fluctuations and policy changes, using scenario analysis to ensure robust planning.

2. PED RA

The PED RA Framework gathers data on demos current status and various PEDvolution solutions. This includes information four dimensions concerning market, social, technology, and interoperability (the PEDvolution phenotypes) are as follows:

1. The market dimension focuses on the economic viability and business models that support the development and operation of PEDs. It includes financing, investment, and revenue generation mechanisms, as well as market incentives that encourage the adoption of RES and energy-efficient technologies.
2. The social dimension emphasises community engagement and the social acceptance of PED initiatives. It involves ensuring that the benefits of energy efficiency and renewable energy are equitably distributed among residents, promoting social cohesion, and enhancing the quality of life. Participation of local stakeholders in decision-making processes is also crucial in this dimension.
3. The technology dimension addresses the technological innovations required for the effective functioning of PEDs. It encompasses the integration of smart energy systems, renewable energy technologies, energy storage solutions, and advanced grid management systems. The focus is on creating a resilient and flexible energy infrastructure that can adapt to changing energy demands.
4. The interoperability dimension involves the seamless integration of different systems and technologies within a PED. This includes communication between various energy sources, building management systems, transportation networks, and information and communication technologies (ICT). Effective interoperability ensures that these systems can work together efficiently, optimising energy use and enhancing overall performance.

These dimensions collectively contribute to the successful implementation and sustainability of PEDs, promoting a holistic approach to urban energy management. It must thus be based on a comprehensive set of KPIs as outlined in T2.2. A set of 243 KPIs has been published and is currently being tested.

3. Dynamic Decision Support Guideline for PED Development

The DDSG for PED Development enhances and refines PEDvolution solutions by analysing real-time data on energy demand, costs, geospatial factors, and legislative frameworks. It enables PED planners to generate scenarios that integrate various technologies, energy requirements, and financial constraints, while simultaneously assessing their social, economic, and environmental impacts.

Unlike static frameworks, the DDSG offers a dynamic and interactive platform that adapts to evolving technologies, markets, policies, and social contexts. This tool empowers PED planners and solution providers by offering customised decision support tailored to local conditions and changing circumstances. It facilitates scenario-based exploration of development pathways, equipping decision-makers with up-to-date insights into the performance, interoperability, and trade-offs of different solutions.

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The DDSG process begins by gathering data on the demonstration's current status through the PED RA Framework and various PEDvolution solutions. This includes information on energy demand, generation, storage, prices, financing, geospatial factors, legislation, and business models. Once collected, these inputs are formatted according to the KPIs used by the DDSG. Through a User Interface (UI), PED Planners set their goals and preferences, which the DDSG uses to generate alternative development scenarios, analysing their technological, economic, social, and environmental impacts.

The generated scenarios are presented to PED Planners via the UI, displaying key metrics such as energy balance, emissions, costs, and flexibility indicators. This allows planners to compare trade-offs, such as energy renovation vs. new infrastructure investment, ensuring informed decision-making. Since PED conditions evolve over time, planners can reassess and adjust their preferences, prompting the DDSG to generate new scenarios dynamically. This iterative process enables data-driven, adaptive PED development, ensuring optimal performance, sustainability, and risk reduction.

4. PED Energy Manager

The PED Energy Manager is an advanced solution designed to holistically optimise and manage energy assets within PEDs. It integrates and coordinates various energy assets, including flexible assets across industrial, commercial, and household sectors, to enhance their flexibility and support the overall energy optimisation of PEDs. It enables sector coupling, allowing the coupled management of different energy systems like electrical and thermal sectors, and makes diverse assets adaptable to support the needs of PEDs. Additionally, PED Energy Manager systems deployed across multiple PEDs can be interconnected to form collaborative networks, such as sister PEDs or hierarchical structures like parental PEDs. These interconnected PEDs can share resources and operational insights, improving efficiency and resilience across the entire network, with the PED Energy Manager controlling and coordinating these processes to ensure global optimal performance.

Key functionalities include:

- Real-time Monitoring and Control: Integrates data from various sources to monitor PED assets and dynamically manage energy flows.
- Demand Response and Flexibility Management: Assesses and utilises energy flexibility to adjust operations based on demand and supply conditions.
- Prediction and Optimisation: Predicts future operations and adjusts in near real-time to optimise energy use across multiple sectors.
- User Engagement: Provides a user-friendly interface for PED residents to monitor and manage their energy use while receiving performance feedback.

5. Data Exchange, Integration and Interoperability Platform

The Interoperability Platform will establish robust mechanisms to achieve both semantic and syntactic interoperability, enabling secure and frictionless data exchanges between PEDvolution solutions, IoT platforms, and connected devices within the PED ecosystem. To accomplish this, the platform will be implemented as a Data Space – a decentralised architecture designed to facilitate trusted data sharing and collaboration amongst diverse stakeholders. This approach will ensure that all data transactions between systems adhere to strict security standards, while appropriate privacy measures will be enforced when processing sensitive information.

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To support its core functionalities, the Data Space will provide mechanisms for organising and cataloguing available offerings of data and services, ensuring that stakeholders can easily discover and access relevant resources. Secure authentication and access control mechanisms will enable regulating data availability and maintaining a trusted exchange environment. Additionally, the Data Space will incorporate adaptable interfaces and data exchange mechanisms to facilitate interoperability across different systems, allowing for necessary transformations and processing to meet diverse technical requirements.

6. PED Business Model Innovation Tool

The PED Business Model Innovation tool builds business model approaches which are relevant for community-based energy systems. Its primary objective is to create a typology of various business model options or building blocks for PED (PEDs), tailored to the PEDvolution context while also being adaptable for other PEDs in general.

The tool comprises a structured co-development and co-validation process designed to provide PEDs with adaptable business model patterns through three key phases: Adaptation, Implementation, and Validation.

1. Adaptation Phase: This phase focuses on adapting the E-LAND community-based business model innovation tool to meet the specific needs of PEDs. The tool will provide a set of building blocks, known as 'business model patterns,' that have been proven effective in community-based business solutions. These patterns will be customised using additional tools such as the Value Proposition Tool, Force Field Analysis, and SWOT Analysis to understand the pains and gains, as well as the driving and restraining forces for individual PEDs and their integrations. The aim is to formulate the first set of business model patterns tailored to the PEDvolution context while ensuring flexibility for wider application.

2. Implementation Phase: During this phase, the co-development process actively involves PEDvolution demonstration sites, leverage the outcome from the integration of various tools, and technology developers. The business model patterns will be fine-tuned through a series of workshops aimed at co-developing tailored business models for each site. This process follows a step-by-step approach, starting with the initiation phase, which focuses on identifying and understanding local challenges and opportunities. This is followed by the ideation phase, where innovative business model options are generated, and the integration phase, which combines and adapts business model patterns to fit local contexts. Finally, the implementation phase applies the tailored business models to PEDs with active stakeholder (focusing on business model) involvement. Feedback gathered throughout this process will be used to enhance the design of the BMI Tool, ensuring it effectively addresses the specific needs and opportunities within local contexts.

3. Validation Phase: In the final phase, the developed business models will be co-validated by actively engaging PED managers and relevant stakeholders and gather quantifiable project consequences from the use cases tested and measured KPIs. This phase also involves assessing economic viability, assess users-acceptance, investigating barriers including regulations, and investigate the potential for the involvement of social entrepreneurs. In line with the PEDvolution business model process, the co-validated business models will be adaptable which will promote various sustainable PED tools and solutions.

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7. Social Innovation Tool

PED social innovation tool is a methodology that provides guidance for understanding stakeholders within PEDs and addressing the multiple needs and priorities of them. PEDs can be seen as business ecosystems with multiple participants, yet at the same time, PEDs are home to a number of people whose daily life may be influenced by the planned action. In this context, stakeholder alignment, engagement, and social innovation are key elements in building long lasting social acceptance of local energy initiatives.

The SI tool involves a four-phase process, with guidance available for each phase. The phases include; Community/ ecosystem scoping phase to identify relevant stakeholders and to collect information about their views, analysis phase to summarise the findings and to co-create action plans for incorporating stakeholder views into the project activities, implementation phase to address identified barriers through the co-created action plans, and an assessment phase to evaluate the success and refine activities if need be. Each of the steps is accompanied by tools and methodologies to support the implementation.

All in all, the SI tool is expected to support the planning and operation of PEDs through multiple stakeholder alignment, and support to decision-making and stakeholder engagement within PEDs as they evolve.

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