PEDvolution

Interoperable solutions to streamline
PED evolution and cross-sectoral integration

Deliverable 7.3

Data Exchange Platform and Connection with EU Data Spaces

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Glossary of terms and abbreviations used

ABBREVIATION / TERM	DESCRIPTION
IDSA	International Dataspace Association, https://internationaldataspaces.org/
EDC	Eclipse Dataspace Components, https://projects.eclipse.org/projects/technology.edc
IEC	International Electrotechnical Commission, https://www.iec.ch
OMEGA-X	Omega-X – Orchestrating an interoperable sovereign federated Multi-vector Energy Data Space built on open standards and ready for GAia-X
CIM	Common Information Model
PED	Positive Energy District
SAREF	Smart Applications REFerence
SAREF4ENER	SAREF extension for Energy Flexibility
SAREF4CITY	SAREF extension for Smart City
Energy ADE	Energy Application Domain Extension
CSDM	Common Service Data Model, https://fz-hannou.github.io/Omega-X/
QUDT	Quantities, Units, Dimensions, and Types, https://qudt.org/
REC	Real Estate Core
CSV	Comma-Separated Values
JSON	JavaScript Object Notation
GeoJSON	Geographic JavaScript Object Notation, https://geojson.org/
MVD	Minimum Viable Dataspace, https://github.com/eclipse-edc/MinimumViableDataspace
RDF	Resource Description Framework
FTP/FTPS	File Transfer Protocol / File Transfer Protocol Secure
HTTPS	Hypertext Transfer Protocol Secure

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MQTT	Message Queuing Telemetry Transport
TCP	Transmission Control Protocol
VPN	Virtual Private Network
RESTfull API	Representational State Transfer Application Programming Interface
API	Application Programming Interface
JWT	JSON Web Token
JSON-LD	JSON for Linking Data
DIDs	Decentralised Identifiers
VCs	Verifiable Credentials
GA	Grant Agreement
WP	Work Package
CCS	Combined Charging System
CHAdeMO	A fast-charging standard for electric vehicles (EVs) originally developed in Japan
SAE J1772	Is a North American standard for electrical connectors for electric vehicles
IEC 62196	Is an international standard series that defines the physical plugs, sockets, vehicle connectors, and inlets used for conductive EV charging
GeoSPARQL	Open Geospatial Consortium (OGC) standard, https://www.ogc.org/standards/geosparql/

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EXECUTIVE SUMMARY

Deliverable D7.3 presents the final implementation, validation, and deployment of the PEDvolution Data Exchange Platform, establishing a fully operational dataspace-enabled interoperability infrastructure for secure and sovereign data exchange across Positive Energy Districts (PEDs) and Solution Tools.

The platform enables interoperable, policy-driven data sharing between PEDs and Solution Tools, while supporting integration with the European Data Space ecosystem through federation mechanisms and the OMEGA-X [1] marketplace. Its operational readiness and applicability in real PED environments will be further assessed through real-world demonstrators in Work Package 9 (WP9 – Demonstrators and Performance Assessment).

Building on the architectural design defined in D7.1 (*Data Exchange Platform Design*) [2] and the energy market mechanisms introduced in D7.2 (*Energy Market Mechanisms*) [3], this deliverable focuses on the technical realisation and operational validation of the platform. It documents the integration of datasets, services, and tools developed in Work Packages 3–5 and demonstrates alignment with key European frameworks, including IDSA [4], Gaia-X [5], and the Eclipse Dataspace Components (EDC) [6].

The PEDvolution Interoperability Platform adopts a dataspace-by-design approach, enabling:

- Cross-sector data exchange across platforms and systems within the PED ecosystem, supporting interoperable interactions between PEDs and Solution Tools.
- Data-driven decision-making for PED management.
- Participation in energy markets at PED and Super-PED levels.
- Secure, policy-controlled data sharing in line with EU Data Space principles.

The implementation follows a modular and scalable architecture, combining:

- Eclipse Dataspace Components (EDC) [6] for contract-based data exchange.
- A Common Information Model (CIM) for semantic interoperability.
- The integration of WP3–WP5 Solution Tools and pilot assets through the Interoperability Platform.
- An API-based abstraction layer for simplified integration.

The platform integrates heterogeneous data sources, including building systems, smart devices, photovoltaic installations, energy storage systems, EV charging infrastructure, and simulation tools. Semantic interoperability is achieved through the PEDvolution CIM, aligned with established standards such as SAREF [7], BRICK [8], Energy ADE [9], CSDM (OMEGA-X) [10], Smart Data Models [11], QUDT [12], and relevant geospatial [13] specifications, while also incorporating domain-specific models, such as SAREF4CITY [14], UNIT [15], and REC [16].

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Security and trust constitute core design principles of the platform, implemented through:

- Token-based authentication and authorisation.
- Policy-driven access control.
- Secure HTTPS communication.
- Network-level isolation of critical components.

These mechanisms ensure compliance with key requirements of confidentiality, integrity, availability, and data sovereignty.

Validation activities demonstrate the operational maturity of the platform, including:

- Integration of Solution Tools and real PED assets.
- Execution of end-to-end data exchange workflows.
- Successful federation with external data spaces via the OMEGA-X marketplace.

These validation activities are closely linked to WP9 (PEDvolution demonstrators and performance assessment), where the platform will be deployed and evaluated in real PED environments through demonstrators. These activities will provide the operational context for testing interoperability workflows, validating data exchange mechanisms, and assessing platform performance under real-world conditions.

The integration with OMEGA-X enables PEDvolution to operate as a federated participant in the European Data Space ecosystem, supporting cross-dataspace interoperability and marketplace-based data sharing.

Main Conclusions:

- PEDvolution has successfully implemented a fully operational, dataspace-enabled interoperability platform, establishing the dataspace paradigm as the project's foundational mechanism for secure and sovereign data exchange across PEDs.
- The Eclipse Dataspace Components have been validated as the selected dataspace technology, supporting contract-based sharing, policy enforcement, identity management, and federation with external ecosystems.
- The platform's multilayer architecture, combined with the PEDvolution Common Information Model, ensures semantic consistency and interoperability across heterogeneous data sources, Solution Tools, and pilot infrastructures.
- End-to-end integration and validation activities confirm the technical maturity and scalability of the platform for real-world deployment.
- The successful federated connection with OMEGA-X demonstrates compatibility with emerging European Data Space initiatives and provides a solid foundation for replication, extension, and long-term sustainability.

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Overall, Deliverable D7.3 confirms that the PEDvolution interoperability infrastructure is robust, future-proof, and fully aligned with EU Data Space principles, enabling Positive Energy Districts to actively participate in a federated European energy data ecosystem.

1 INTRODUCTION

Deliverable D7.3 presents the complete design, implementation, and validation of the PEDvolution Data Exchange Platform, establishing a fully operational dataspace-enabled interoperability infrastructure for secure and sovereign data exchange between Positive Energy Districts (PEDs) and Solution Providers (Tools).

Building on the conceptual and architectural foundations defined in D7.1 [2] (Data Exchange Platform Design) and the market-oriented mechanisms introduced in D7.2 [3] (Energy Market Mechanisms), this deliverable finalizes the technical realisation of the dataspace-enabled data exchange mechanisms and integration middleware usable across all Positive Energy District (PED) pilots and Solution Providers. It consolidates the work carried out in WP7 to implement a robust, scalable, and standards-based interoperability layer that enables secure and consistent exchange of energy data between PEDs and Solution Providers.

D7.3 also details the technical interfaces that enable seamless integration with the Solution Tools developed in WP3 (PED Design and Planning Toolset), WP4 (PED Readiness Assessment), and WP5 (PED Energy Manager), ensuring that all analytical, decision-support, and control components can reliably access data produced in PEDs. The deliverable is further supported by validation activities planned in WP9, where the PEDvolution Interoperability Platform will be evaluated through real-world demonstrators. These activities are expected to validate the developed interoperability mechanisms under realistic operational conditions. Furthermore, the deliverable describes how the Interoperability Platform incorporates and aligns with European Data Space principles, particularly through the adoption of dataspace technologies, to enable sovereign, interoperable, and federated data exchange beyond the project's internal ecosystem.

Overall, the deliverable documents the finalised system architecture, integration approach, and technologies deployed to operationalise the PEDvolution Interoperability Platform, supporting both project-internal workflows and future interactions with external data ecosystems. This positions PEDvolution as an active contributor to the European Data Space ecosystem, enabling interoperability beyond the project scope.

1.1 Mapping Project's Outputs

Table 1 summarises how the content of this document corresponds to the project's GA expectations:

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

PROJECT GA COMPONENT TITLE	PROJECT GA COMPONENT OUTLINE	RESPECTIVE DOCUMENT CHAPTER(S)	JUSTIFICATION
DELIVERABLE			
D7.3	Integration of the services developed in: • WP3, PED design and planning tool	Chapters 2-5	D7.3 implements and validates the PEDvolution Interoperability Platform as an integration of

	• WP4, PED Readiness Assessment • WP5, PED Energy Manager via the integration of middleware. Seamless access to data and control plane and enablement of market participation at PED or Super PED level. Extension of an open-source connector (e.g. Eclipse, IDSA) and the supporting federation infrastructure enabling interlink with Energy Data Spaces. Utilisation of OMEGA-x project's marketplace as a reference case study for integration (T7.3 and T7.4)		middleware enabling secure and seamless data exchange across PEDs and Solution Providers. It supports the integration of services developed in WP3-WP5, facilitating interoperability and enabling participation in energy markets at PED and Super-PED levels. Chapter 2 presents the PEDvolution Common Information Model (CIM), which provides the semantic foundation for harmonising heterogeneous PED data and enabling interoperable data exchange between PEDs and Solution Providers. Chapter 3 describes the architecture, API layer, security mechanisms, and dataspace-based implementation of the Interoperability Platform. Chapter 4 focuses on the integration of PEDvolution Solution Providers and PED assets through the interoperability platform, including the validation of end-to-end interoperable data exchange workflows. Chapter 5 presents the connection with external EU Data Spaces through federation mechanisms aligned with IDSA and Gaia-X principles, together with the integration of the OMEGA-X marketplace as a reference implementation. Finally, the platform will be further validated through the real-world demonstrators in WP9, where its technical maturity, robustness, deployment readiness, and capability to support scalable data exchange across multiple data spaces will be assessed.

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TASKS			
T7.1 Integration of Smart Homes and Buildings and Grid Infrastructure	Task 7.1 Integration of Smart Homes and Buildings and Grid Infrastructure provide an abstraction layer of assets in the PED, enabling transparent data exchanges and enabling system's extensibility (D7.1). Standard information models will be analysed (e.g. SAREF, CSDM) for the creation of a common information model. During this task, the different platforms/systems/devices of the PED ecosystems integrated via a cross-sectorial data exchange platform.	Chapters 2-4	Chapter 2 presents the PEDvolution Common Information Model (CIM), developed based on the data requirements identified in D1.3 System Architecture and Technical Specifications. The CIM defines harmonised data models covering key PED domains and supports semantic interoperability across heterogeneous systems. Chapter 3 documents the architecture and design of the PEDvolution Interoperability Platform, including the abstraction layer that enables the integration of smart homes, buildings, and grid infrastructure within a cross-sectorial data exchange environment through standardised APIs. Chapter 4 (Section 4.2) details the integration of heterogeneous PED assets, describing how real-world data sources, aligned with the CIM, are exposed through the Interoperability Platform, thereby enabling interoperable data exchange across PED systems and Solution Providers.
T7.3 Services integration	This task concerns integration of the services developed in WPs 3, 4, 5 via the integration of middleware enabling on one hand seamless access to the data and control plane, on the other, enabling market participation at PED or Super PED level. ICOM will lead the task with all service providers contributing (D7.3). The C&D&E (WP 10-12) will leverage the service integration benefits and incorporate them into the business model and social innovation impact assessment.	Chapters 3-4	Chapter 3 presents the implemented integration framework of the PEDvolution Interoperability Platform, including standardised APIs and data exchange workflows supporting data discovery and consumption by Solution Providers. It further describes the mechanisms for catalogue querying, contract negotiation, and secure data retrieval. Chapter 4 (Section 4.1) demonstrates the integration of

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			WP3, WP4, and WP5 services, enabling Solution Providers to discover, access, and consume PED data through policy-based access control mechanisms, ensuring interoperable and secure data exchange.
T7.4 Connection with EU Data Spaces	This task aims to provide the mechanisms for enabling data and services of the project to be exposed as interoperable offerings in the EU Data Space Ecosystem. During this task ICOM extends an open-source connector (e.g. Eclipse, IDSA) and the supporting federation infrastructure (i.e. federation services) enabling interlinks with Energy Data Spaces. OMEGA-x project's marketplace will be utilized as a reference case study for integration.	Chapter 5	Chapter 5 defines the mechanisms for exposing PEDvolution data and services as interoperable offerings within the European Data Space ecosystem. It presents the adoption of Eclipse Dataspace Components (EDC) and federation mechanisms aligned with IDSA and Gaia-X principles. It also documents the integration with the OMEGA-X marketplace as a reference case, demonstrating cross-dataspace interoperability and enabling federated data discovery and policy-based data access.

1.2 Deliverable Overview and Report Structure

This deliverable consolidates the work carried out in WP 7 to design, implement, integrate, and validate the interoperability infrastructure enabling secure, sovereign, and standards-based data exchange across Positive Energy Districts (PEDs), Solution Providers (Tools), and external data ecosystems.

The integration and interoperability approach and specifications presented in this deliverable aim to facilitate the alignment of all solutions developed in the implementation Work Packages (WP3, WP4, and WP5), as well as the interactions between different stakeholders and secure access to data produced by PEDs. In this context, interoperable interfaces for integrating PEDvolution solutions and PED assets have been designed and implemented within Tasks T7.1 (Integration of Smart Homes and Buildings and Grid Infrastructure) and T7.3 (Services Integration). Additionally, federation services developed under Task T7.4 (Connection with EU Data Spaces) enable the exposure of PEDvolution data and services beyond the project. The energy market mechanisms developed in Task T7.2 (Market Integration) are reported separately in Deliverable D7.2 and are therefore referenced but not further detailed in this document. As a result, D7.3 presents the final data exchange platform prototype, including integrated PEDvolution solutions, access to PED assets, and established federation capabilities with external European Data Spaces. The platform will be further validated through real-world demonstrators in WP9, where its operational readiness and performance under real PED conditions will be assessed.

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Deliverable D7.3 builds upon the conceptual and architectural foundations established in D7.1 Data Exchange Platform Design, which defined the initial interoperability architecture and Common Information Model, as well as D7.2 Energy Market Mechanisms, which documented the interfaces and mechanisms for energy market participation. It consolidates and finalises these developments by presenting the implemented system architecture, the integration of services and pilot assets, and the operationalisation of dataspace technologies enabling federation with European Data Spaces.

Below is an outline of the report structure:

- **Chapter 1, Introduction,** presents the objectives of Deliverable D7.3, its relevance within the PEDvolution project, and its alignment with Grant Agreement expectations. It defines the scope and purpose of the deliverable, outlines its contribution to the overall project objectives, and maps its connections to related project outputs and deliverables.
- **Chapter 2, Overview**, describes the methodological approach followed for the implementation of the Data Exchange Platform. It presents the PEDvolution Common Information Model (CIM), developed to achieve semantic interoperability among heterogeneous PED data sources and Solution Tools.
- **Chapter 3, PEDvolution's Interoperability Platform,** details the finalized system architecture of the platform, structured into functional, implementation, deployment, and process layers. It documents the adoption of dataspace technologies, the Eclipse Dataspace Components, security and policy enforcement mechanisms, and the connection with external European Data Spaces, including the OMEGA-X marketplace.
- **Chapter 4, Assets and Services Integration,** presents the integration of Solution Tools developed in WP3, WP4, and WP5 with the Interoperability Platform. It further describes the onboarding of pilot assets, data ingestion mechanisms, and the APIs enabling secure querying and consumption of PED data.
- **Chapter 5, Integration with other EU Data Spaces**, presents the integration of the PEDvolution Interoperability Platform with external EU Data Spaces, highlighting the connectivity of its dataspace infrastructure through federation mechanisms and the OMEGA-X marketplace, enabling cross-dataspace data exchange and interoperability.
- **ANNEX XIV** elaborates the security and privacy requirements of the PEDvolution project, based on the work carried out in WP1 (D1.2 – Functional and Operational Requirements of the Demo Sites and Reference Use Cases and D1.3 - System architecture and technical specifications), considering also the guidelines provided by the first periodic review of PEDvolution. These requirements are reflected in the design and implementation of the PEDvolution Interoperability Platform, as described in Chapter 3, including the Security Architecture and Network Isolation (Section 3.1.3.4), Authentication and Security (Section 3.2.3), Trust Flow and Identity-Based Access Control (Section 3.1.4.5), Participant Onboarding Identity and Trust Establishment (Section 3.1.4.4) ensuring secure, policy-compliant, and privacy-aware data exchange.

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2 PEDVOLUTION COMMON INFORMATION MODEL (CIM)

Semantic interoperability plays a central role in the PEDvolution data exchange infrastructure. As defined in Deliverable D7.1, a Common Information Model [19] was developed to provide a unified and semantically consistent representation of PED data across all project components. In D7.3, this CIM has been finalized and operationalised as the reference data model for all data exchanges through the Interoperability Platform.

The CIM ensures a shared and consistent understanding of the Positive Energy District (PED) ecosystem by providing a unified structure and common vocabulary for describing data produced and exchanged within the PEDvolution ecosystem. It constitutes a key enabler of both syntactic and semantic interoperability across PED pilots and Solution Tools.

From a semantic perspective, the CIM defines the meaning of data elements and their relationships, establishing a shared conceptualisation of PED-related entities, assets, and processes. This semantic layer is formalised through the PEDvolution Semantic Data Model (presented in Deliverable 7.1, Data Exchange Platform Design, Chapter 4), which captures the concepts, attributes, and relationships required to support cross-domain data exchange and interpretation.

From a syntactic perspective, the CIM specifies common data structures and representations to ensure that exchanged data conforms to a shared schema and format. Syntactic interoperability leverages widely accepted data formats such as JSON, GeoJSON, and CSV, ensuring compliance with agreed syntactic rules during data exchange. This combined semantic–syntactic approach reduces integration complexity and enhances scalability across the PEDvolution data sharing ecosystem.

2.1 Design and Methodology

The design of the PEDvolution Common Information Model followed an iterative and requirements-driven process. During the course of the project, and through detailed technical discussions involving PED pilots and Solution Providers from WP3–WP5, it was recognised that the CIM needed to address a broader and more structured set of energy-related domains to fully support interoperability between PEDs and Solution Providers.

To systematically collect inputs and validate assumptions, an Excel-based questionnaire was distributed through the project's repository, to PED pilots and Solution Tool Providers. This questionnaire was used to gather structured feedback on the relevance, structure, and granularity of the identified energy domains, as well as on the required attributes, data availability, and expected usage of each domain. The feedback received through this process was incorporated into successive iterations of the CIM design, ensuring that the model reflects both pilot-specific realities and Solution Tool requirements.

As illustrated in Figure 1, the methodology consists of successive cycles of refinement, where input from project partners is systematically incorporated to enhance domain coverage and ensure alignment with real-world data requirements. This iterative approach enabled the progressive evolution of the CIM, ensuring its applicability and consistency across heterogeneous PED environments, while supporting interoperable data exchange between PEDs and Solution Providers.

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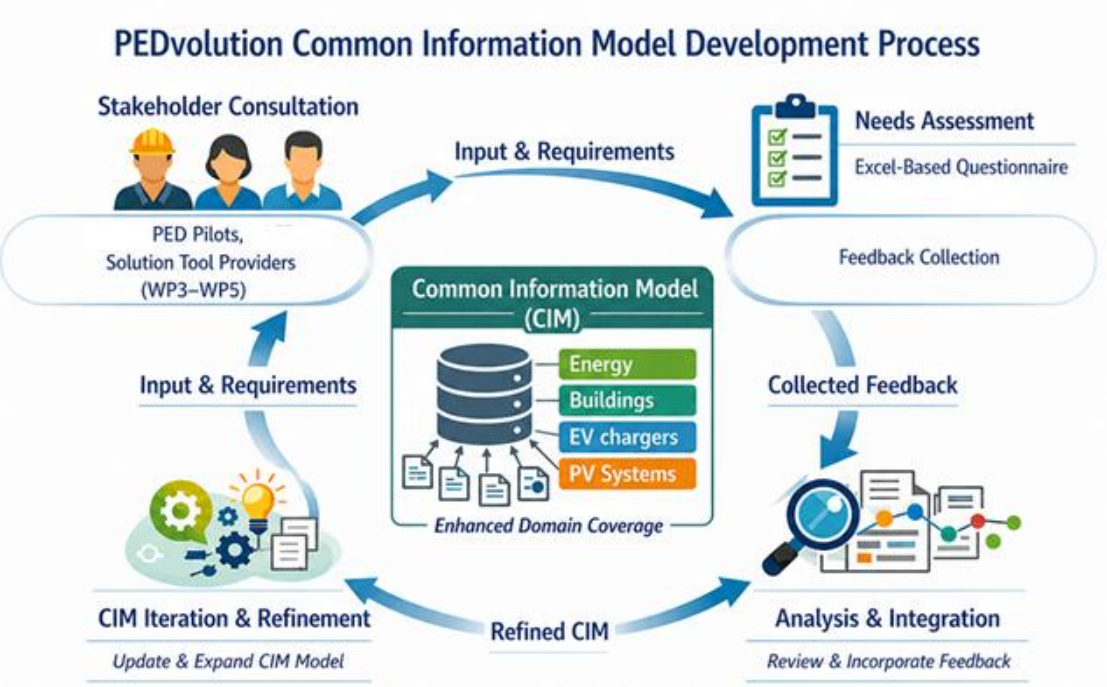


Figure 1: PEDvolution CIM development lifecycle through stakeholder-driven iteration and refinement.

As a result of this iterative and collaborative design process, the PEDvolution CIM was structured to encompass a comprehensive set of key energy domains, hereafter referred to as characteristics, as illustrated in the Figure 2.



Figure 2: Overview of the PEDvolution Common Information Model, illustrating the key energy domains and characteristics that enable a holistic and interoperable representation of PED environments.

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These characteristics were identified as essential to enable comprehensive data exchange across PED pilots and Solution Providers and to support the analytical, optimisation, and forecasting functions of the Solution Tools. The CIM design ensures that each characteristic is semantically well-defined and interconnected, enabling cross-domain analysis and integrated energy management at district level. Where possible, the CIM design was aligned with established ontologies and data models, including SAREF, SAREF4CITY, BRICK, REC, Energy ADE, CSDM, Smart Data Models, and relevant Geospatial specifications, in order to maximise interoperability with external systems and European Data Spaces.

The Common Information Model (CIM) specifies the structure and semantics of the datasets produced by PEDs, ensuring that all data follows a common and consistent format. Data provided by different PEDs is structured according to the CIM before being made available for consumption. This allows the data to be consistently interpreted and processed by Solution Tools, regardless of the underlying systems or technologies used by each PED.

The CIM further supports interoperability workflows by ensuring consistency across all stages of data exchange. During data access, CIM-compliant data structures enable retrieved datasets to be seamlessly interpreted and processed by Solution Tools without additional transformation. This facilitates end-to-end interoperability, from asset registration and discovery to data consumption within the PEDvolution dataspace.

The development and validation of the PEDvolution Common Information Model were supported by established semantic modelling and data validation tools. The ontology was designed, implemented, and validated using Protégé tool [20], enabling consistency checking and semantic verification. JSON-based data representations were validated using online tools (e.g. https://jsonformatter.org/) to ensure syntactic correctness and structural consistency. Furthermore, GeoJSON datasets were validated using tools such as https://geojson.io/, supporting both structural validation and visual inspection of geospatial information.

2.2 Lessons Learned from CIM Development and Data Harmonisation

The development and harmonisation of the PEDvolution Common Information Model proved to be a complex and iterative process, requiring continuous alignment between PED pilots and Solution Providers. The definition of harmonised data formats, was not straightforward and evolved through extensive collaboration and feedback across project partners. The final data formats represent the outcome of this collaborative effort, balancing the requirements and constraints of both data providers and data consumers. In several cases, PED pilots already maintained existing data structures, requiring Solution Providers to adapt their tools and data ingestion pipelines accordingly. Conversely, some Solution Providers had pre-defined data format requirements, which necessitated adjustments and transformations on the side of the data providers. To ensure correctness and interoperability, JSON and GeoJSON data formats were systematically validated using online validation tools (e.g. https://jsonformatter.org/ and https://geojson.io/), supporting both syntactic validation and structural consistency.

The experience gained during this process also provides valuable insights for the onboarding of new PEDs. A clear definition of data models, validation procedures, and agreed data formats significantly

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facilitates the integration of additional participants, reducing onboarding effort and accelerating interoperability with existing Solution Tools.

Overall, the CIM development process highlighted the importance of flexibility, iterative design, and close collaboration between stakeholders to achieve a harmonised and interoperable data model across heterogeneous environments. These lessons can inform future standardisation efforts and support the scalable expansion of the PEDvolution ecosystem.

2.3 Common Information Model Structure

To ensure scalability and flexibility, the CIM is structured into multiple conceptual layers, each addressing a specific aspect of the PED ecosystem:

1. District Layer (PED level) – describes the Positive Energy District as a whole.
2. Building Layer – describes buildings belonging to the district.
3. Asset Layer – describes energy systems and technical characteristics.
4. Operational Layer – describes measurable values (energy vectors, prices).

2.3.1 District Layer (PED level)

At the highest level, the model represents a PED as a district entity containing buildings and spatial information. A PED is modelled as a subclass of a city district concept (SAREF4CITY ontology), defined by its geospatial boundaries and its constituent buildings, and may also belong to a SuperPED aggregation.

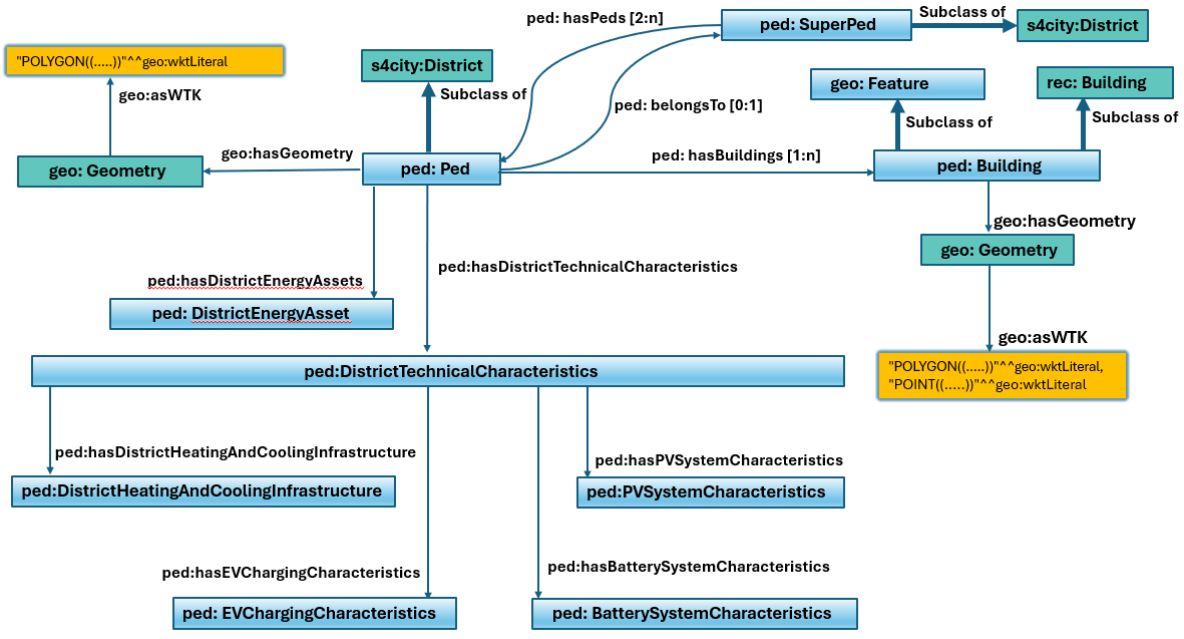


Figure 3: CIM ontology illustrating district-level entities, relationships, and technical characteristics.

In addition, the model captures district-level energy infrastructure characteristics, including district heating and cooling systems, photovoltaic (PV) installations, battery systems, and electric vehicle (EV) infrastructure, enabling a comprehensive representation of both the spatial context and energy characteristics of the PED. As illustrated in the Figure 3, the CIM ontology organises domain-specific entities and their relationships, facilitating semantic interoperability and consistent data representation across heterogeneous data sources and systems within the PEDvolution ecosystem.

2.3.2 Building and Energy Asset Layer

Each building within the PED is modelled as an individual entity linked to the district, capturing its geometry, internal units (apartments or zones), construction and occupancy properties, and associated energy assets with their technical characteristics as illustrated in Figure 4. The model also incorporates energy-related data, including energy vectors and real-time measurements.

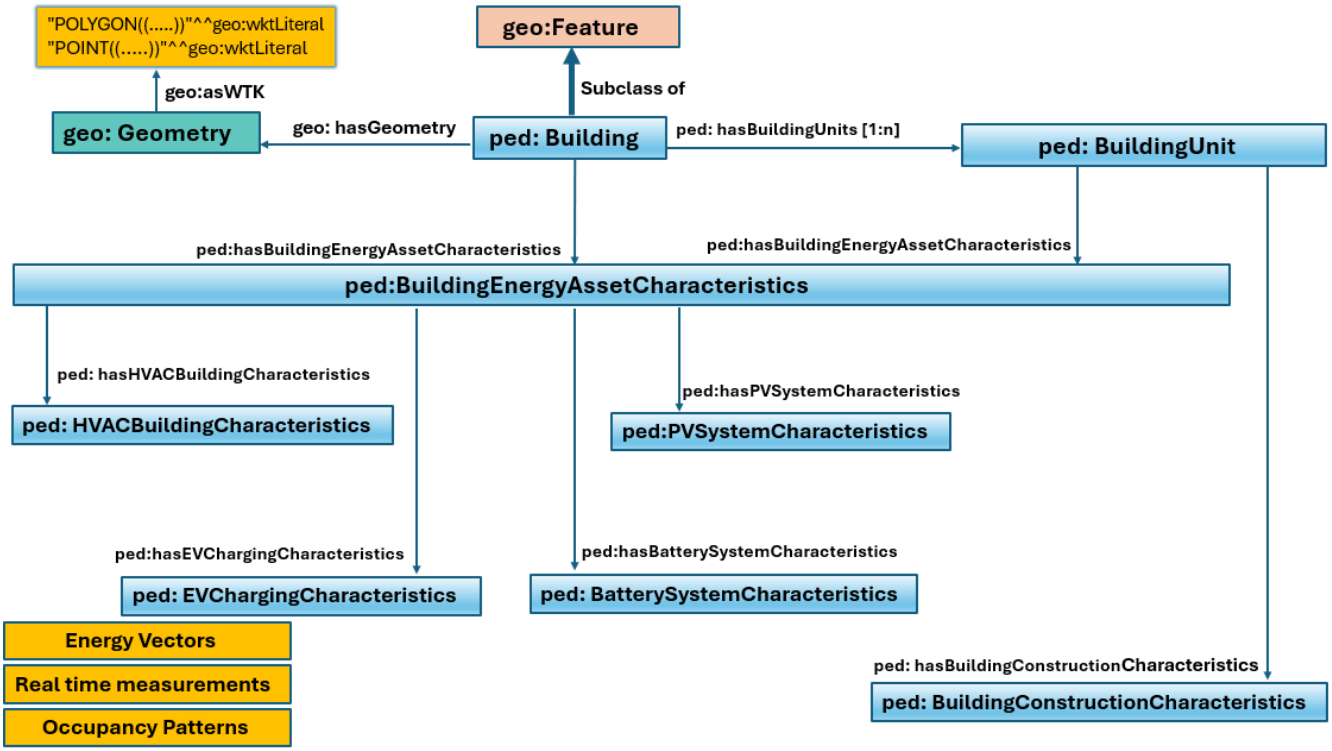


Figure 4: Building-level CIM representation showing buildings as district-linked entities and their associated modular energy asset characteristics within an interoperable framework.

Energy assets are modelled in a modular way through the BuildingEnergyAssetCharacteristics abstraction, which groups the technical properties of building-level systems, including HVAC systems, photovoltaic (PV) installations, battery systems, and electric vehicle (EV) charging infrastructure.

This structure allows different solution tools from WP3-WP5 (simulation, monitoring, optimisation) to access the same building description while using only the parts they require.

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2.3.3 Operational Layer

In addition to static technical characteristics, the CIM incorporates dynamic operational datasets, including energy vectors (consumption and production indicators), energy prices (tariff and market price information), and real-time measurements. These datasets are not embedded as structural elements but linked as operational information layers, ensuring a clear separation between infrastructure description and measurements, while supporting scalability and compatibility with analytics and optimisation services.

2.3.4 Conceptual Role

The CIM connects three complementary aspects of the PED ecosystem:

Physical structure → Technical assets → Operational behavior

The PEDvolution Common Information Model is designed to integrate multiple conceptual layers of the PED ecosystem, providing a unified representation that links structural, technical, and operational aspects. This layered approach enables a comprehensive understanding of how physical infrastructure, energy systems, and dynamic behaviors interact within a Positive Energy District.

As illustrated in the Figure 5, the CIM establishes clear relationships between these complementary layers, supporting a coherent and semantically consistent framework for data representation and exchange.

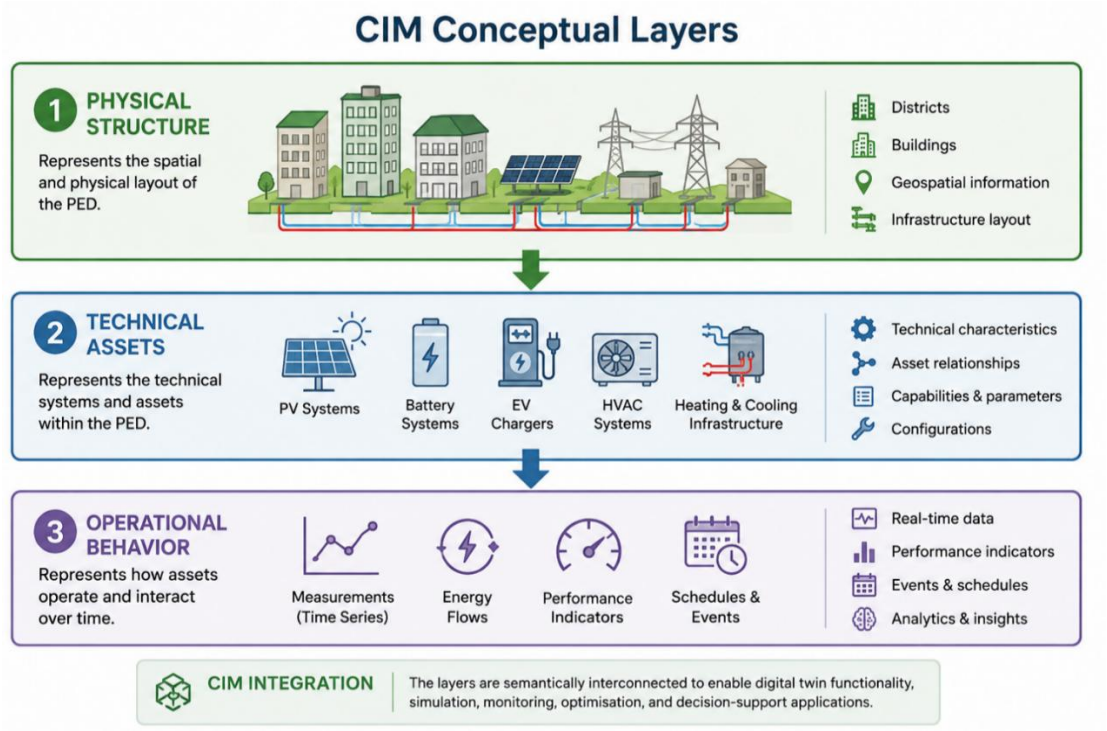


Figure 5: Conceptual layers of the PEDvolution CIM, linking physical structure, technical assets, and operational behavior.

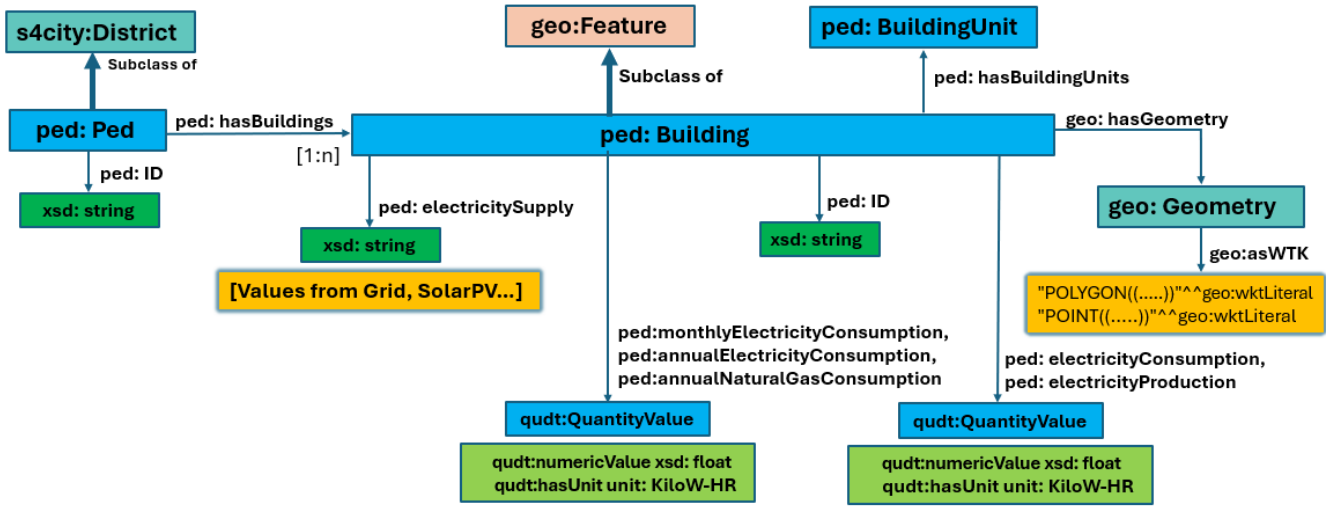
By combining these layers, the CIM supports digital twin functionality, enabling simulation, monitoring, optimisation, and decision-support tools to operate on a shared semantic representation of PED assets and systems within a Positive Energy District.

The applicability of the CIM will be validated through its use in real-world data exchange workflows within WP9 demonstrators, confirming its suitability for supporting interoperable data exchange across PED pilots and Solution Tools under operational conditions.

2.4 Energy Vectors Characteristics Ontology

The Energy Vectors Characteristics ontology has been developed within the PEDvolution Common Information Model to provide a unified semantic structure for representing energy consumption, production, and aggregated monthly and annual energy indicators across Positive Energy Districts. Its purpose is to support consistent modelling, exchange, and interpretation of energy-related data at the building level across heterogeneous pilot environments and Solution Tools.

As illustrated in Figure 6, the CIM models the relationships between the PED, its buildings, and associated energy vector properties, providing a structured representation of energy data at building level. The model is further extended to building units (e.g. apartments or zones), enabling more granular analysis of energy consumption and production patterns, as illustrated in Figure 7, and supporting use cases related to optimisation, monitoring, and demand-side management.



*The figure illustrates the core and most relevant part of the **Energy Vectors** ontology used for modelling consumption, production, and aggregated energy indicators within PEDvolution. Additional ontology components are omitted for clarity.*

Figure 6: Conceptual representation of Energy Vectors characteristics at building level within the PEDvolution Common Information Model.

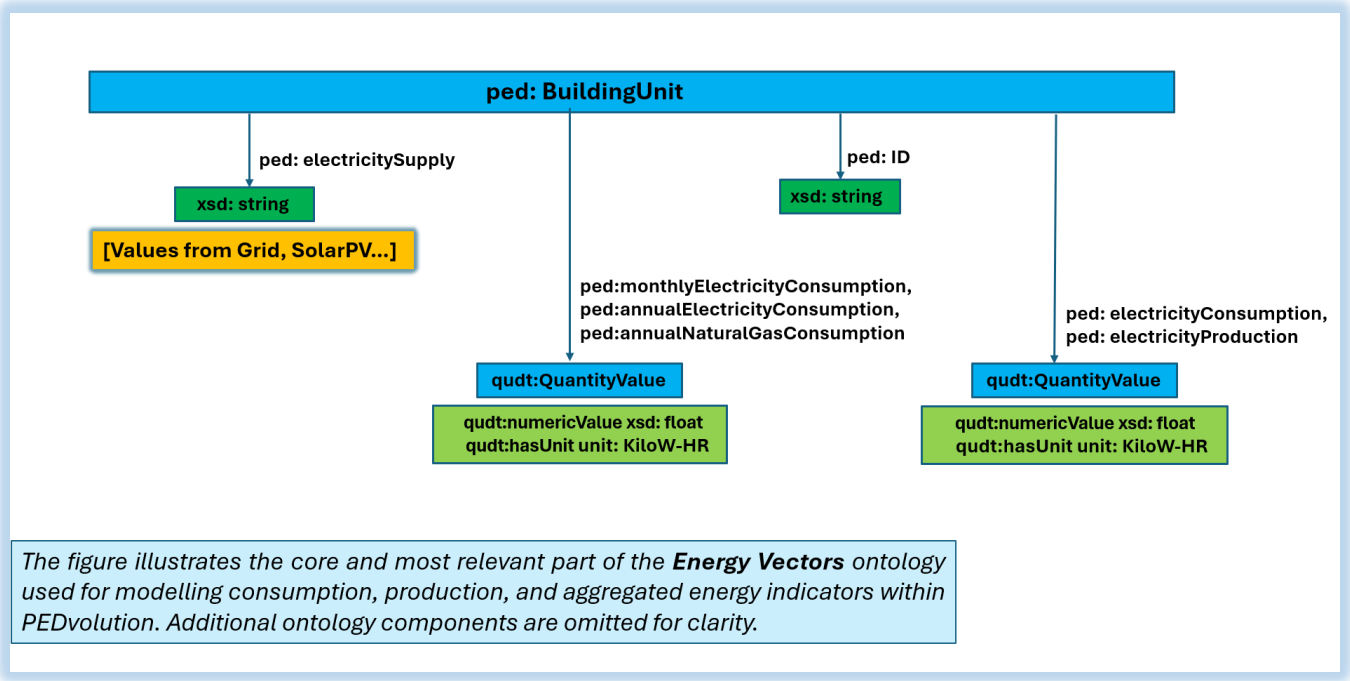


Figure 7: Conceptual representation of Energy Vectors characteristics at building unit level within the PEDvolution Common Information Model.

2.4.1 Structure and alignment with Standard Ontologies

The Energy Vectors ontology is aligned with established semantic models to ensure interoperability and standardisation, including SAREF4CITY for district representation, QUDT for quantitative values and units, and GeoSPARQL geospatial ontology for modelling topology, spatial relationships, and geometric information.

The ontology extends the PEDvolution CIM by introducing a structured set of energy-related properties that enable the semantic modelling of energy consumption, production, supply, and aggregated indicators at both building and building-unit levels.

The ontology defines the following core properties:

- ped:electricityConsumption
- ped:electricityProduction
- ped:monthlyElectricityConsumption (monthly aggregated values)
- ped:annualElectricityConsumption (yearly aggregated values)
- ped:annualNaturalGasConsumption (yearly aggregated values)
- ped:annualOilConsumption (yearly aggregated values)
- ped:electricitySupply

Quantitative values are modelled using qudt:QuantityValue, ensuring explicit representation of numerical values (qudt:numericValue), measurement units (qudt:hasUnit), and standardised data types (xsd:float).

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This approach ensures unit-aware, machine-readable, and semantically consistent energy data exchange across PED platforms and Solution Tools. A detailed example of the Energy Vectors Characteristics ontology is provided in ANNEX I.

2.5 Energy Prices Ontology

The Energy Prices Ontology models the economic dimension of Positive Energy Districts by providing a harmonised semantic representation of tariffs, market prices, and regulatory costs associated with different energy carriers. It enables PED services, including simulation, optimisation, flexibility, and decision-support tools, to evaluate operational strategies from both technical and economic perspectives.

It represents energy prices as structured data objects associated with a PED and characterised by time validity, sector applicability, and energy carrier type.

As illustrated in Figure 8, the ontology organises pricing-related entities and their associations, enabling a structured and interoperable modelling of energy price information.

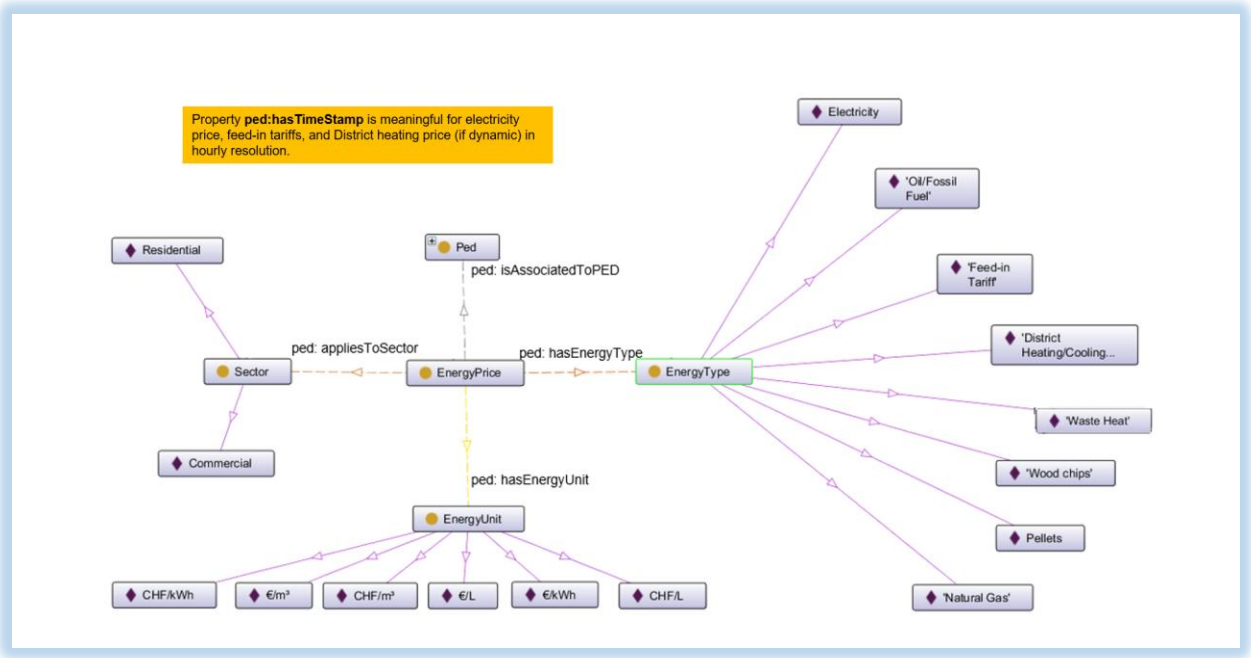


Figure 8: Energy Prices ontology in the PEDvolution Common Information Model, illustrating relationships between price, energy type, sector, and units (time dependency not depicted).

To support comprehensive economic analysis, the Energy Prices ontology categorises pricing information across different sectors and energy carriers. It incorporates various cost components, including tariffs, fuels, and alternative energy sources, along with their corresponding units of measurement.

Figure 9 presents the classification of energy cost categories and units, highlighting how the model supports diverse pricing structures across residential, commercial, and other application domains.

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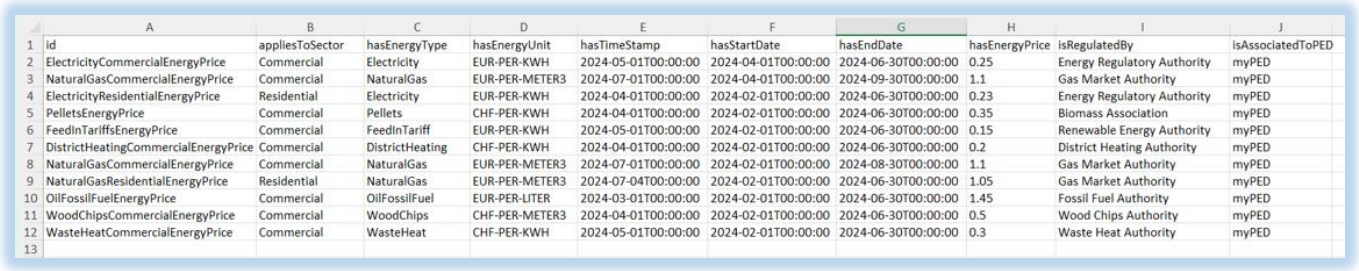
Parameter	Unit	Description
Electricity Price Residential	€/kWh	Average cost of electricity for residential users
Electricity Price Commercial	€/kWh	Average cost of electricity for commercial, or industrial users.
Natural Gas Price Residential	€/kWh or m³	Cost of natural gas for residential users
Natural Gas Price Commercial	€/kWh or m³	Cost of natural gas for commercial, or industrial users.
Oil/Fossil Fuel Costs	€/kWh or Liter	Cost of heating oil or other fossil fuels used in heating systems.
District Heating/Cooling Tariffs	€/kWh	Tariffs for district heating and cooling services.
Feed-in Tariffs (FITs)	€/kWh	Rates paid for feeding renewable energy into the grid.
Pellets Price Commercial	€/kWh	Average cost of pellets for Commercial use (CHP or Boilers)
Wood chips Price Commercial	€/kWh	Average cost of Woodchips for commercial, or industrial users.
Waste Heat Price Commercial	€/kWh	Cost of waste heat from Industry

Figure 9: Energy cost categories and units defined in the PEDvolution Energy Prices model (residential, commercial, fuels, tariffs, and waste heat).

In addition to the conceptual model, the Energy Prices Ontology supports the practical representation of pricing data in a structured and semantically consistent manner. This enables integration with digital platforms and analytical tools that require machine-readable economic information.

Figure 10 illustrates how energy prices can be modelled and associated with PED entities, energy carriers, sectors, and time periods within the PEDvolution CIM. The example is provided solely for demonstration purposes and does not represent real operational or pilot deployment data.

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	A	B	C	D	E	F	G	H	I	J
1	id	appliesToSector	hasEnergyType	hasEnergyUnit	hasTimeStamp	hasStartDate	hasEndDate	hasEnergyPrice	isRegulatedBy	isAssociatedToPED
2	ElectricityCommercialEnergyPrice	Commercial	Electricity	EUR-PER-KWH	2024-05-01T00:00:00	2024-04-01T00:00:00	2024-06-30T00:00:00	0.25	Energy Regulatory Authority	myPED
3	NaturalGasCommercialEnergyPrice	Commercial	NaturalGas	EUR-PER-METER3	2024-07-01T00:00:00	2024-04-01T00:00:00	2024-09-30T00:00:00	1.1	Gas Market Authority	myPED
4	ElectricityResidentialEnergyPrice	Residential	Electricity	EUR-PER-KWH	2024-04-01T00:00:00	2024-02-01T00:00:00	2024-06-30T00:00:00	0.23	Energy Regulatory Authority	myPED
5	PelletsEnergyPrice	Commercial	Pellets	CHF-PER-KWH	2024-04-01T00:00:00	2024-02-01T00:00:00	2024-06-30T00:00:00	0.35	Biomass Association	myPED
6	FeedInTariffsEnergyPrice	Commercial	FeedInTariff	EUR-PER-KWH	2024-05-01T00:00:00	2024-02-01T00:00:00	2024-06-30T00:00:00	0.15	Renewable Energy Authority	myPED
7	DistrictHeatingCommercialEnergyPrice	Commercial	DistrictHeating	CHF-PER-KWH	2024-04-01T00:00:00	2024-02-01T00:00:00	2024-06-30T00:00:00	0.2	District Heating Authority	myPED
8	NaturalGasCommercialEnergyPrice	Commercial	NaturalGas	EUR-PER-METER3	2024-07-01T00:00:00	2024-02-01T00:00:00	2024-08-30T00:00:00	1.1	Gas Market Authority	myPED
9	NaturalGasResidentialEnergyPrice	Residential	NaturalGas	EUR-PER-METER3	2024-07-04T00:00:00	2024-02-01T00:00:00	2024-06-30T00:00:00	1.05	Gas Market Authority	myPED
10	OilFossilFuelEnergyPrice	Commercial	OilFossilFuel	EUR-PER-LITER	2024-03-01T00:00:00	2024-02-01T00:00:00	2024-06-30T00:00:00	1.45	Fossil Fuel Authority	myPED
11	WoodChipsCommercialEnergyPrice	Commercial	WoodChips	CHF-PER-METER3	2024-04-01T00:00:00	2024-02-01T00:00:00	2024-06-30T00:00:00	0.5	Wood Chips Authority	myPED
12	WasteHeatCommercialEnergyPrice	Commercial	WasteHeat	CHF-PER-KWH	2024-05-01T00:00:00	2024-02-01T00:00:00	2024-06-30T00:00:00	0.3	Waste Heat Authority	myPED
13										

Figure 10: Illustrative semantic representation of energy prices within the PEDvolution CIM (for demonstration purposes only).

2.6 Electric Vehicle (EV) Charging Characteristics Ontology

The Electric Vehicle (EV) Charging Characteristics Ontology models the infrastructure and technical characteristics of electric vehicle charging within the PEDvolution Common Information Model. Its purpose is to provide a harmonised semantic representation of charging stations, charging equipment, and their operational parameters, enabling interoperability between PED data providers and Solution Providers. The ontology extends the building and PED level energy asset modelling and allows the representation of both individual charging devices and aggregated charging pools.

The ontology enables the integration of electromobility infrastructure as a semantically structured energy asset within PEDs, supporting interoperability, optimisation, and data-driven services across the PEDvolution ecosystem.

2.6.1 Structure and alignment with standard ontologies

The ontology is aligned with established semantic standards and ontologies, including

- Brick Ontology, Brick Ontology
- Omega-X Electromobility Ontology, Omega-X Electromobility
- Omega-X Property Ontology, Omega-X Property
- Omega-X Infrastructure Ontology. Omega-X Infrastructure
- QUDT for quantitative values and units, qudt.org
- GeoSPARQL geospatial ontology for modelling topology, spatial relationships, and geometric information

The EV Charging Characteristics Ontology provides a unified semantic framework for modelling electric vehicle charging infrastructure within the PEDvolution CIM, covering charging stations, supply equipment, and their technical and spatial characteristics. Figures Figure 11, Figure 12 and Figure 13 illustrate the overall structure, detailed equipment modelling, and geospatial representation of EV charging systems within the PEDvolution ecosystem.

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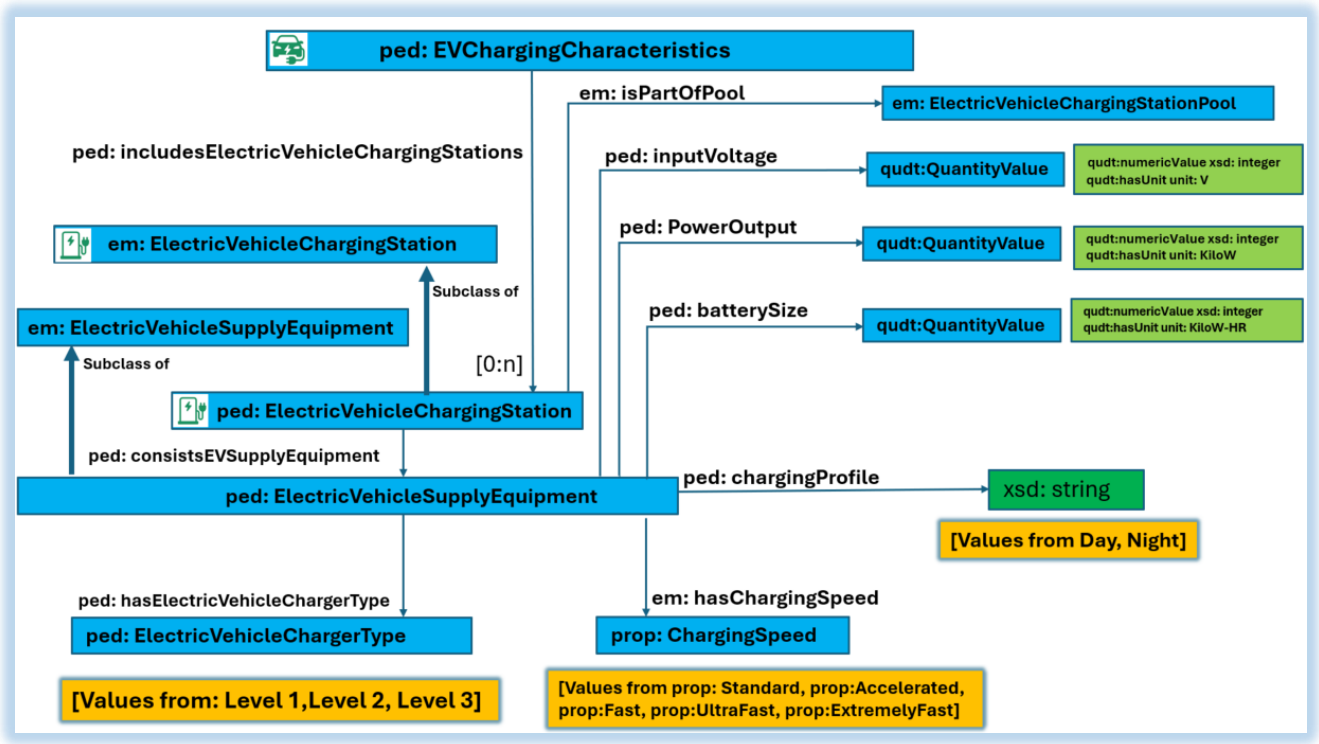


Figure 11: Modelling of Electric Vehicle Charging Stations, Equipment, and Charging Profiles using Standard Ontologies

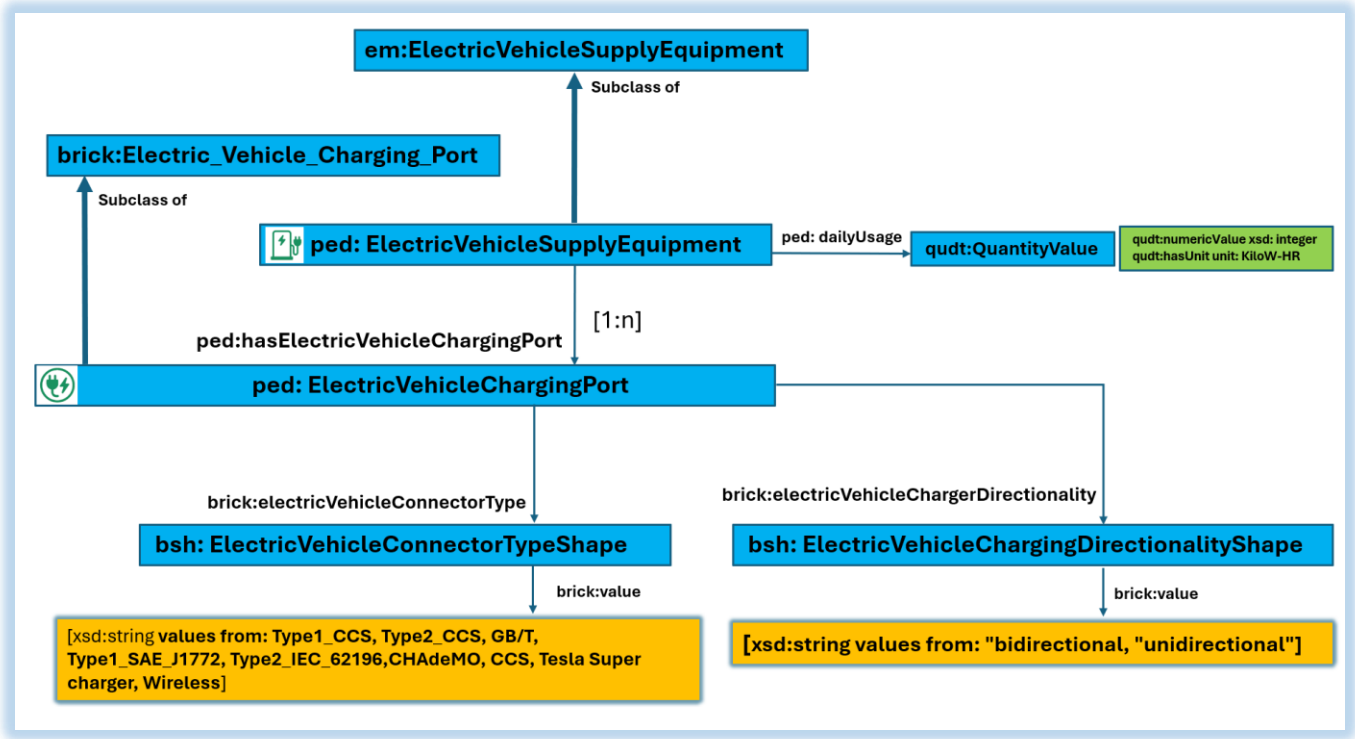


Figure 12: Representation of Electric Vehicle Supply Equipment within the PEDvolution CIM

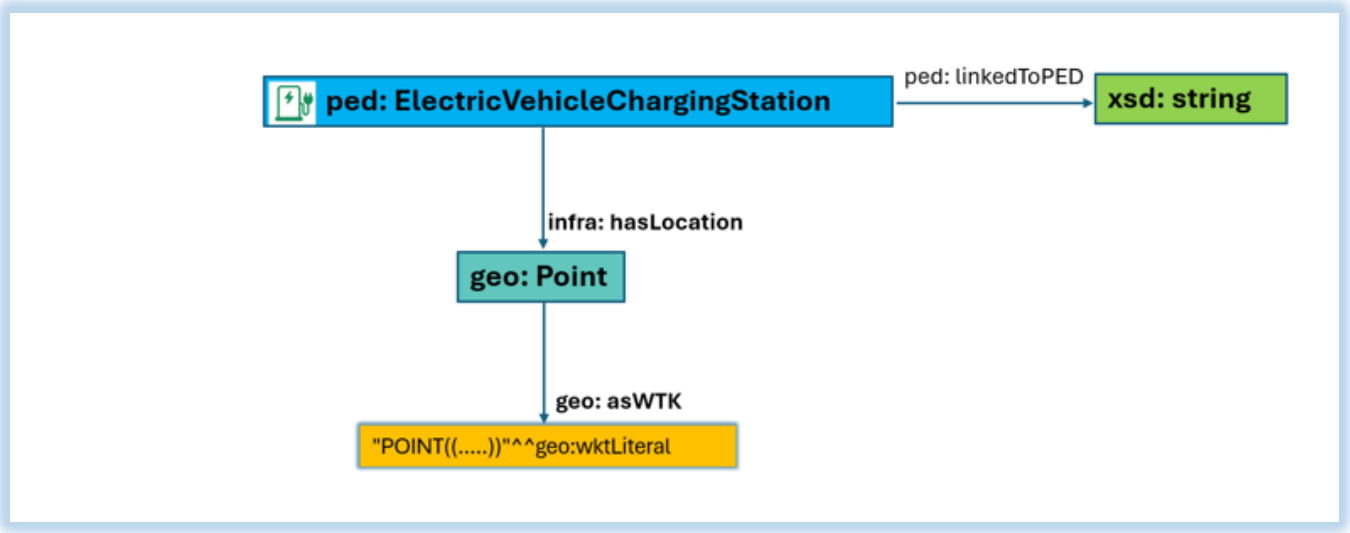


Figure 13: Geospatial Representation of Electric Vehicle Charging Stations within the PEDvolution Common Information Model

Conceptual Structure

At the highest level, the class ped:EVChargingCharacteristics describes the charging infrastructure associated with a building or a PED (as described in Figure 3 and Figure 4). It aggregates multiple charging stations through:

ped:includesElectricVehicleChargingStations → ped:ElectricVehicleChargingStation

A charging station can optionally belong to a charging pool, represented through the relation: *em:isPartOfPool* linking *em:ElectricVehicleChargingStation* to *em:ElectricVehicleChargingStationPool*. This enables modelling of parking facilities, or public charging hubs where several EV Chargers operate collectively.

Each EV charging station is spatially located using GeoSPARQL geospatial ontology:

infra:hasLocation → geo:asWKT → geo:Point → coordinates

The ontology distinguishes between:

- **EV Charging Station** (logical asset), represents a charging point accessible to EV users: *ped:ElectricVehicleChargingStation* subclass of *em:ElectricVehicleChargingStation*

- **EV Supply Equipment** (physical charger hardware), represents the technical charging hardware installed at the station:
  ped:ElectricVehicleSupplyEquipment subclass of *em:ElectricVehicleSupplyEquipment*

An EV charging station may consist of one or more EV supply equipment units through the property:

ped:consistsEVSupplyEquipment

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Charger Classification and Performance

The ontology distinguishes between regulatory classification and operational performance. Charger type, defined through ped:hasElectricVehicleChargerType, represents the regulatory classification (Level 1, Level 2, Level 3), while charging speed, defined through em:hasChargingSpeed, captures performance characteristics (Standard, Accelerated, Fast, UltraFast, ExtremelyFast). This separation enables the modelling of both regulatory charger levels and operational charging performance.

Electrical and operational characteristics

Technical specifications are represented in Table 2, using QUDT quantities:

Table 2: EV Charging Technical Specifications

Property	Description	Unit
ped:inputVoltage	Electrical input voltage	Volt (V)
ped:powerOutput	Maximum charging power	kW
ped:batterySize	Typical battery capacity supported	kWh

Each parameter is represented as: *qudt:QuantityValue → qudt:numericValue + qudt:hasUnit*.This enables machine-interpretable representation of physical quantities and consistent use of units.

Charging behavior

The charging usage pattern is represented via: *ped:chargingProfile → xsd:string*

Typical values: Day, Night.

Charging ports and connector interoperability

The ontology further describes the physical interface between vehicle and charging equipment. Each equipment unit may include one or more charging ports:

ped:hasElectricVehicleChargingPort → ped:ElectricVehicleChargingPort

Connector type is defined using Brick ontology connector taxonomy:

brick:electricVehicleConnectorType → bsh:ElectricVehicleConnectorTypeShape

Indicative values: Type1_CCS, Type2_CCS, GB/T, Type1_ SAE_J1772, Type2_IEC_62196, CHAdeMO, CCS, TeslaSuperCharger, Wireless.

Charging directionality

brick:electricVehicleChargerDirectionality → bsh:ElectricVehicleChargingDirectionalityShape

Values: Unidirectional, Bidirectional.

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Functional role in PEDvolution ecosystem

The EV Charging ontology enables modelling of electromobility infrastructure at building and district level, integration with flexibility and demand-response services, coupling with energy production and storage assets, optimisation of charging schedules using real-time measurements and energy prices, and interoperable data exchange across PEDs and Solution Tools via the PEDvolution Interoperability Platform.

By semantically structuring EV charging data, the ontology enables digital twins and decision-support tools to treat electric mobility as an integrated energy asset within the Positive Energy District. An example of the EV Charging Ontology using the PEDvolution CIM is provided in ANNEX II.

2.7 Heat Recovery Potential Characteristics Ontology

Waste heat refers to excess thermal energy released by industrial processes and energy systems, such as steel production, cement manufacturing, power generation systems, and building energy systems. This thermal energy is not utilized and is typically dissipated into the air or water. Although often treated as a by-product, this thermal energy constitutes a valuable locally available energy resource for PEDs.

Instead of being rejected into the environment, this heat can be captured and reused for electricity generation, district heating, domestic hot water production, or cooling through heat pumps and absorption chillers. Recovering this energy improves overall system efficiency, reduces primary energy consumption, and contributes significantly to greenhouse gas emission reduction.

Within Positive Energy Districts, waste heat recovery plays a key role in achieving energy positivity. Besides industrial sources and geothermal installations, buildings themselves can act as distributed thermal energy sources. The temperature difference between inlet and outlet thermal flows (e.g., heating circuits, ventilation exhaust air, or cooling systems) represents recoverable energy potential that can be aggregated and reused at district scale.

The PEDvolution Common Information Model introduces the Heat Recovery Potential Characteristics Ontology, as presented in Figure 14–Figure 17, providing a harmonised semantic representation of recoverable thermal energy sources at both building and district level. It supports the identification of waste heat sources (e.g. industrial processes, geothermal plants, buildings), quantification of

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recoverable heat using parameters such as temperature and thermal power, spatial localisation through geospatial modelling, and interoperability between PED data providers and Solution Providers.

By modelling waste heat as an energy asset rather than an energy loss, the PED can enable industrial symbiosis, building-to-district heat exchange, and geothermal integration within optimisation and planning workflows.

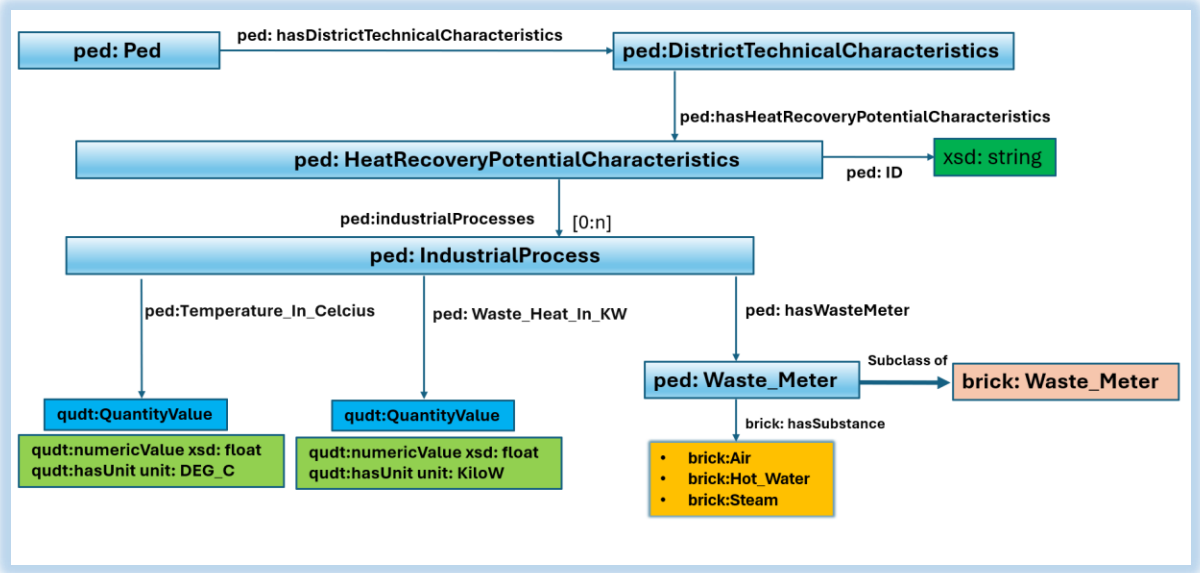


Figure 14: Conceptual model of Industrial Waste Heat Recovery Potential in the PEDvolution Common Information Model, including process temperature, recoverable thermal power, and waste medium classification.

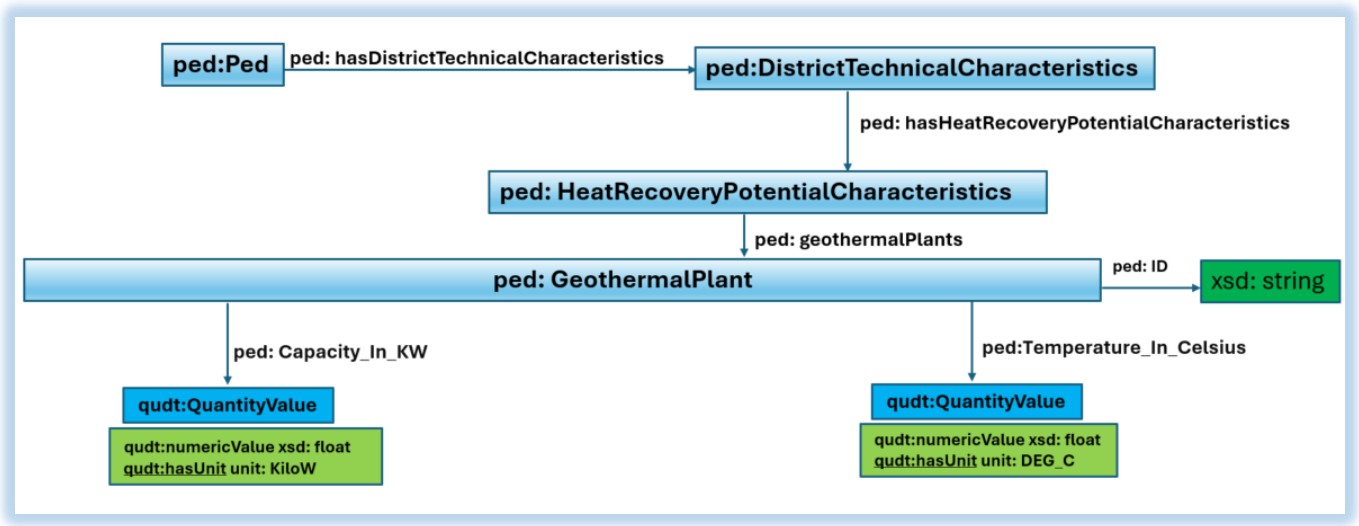


Figure 15: Geothermal plant heat recovery characteristics in the PEDvolution CIM (capacity and temperature).

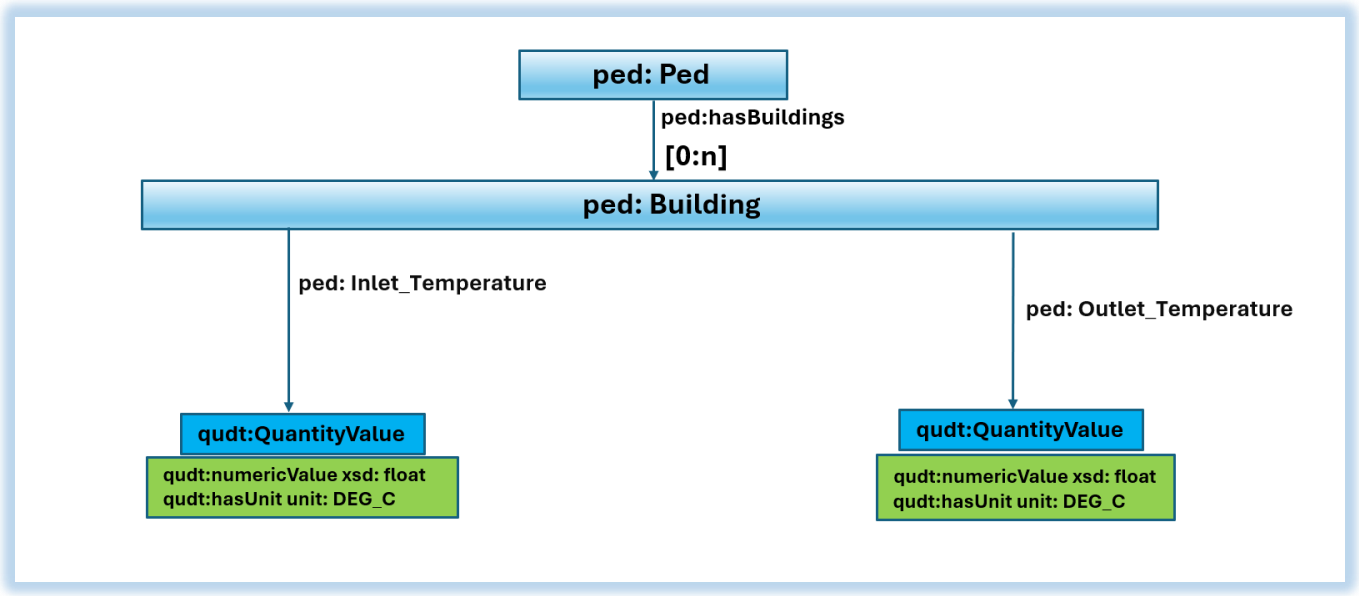


Figure 16: Building inlet and outlet temperature modelling using QUDT quantities in the PEDvolution CIM.

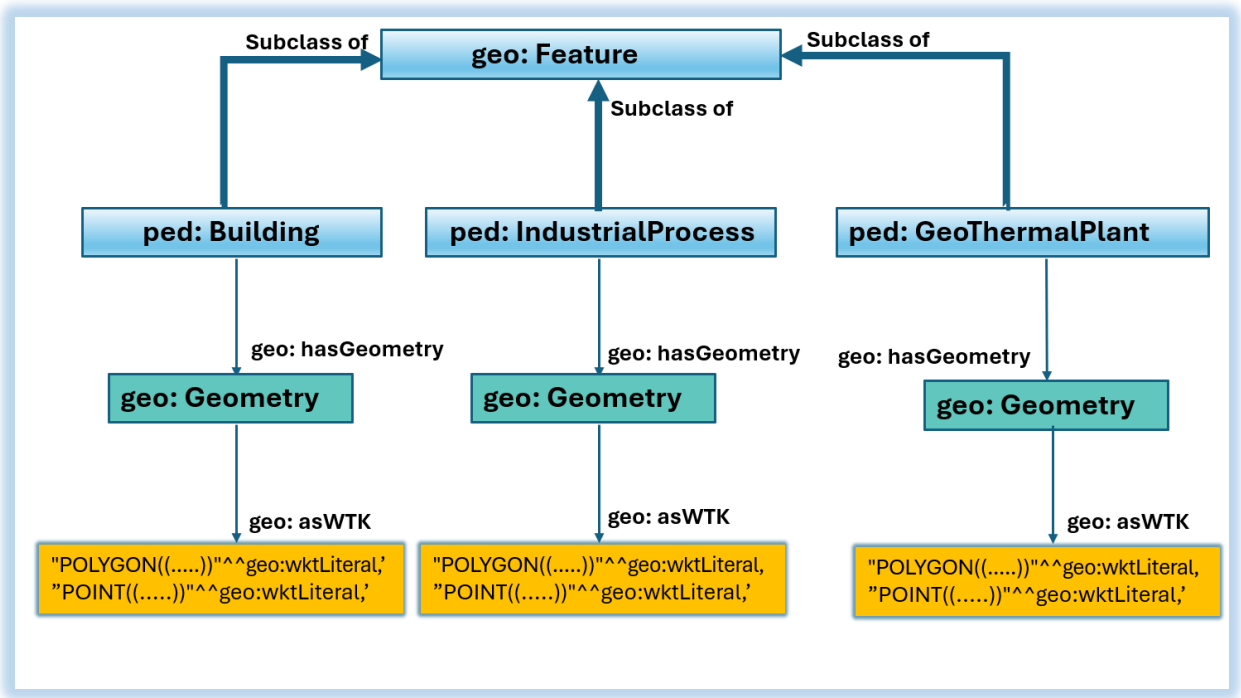


Figure 17: Geospatial modelling of PED entities (district, buildings, industrial processes and geothermal plants) using Geospatial geometries and WKT representations in the PEDvolution CIM.

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Its goal is to enable the identification of locally available thermal resources, coupling between buildings and industrial processes, integration with district heating networks, and support for energy planning, optimisation tools, and digital twin simulations.

The ontology provides a semantically enriched framework for modelling recoverable thermal energy within PEDs, supporting interoperability, optimisation, and integration with digital twin and analytics platforms.

2.7.1 Structure and relation to standard ontologies

The ontology is aligned with established semantic standards and ontologies, including Brick Ontology, QUDT for quantitative values and units, and GeoSPARQL geospatial ontology for modelling topology, spatial relationships, and geometric information.

Conceptual Structure

The Heat Recovery Potential Characteristics describe recoverable thermal energy sources within a PED at both district and building level. The model links the district (ped:Ped) to its technical characteristics (ped:DistrictTechnicalCharacteristics) and further to potential heat sources through ped:hasHeatRecoveryPotentialCharacteristics.

The ontology represents three main categories of heat sources: industrial processes (ped:IndustrialProcess), geothermal plants (ped:GeothermalPlant), and buildings (ped:Building). These are characterised by parameters such as temperature, thermal capacity or recoverable power, and, where applicable, inlet and outlet temperatures, as well as the type of waste heat medium.

All measurable parameters are represented using qudt:QuantityValue, ensuring consistent units and machine-interpretable physical quantities. Spatial information is modelled through geospatial properties (geo:hasGeometry → geo:asWKT), enabling mapping and integration with GIS-based planning tools.

ANNEX III provides an illustrative example of the Heat Recovery Potential ontology using the PEDvolution CIM.

2.8 Photovoltaic (PV) System Characteristics Ontology

The PV System Characteristics ontology describes photovoltaic energy assets deployed within Positive Energy Districts (PEDs) at both district and building level. Within the PEDvolution project, this ontology enables Solution Tools and PED platforms to exchange harmonised solar production data through the Interoperability Platform. By providing a common semantic structure, it supports energy balancing calculations, flexibility estimation, predictive analytics, and cross-district service deployment, contributing to the project's objective of interoperable and scalable Positive Energy District operation.

2.8.1 Structure and relation to standard ontologies

The ontology is aligned with established semantic standards, ensuring interoperability and extensibility across systems:

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- QUDT for quantitative values and units.
- GeoSPARQL geospatial ontology for modelling topology, spatial relationships, and geometric information.
- SAREF4CITY for modelling district-level entities and urban infrastructures.

Conceptual Structure

A ped:Ped entity may include multiple ped:Building entities, each associated with ped:BuildingEnergyAssetCharacteristics, while district-level installations are represented through ped:DistrictTechnicalCharacteristics. Both may reference ped:PVSystemCharacteristics.

The ontology captures the technical and operational properties of PV systems, including installed capacity, annual energy production, and solar thermal output. Measurements are expressed through qudt:QuantityValue to ensure semantic consistency and unit interoperability (kW and MW).

Panel orientation is represented as a discrete angular value (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°), enabling simplified solar exposure modelling. Additionally, the attribute ped:isControllable specifies whether the PV installation can participate in automated control or flexibility services (e.g., curtailment, demand response, or energy optimisation algorithms).

All PV assets may be linked to spatial information via geo:hasGeometry and WKT geometries, allowing integration with GIS systems, visualisation tools, and spatial analytics services within the PED interoperability framework.

The ontology supports both building-level and district-level representation of photovoltaic (PV) assets, enabling detailed modelling of their quantitative and operational characteristics. As illustrated in FiguresFigure 18, the ontology defines the semantic structure for representing PV systems and their associated attributes within the PEDvolution Common Information Model.

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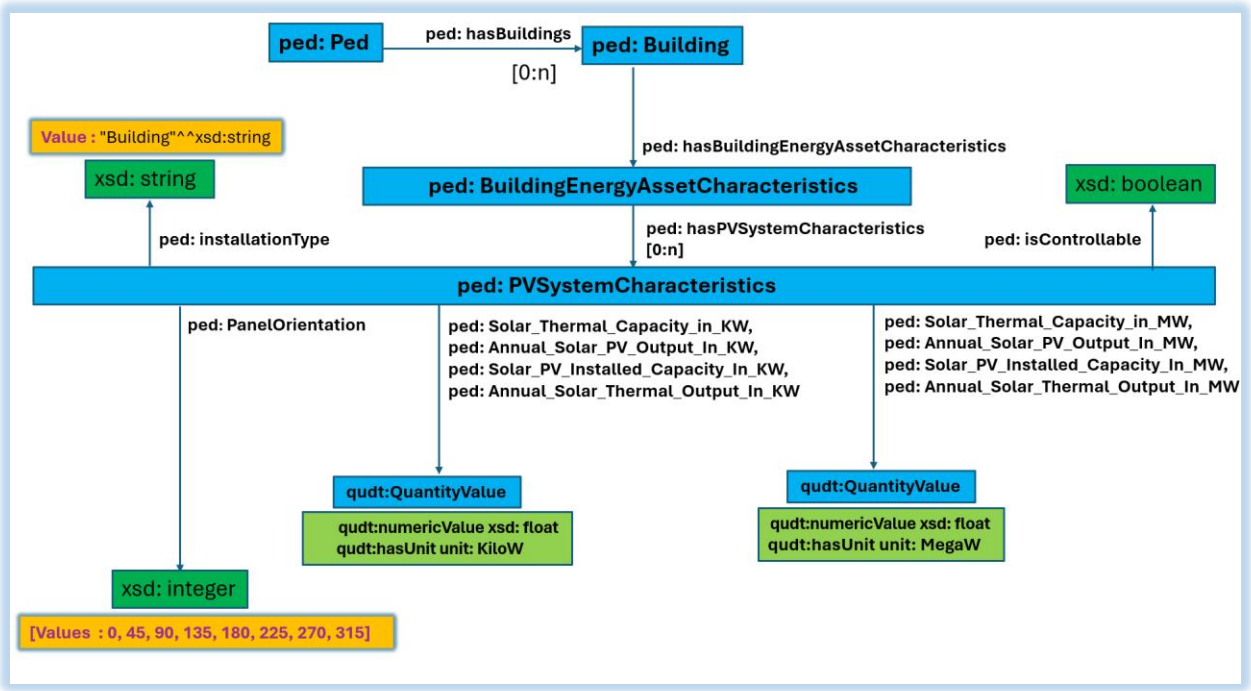


Figure 18: Conceptual model of PV System Characteristics within the PEDvolution Common Information Model, illustrating the relationships between PED, Building, Building Energy Asset Characteristics, and PV system parameters together with their associated quantitative values and units.

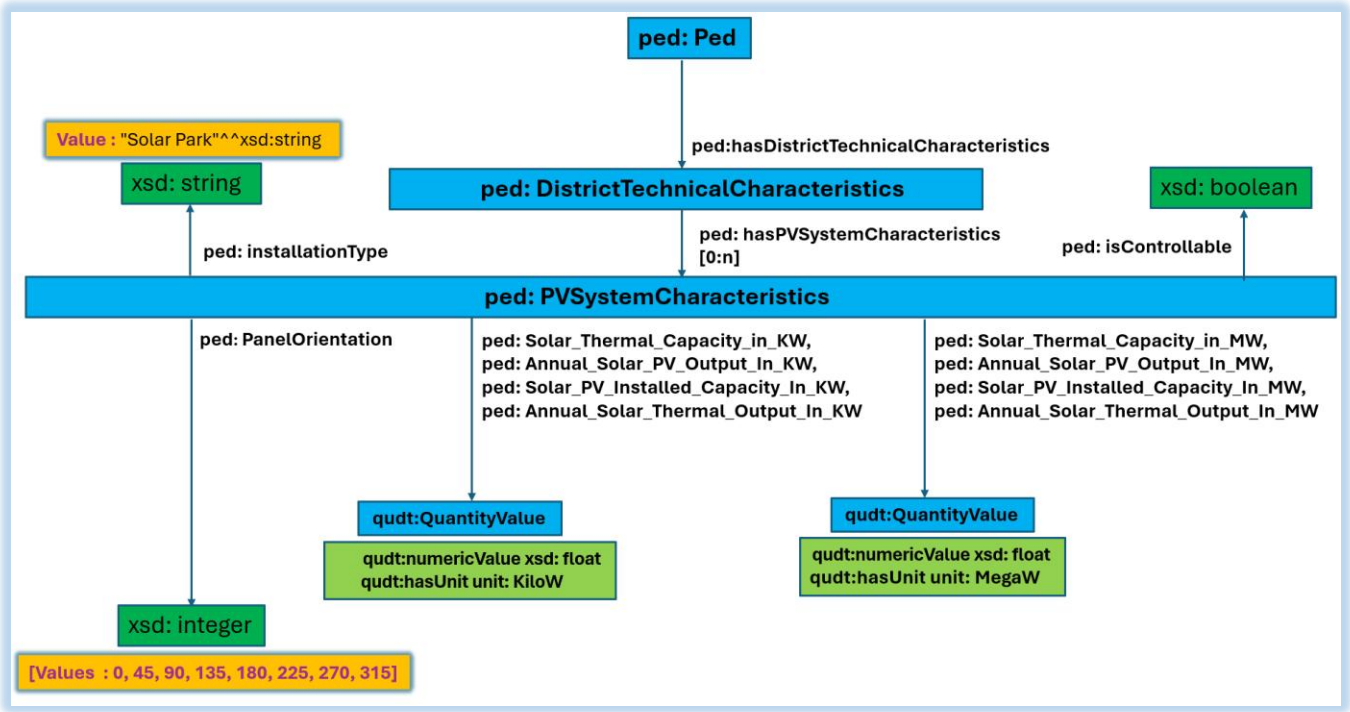


Figure 19: Conceptual model of PV System Characteristics within the PEDvolution Common Information Model, illustrating the relationships between PED's District Technical Characteristics, and PV system parameters together with their associated quantitative values and units.

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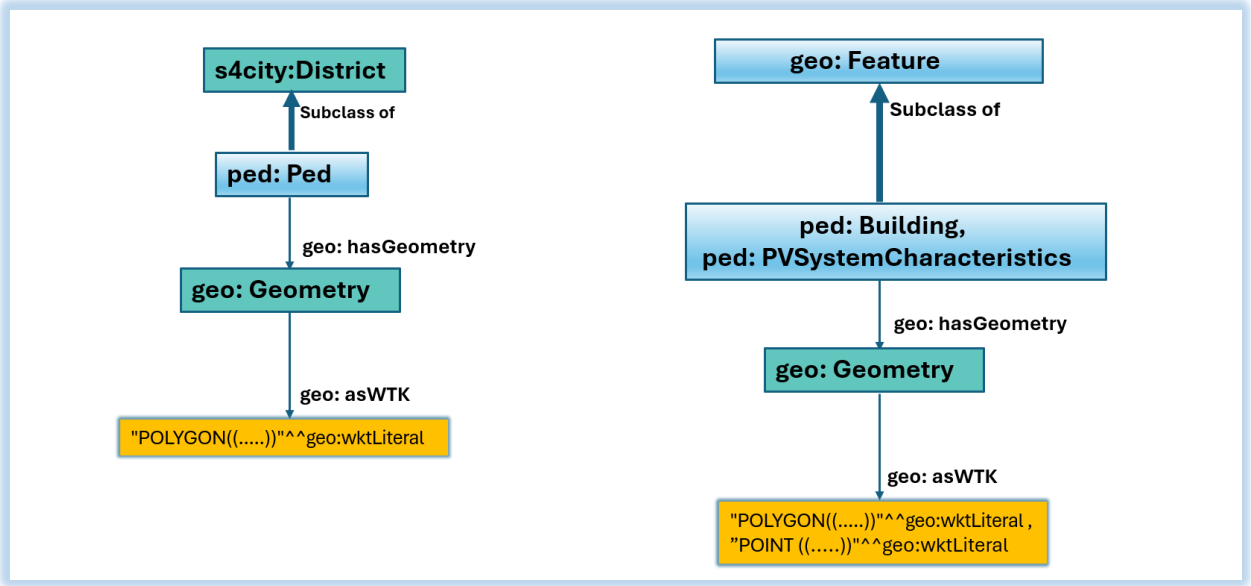


Figure 20: The diagram illustrates how PED, Building, and PV System Characteristics entities are linked to geospatial information. The geometry of each entity is represented using WKT literals, enabling the spatial representation of PED districts as polygons and energy assets as point locations.

Quantitative Characteristics

The PV system is described through quantitative attributes represented using the QUDT ontology, ensuring consistent representation of physical quantities and units. Indicative parameters include annual PV output, solar thermal capacity, installed PV capacity, and annual solar thermal output.

Each parameter is modelled using qudt:QuantityValue, comprising the numeric value (qudt:numericValue) and the measurement unit (qudt:hasUnit).

Operational Characteristics

In addition to quantitative parameters, the PV system description includes operational attributes such as panel orientation (ped:panelOrientation) and a controllability flag (ped:isControllable), indicating whether the system can be managed by external energy services.

ANNEX IV presents an example of the PV System Characteristics Ontology using the PEDvolution CIM.

The ontology provides a consistent framework for modelling photovoltaic assets within Positive Energy Districts, supporting both building-level and district-level representations, and enabling their integration into data-driven services and cross-domain workflows.

2.9 District Energy Assets Ontology

The District Energy Assets ontology is defined as part of the PEDvolution Common Information Model to represent district-level energy generation assets that contribute to the energy balance of a Positive Energy District. These assets include technologies such as Combined Heat and Power (CHP) plants, geothermal plants, solar thermal systems, and other district-scale heat and electricity generators.

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District energy assets are modelled hierarchically, enabling representation from district-level aggregation down to individual asset components. This ontology provides the structural representation of energy assets, while domain-specific characteristics (e.g., PV systems, EV charging, heat recovery) are defined in their respective ontology modules.

The District Energy Assets ontology acts as the integration layer of the PEDvolution CIM, connecting domain-specific asset characteristics across different energy sectors. In the context of the PEDvolution project, this ontology provides a semantic representation of district energy infrastructures, enabling interoperability between PED pilot data sources, energy management systems, and Solution Providers (WP3–WP5). By describing district energy assets through standardised semantic concepts, the ontology facilitates:

- Integration of heterogeneous energy asset data.
- Geospatial representation of district energy infrastructures.
- Exchange of information between PED pilots and Solution Providers.

The ontology presented in Figure 21 and Figure 22, is designed to complement the broader PEDvolution Common Information Model, enabling the representation of energy production systems that operate beyond individual buildings and support the energy needs of the entire PED.

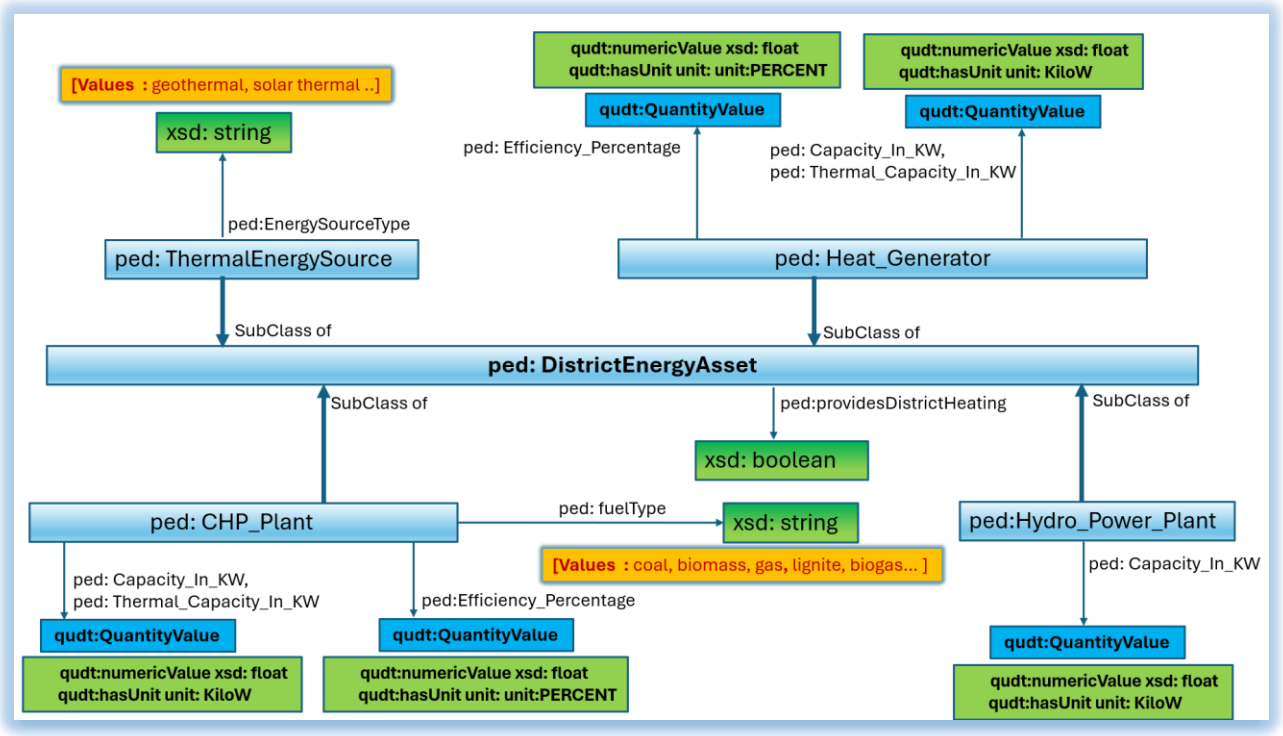


Figure 21: District Energy Assets ontology classes and properties in the PEDvolution CIM, representing thermal energy sources, heat generators, CHP plants, and hydropower plants together with their energy-related attributes.

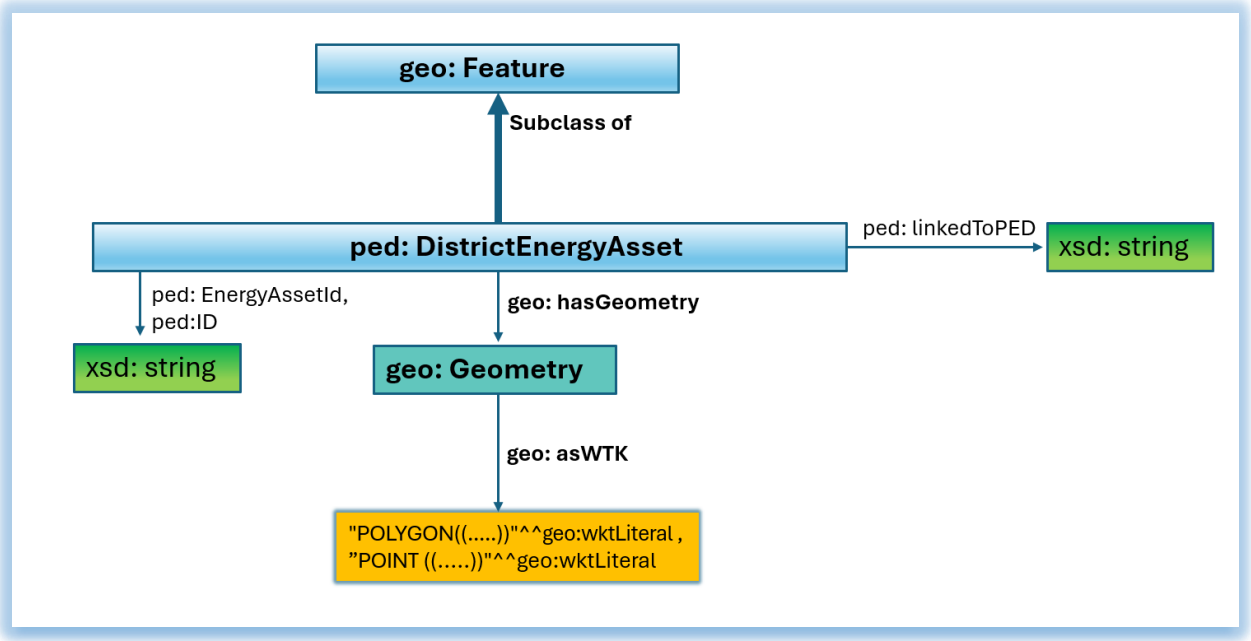


Figure 22: District Energy Assets ontology of the PEDvolution CIM, showing the semantic representation of district-level energy assets, their associated geospatial information, and their linkage to PED pilots.

2.9.1 Structure and relation with standard ontologies

The characteristic is aligned with established semantic standards and ontologies, including QUDT for quantitative values and units, and GeoSPARQL geospatial ontology for modelling topology, spatial relationships, and geometric information.

Conceptual Structure

Within the PEDvolution ontology hierarchy, district energy assets are represented through the abstract class ped:DistrictEnergyAsset, which models energy generation and transformation technologies deployed at district level. This class provides a common semantic framework for representing infrastructure components contributing to the energy balance of a Positive Energy District (PED).

Several specialised subclasses extend this concept to represent different categories of district energy technologies. In particular:

- **ped:Heat_Generator** represents assets that generate thermal energy supplied to district heating systems.
- **ped:ThermalEnergySource** represents primary energy sources used for heat production.
- **ped:CHP_Plant** represents combined heat and power plants that simultaneously generate electricity and heat.
- **ped:Hydro_Power_Plant** represents hydropower generation facilities contributing electrical energy at the district level.

Quantitative characteristics are modelled using qudt:QuantityValue, enabling consistent representation of physical quantities and units for attributes such as electrical and thermal capacity, and energy

efficiency. By using standardised quantity representations, all numerical values are explicitly associated with appropriate measurement units, ensuring semantic clarity and enabling consistent interpretation by external systems and analytical tools.

District energy assets are linked to PEDs through identifiers and geospatial references, enabling spatial analysis, visualisation, and integration with GIS-based applications, digital twins, and urban energy management platforms.

An example of the District Energy Assets Characteristics Ontology using the PEDvolution CIM is provided in ANNEX V.

The ontology provides a structured framework for representing district-level energy systems, supporting interoperability and integration with data-driven services and planning tools.

2.10 District Heating and Cooling Infrastructure Ontology

The District Heating and Cooling (DHC) Infrastructure Ontology is designed to model, describe, and enable the exchange of structured information related to district heating and cooling systems within Positive Energy Districts. In the context of the PEDvolution project, this ontology plays a key role in enabling the representation, integration, and sharing of infrastructure-related data across heterogeneous systems and stakeholders.

The ontology captures the main components of DHC systems, including substations, pipes, and overall infrastructure characteristics, while also linking them with spatial representations and quantitative attributes. It supports the representation of HVAC-related assets, enabling advanced analytics, simulation tools, and decision-support systems within the PEDvolution ecosystem.

As illustrated in Figure 23–Figure 27, the ontology ensures interoperability across Solution Tools and PED pilots by aligning with widely adopted semantic standards and enabling consistent mapping between RDF-based representations and geospatial formats such as GeoJSON.

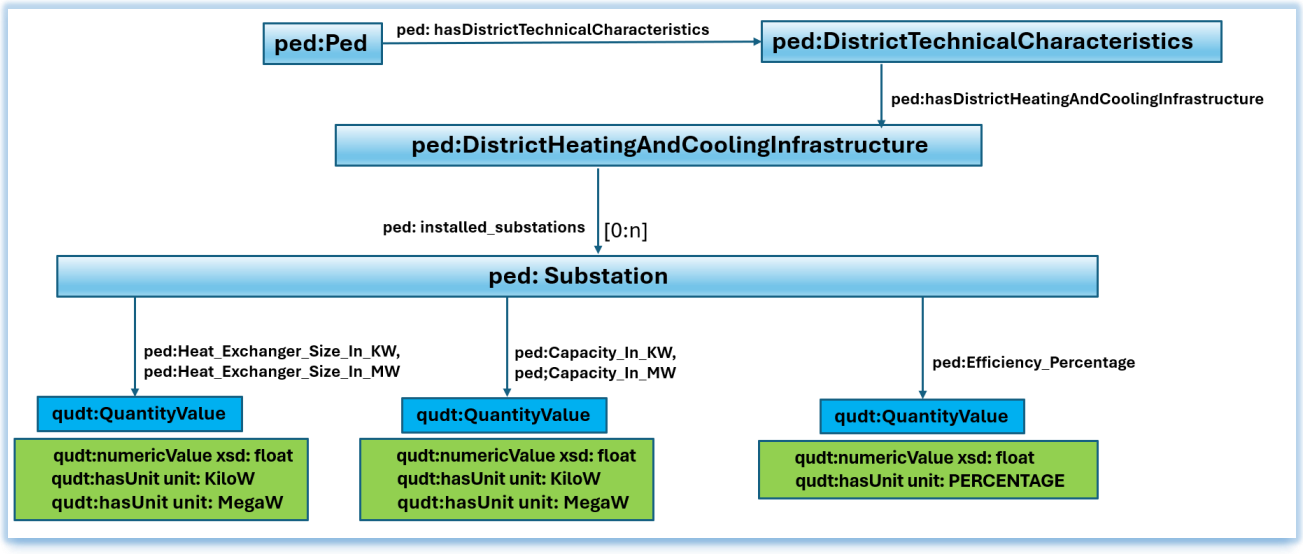


Figure 23: Semantic representation of the District Heating and Cooling Infrastructure ontology within the PEDvolution CIM, including PED technical characteristics and substation-related properties.

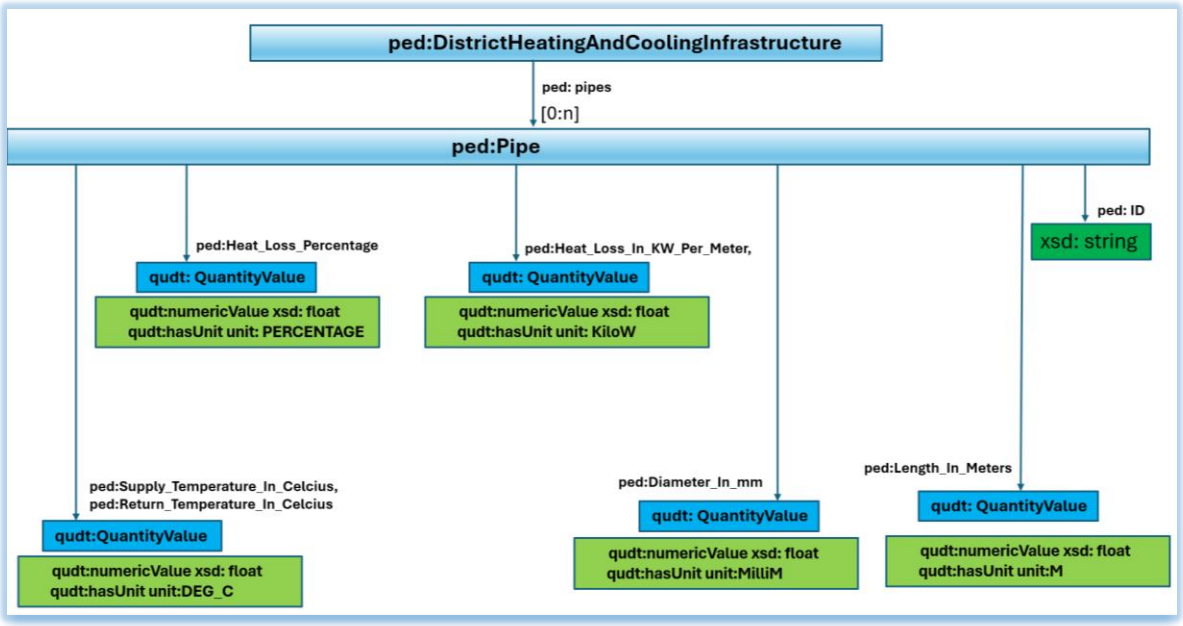


Figure 24: Semantic representation of DHC pipe infrastructure within the PEDvolution CIM, including thermal, dimensional, and operational pipe properties.

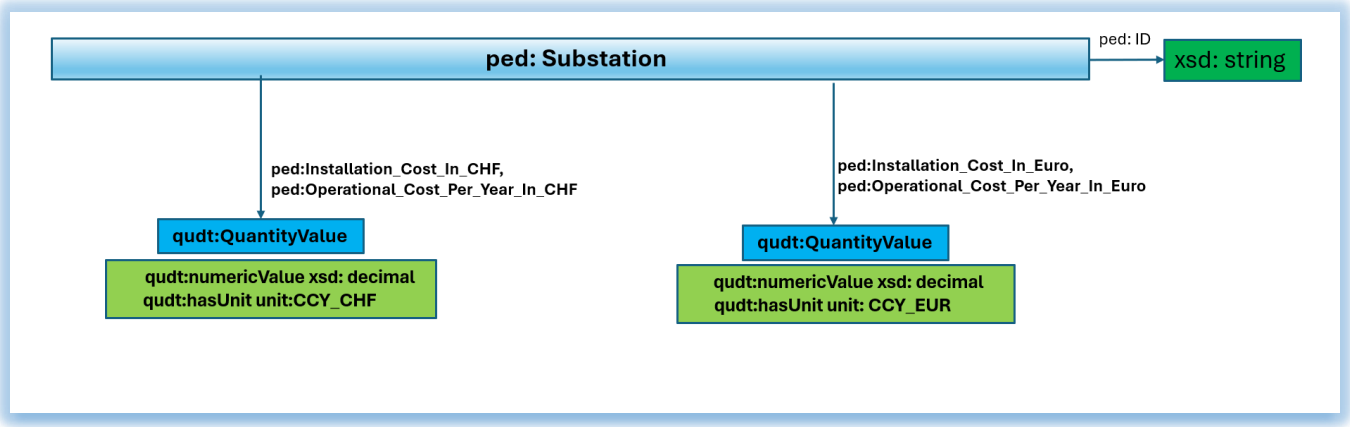


Figure 25: Semantic representation of substation economic properties within the PEDvolution CIM, including installation and operational costs in different currencies.

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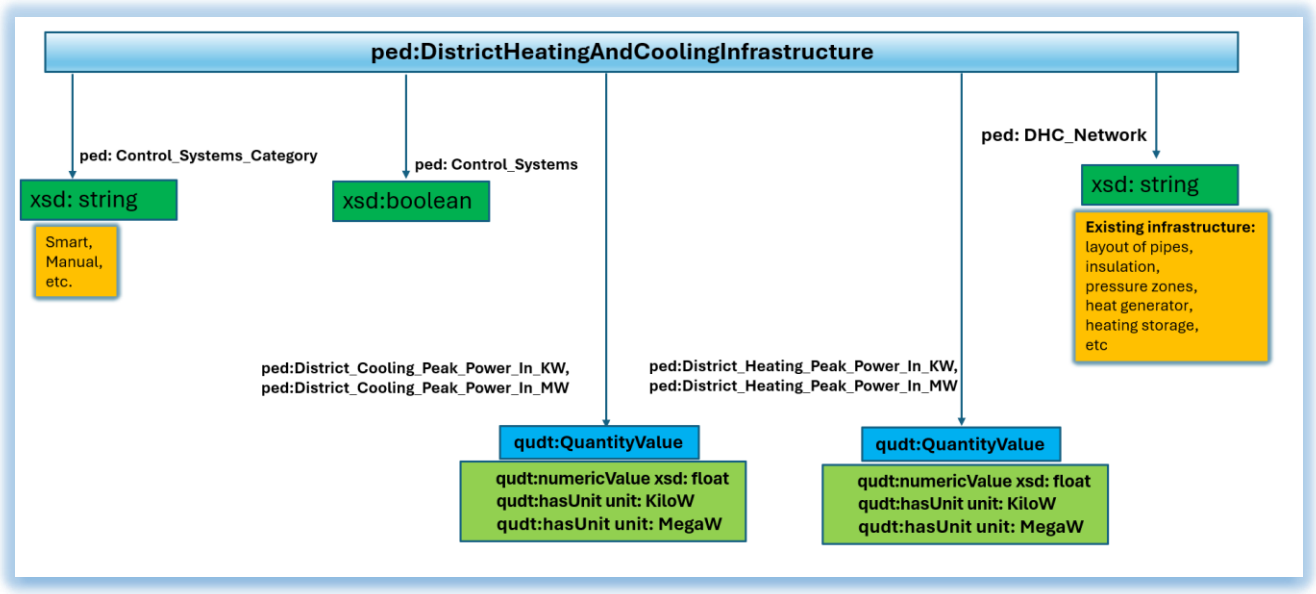


Figure 26: Semantic representation of District Heating and Cooling Infrastructure properties within the PEDvolution CIM, including control systems, network description, and district heating and cooling peak power characteristics.

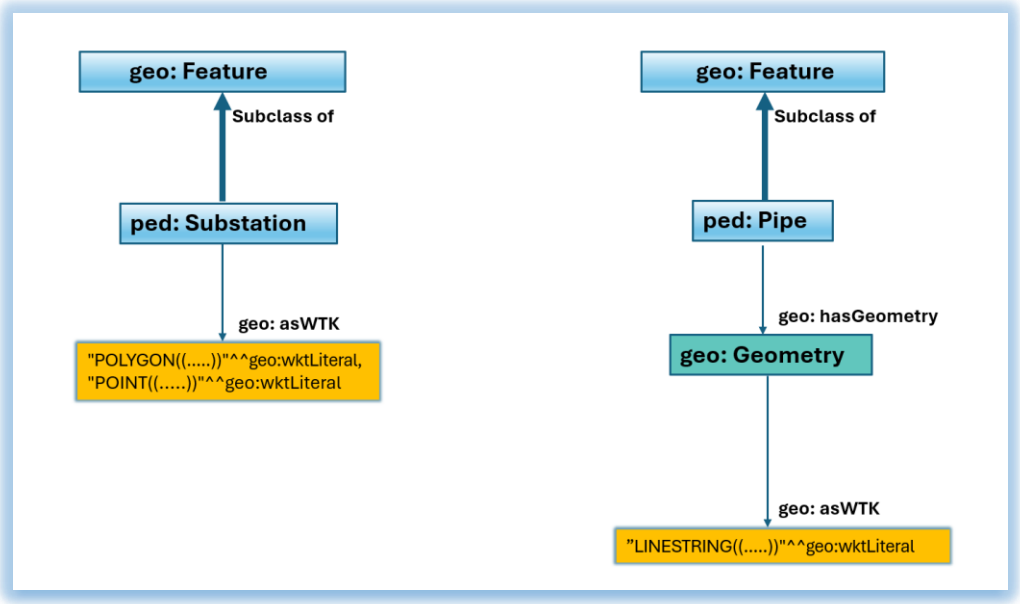


Figure 27: Mapping of the DHC ontology classes and properties to GeoJSON features for geospatial interoperability.

Within the PEDvolution ecosystem, the DHC Infrastructure Ontology provides a semantically enriched framework for representing district heating and cooling systems, supporting interoperability, integration with digital twins, and data-driven optimisation across PEDs.

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2.10.1 Structure and relation to Standard Ontologies

The ontology is aligned with established semantic standards, including QUDT for representing quantitative values (e.g. capacity, heat exchanger size, heat losses, temperatures, and costs) and GeoSPARQL geospatial ontology for modelling topology, spatial relationships, and geometric information. All measurable values are represented as qudt:QuantityValue (qudt:numericValue and qudt:hasUnit), while spatial information is modelled using geospatial properties (e.g. geo:hasGeometry, geo:asWKT). This approach ensures semantic consistency and interoperability across PEDs and Solution Tools.

Conceptual Structure

The ontology models District Heating and Cooling (DHC) systems as a hierarchical structure, where a PED (ped:Ped) is linked to ped:DistrictTechnicalCharacteristics, which includes the district heating and cooling infrastructure (ped:DistrictHeatingAndCoolingInfrastructure).

The infrastructure comprises pipes (ped:Pipe), substations (ped:Substation), and network descriptions, with associated structural and operational properties. Substations are characterised by attributes such as capacity, efficiency, heat exchanger size, and costs, while pipes include properties such as length, diameter, heat loss, and temperature.

All quantitative values are represented using QUDT, and spatial entities are linked through geospatial geometries.

An example of the District Heating and Cooling Infrastructure Ontology using the PEDvolution CIM is provided in ANNEX VI.

2.11 HVAC Systems Characteristics Ontology

The HVAC Systems ontology defines a common semantic model for representing Heating, Ventilation, and Air Conditioning systems within buildings located in a Positive Energy District. Its primary objective within the PEDvolution project is to enable interoperable, structured, and semantically consistent exchange of HVAC-related data between PED platforms and Solution Tools via the Interoperability Platform. The ontology has been specifically tailored to the needs of Solution Providers, supporting use cases such as:

- Energy efficiency assessment.
- Demand response and flexibility services.
- Building-level optimisation.
- Integration with digital twins and simulation tools.

By formalizing HVAC system characteristics, operational modes, and performance indicators, the ontology ensures that heterogeneous data sources across buildings can be integrated, queried, and exploited in a unified manner.

The ontology, presented in Figure 28–Figure 31, builds upon the PEDvolution Common Information Model and extends it with domain-specific constructs for HVAC systems, while maintaining compatibility with widely adopted semantic standards.

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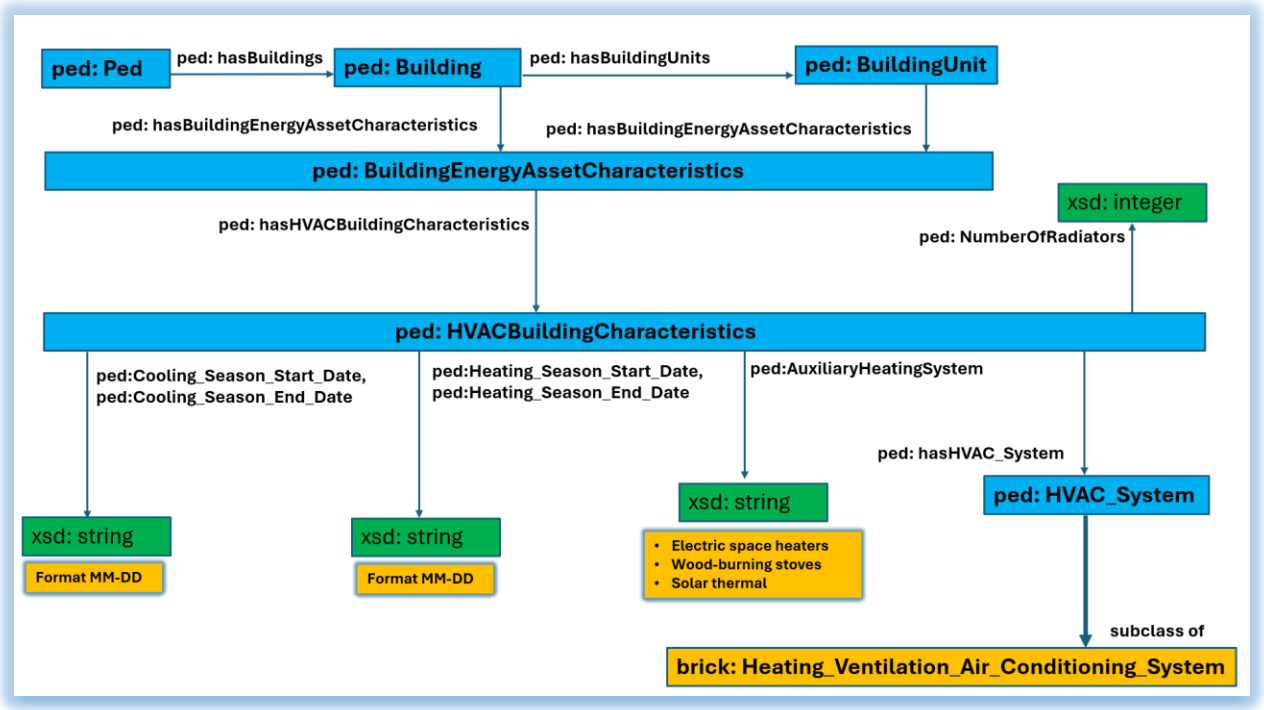


Figure 28: Conceptual overview of the HVAC Systems ontology within the PEDvolution Common Information Model, illustrating the relationships between PED, Building, Building Energy Asset Characteristics, and HVAC Building Characteristics.

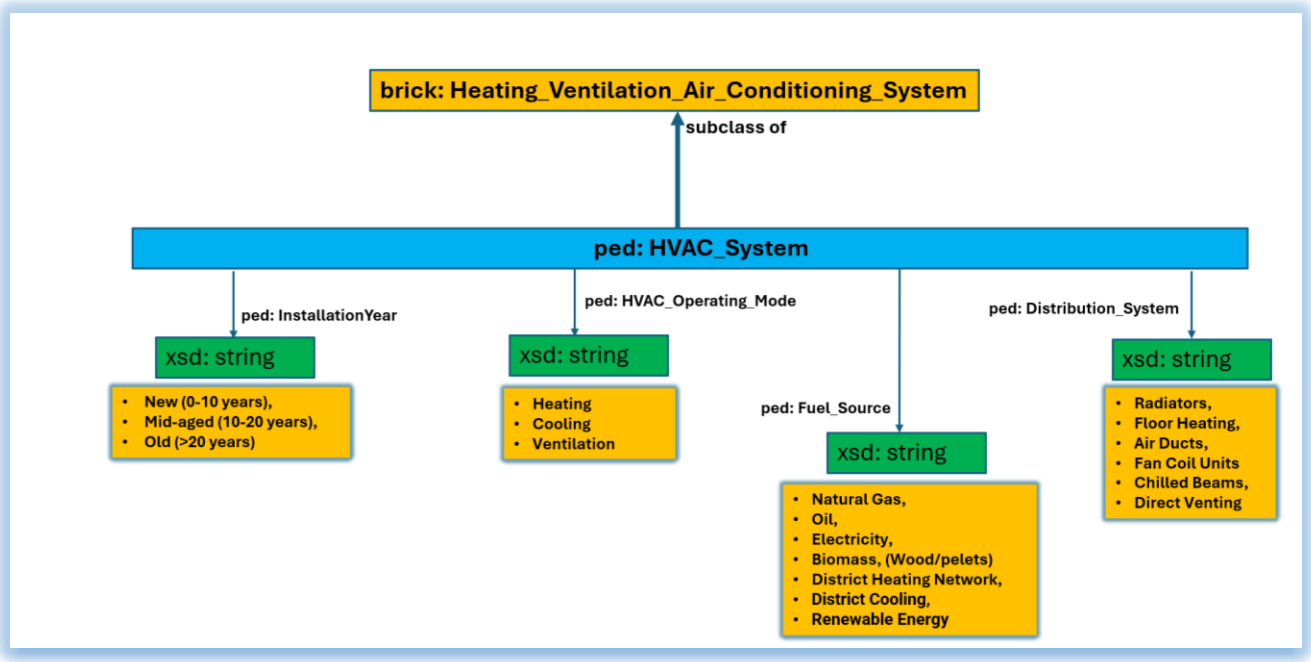


Figure 29: Hierarchical structure of HVAC systems in the PEDvolution ontology, showing the hierarchy of ped:HVAC_System entities and their subclasses.

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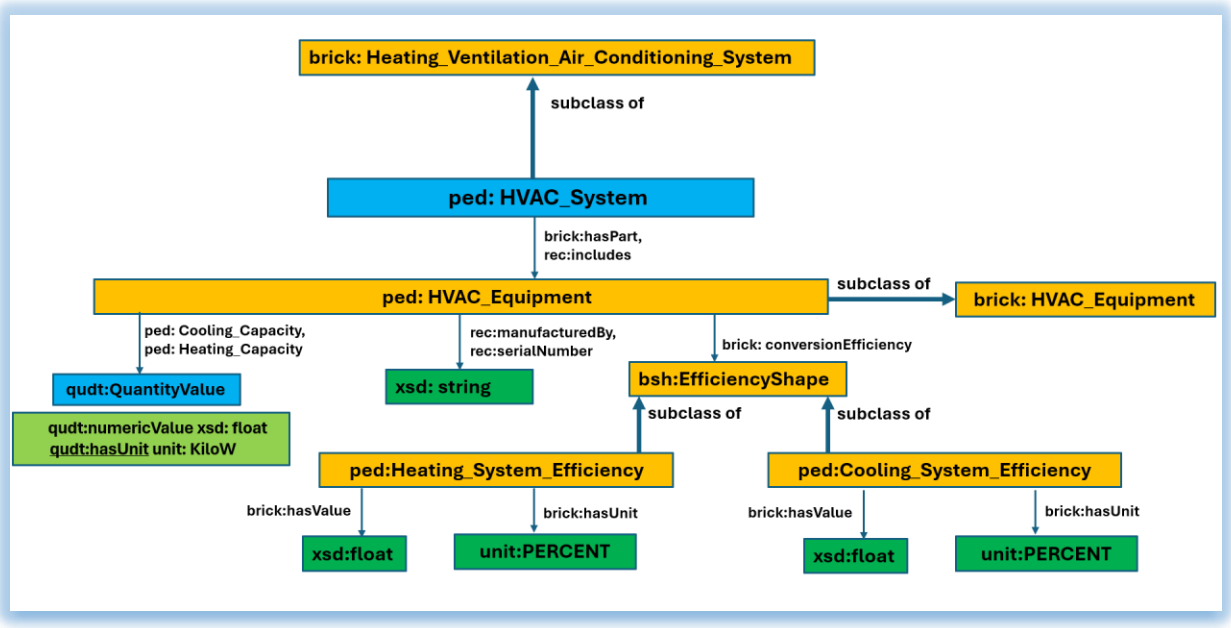


Figure 30: Detailed schema of HVAC system characteristics, including operational attributes such as installation year, fuel source, distribution system, and control mechanisms.

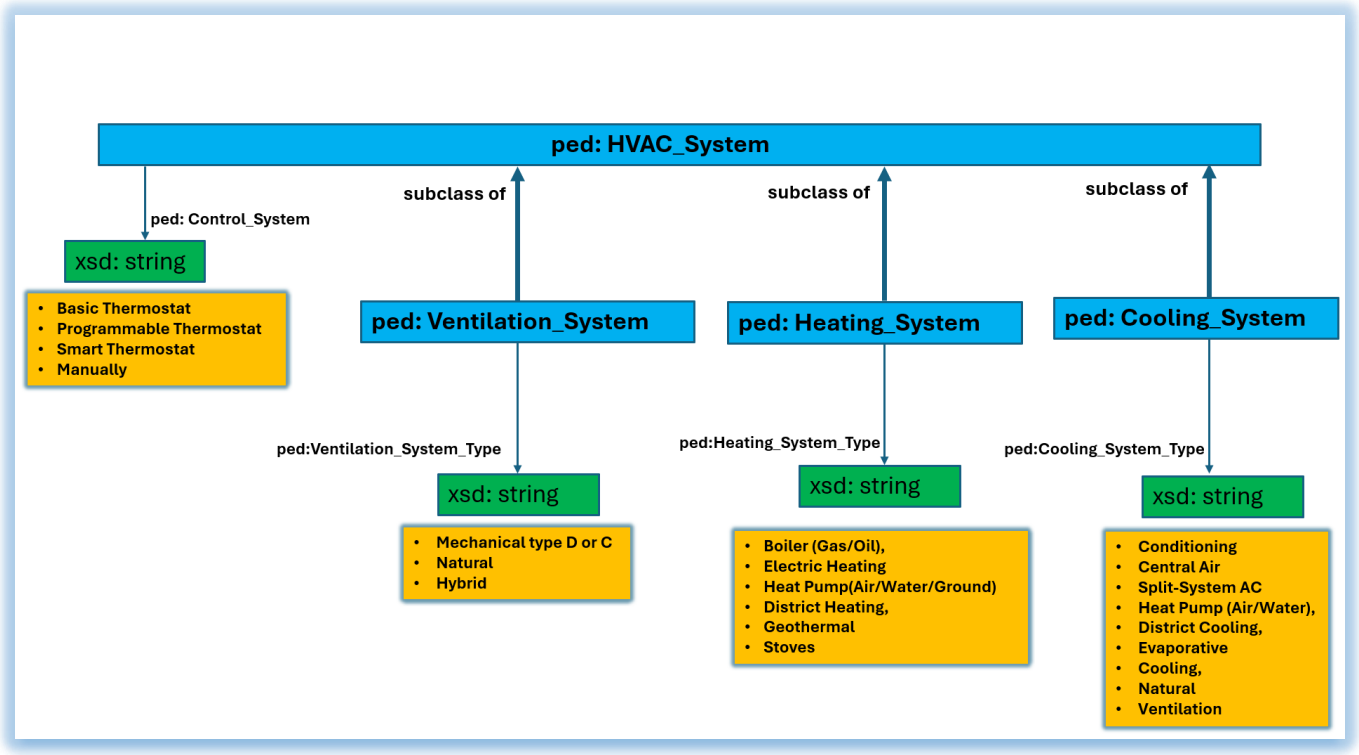


Figure 31: Classification of HVAC system types, including heating, cooling, and ventilation systems, and their respective subclasses within the ontology.

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This ontology contributes to the PEDvolution CIM by enabling the structured representation of HVAC systems as part of the integrated building energy domain within PEDs.

2.11.1 Structure and relation to Standard Ontologies

The HVAC Systems ontology is designed as an extension of the PEDvolution CIM and aligns with established ontologies to ensure interoperability and semantic consistency:

- QUDT for quantitative values and units (e.g., kW, %).
- GeoSPARQL geospatial ontology for spatial representation of PEDs and buildings.
- REC (Real Estate Core) for building and asset modelling.
- SAREF4CITY for district-level representation.
- Brick Ontology for HVAC system representation and equipment modelling.

The ontology follows a hierarchical structure in which a PED (ped:Ped) contains buildings (ped:Building), which may include building units (ped:BuildingUnit). Buildings and building units are associated with energy asset characteristics (ped:BuildingEnergyAssetCharacteristics), including HVAC-specific characteristics (ped:HVACBuildingCharacteristics).

HVAC systems are represented as instances of ped:HVAC_System, a subclass of brick:Heating_Ventilation_Air_Conditioning_System, and include operational attributes (e.g. mode, fuel source, distribution system), system types (heating, cooling, ventilation), control mechanisms, and equipment components (e.g. boilers, heat pumps).

Quantitative parameters such as efficiency and capacity are modelled using qudt:QuantityValue, ensuring unit consistency and machine interpretability, while spatial information is represented through geospatial properties (e.g. geo:hasGeometry, WKT), enabling integration with GIS systems.

Conceptual Structure

The HVAC ontology follows a hierarchical structure linking PEDs, buildings, building units, and HVAC systems. A PED (ped:Ped) aggregates multiple buildings (ped:Building), which may include building units (ped:BuildingUnit), all associated with energy asset characteristics via ped:hasBuildingEnergyAssetCharacteristics.

HVAC-related properties are grouped under ped:HVACBuildingCharacteristics, capturing building-level attributes such as heating and cooling seasons, auxiliary systems, number of radiators, and general HVAC configuration. Buildings may include multiple HVAC systems through ped:hasHVAC_System.

Each HVAC system (ped:HVAC_System) includes operational attributes (e.g. installation year, operating mode, fuel source, distribution and control systems), system types (heating, cooling, ventilation), and associated equipment components.

Equipment is represented as ped:HVAC_Equipment, linked via brick:hasPart or rec:includes, and characterised by attributes such as capacity, efficiency, and identification details. Quantitative parameters are modelled using standard units and numerical values, ensuring consistency and machine interpretability.

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An example of the HVAC Ontology using the PEDvolution CIM is provided in ANNEX VII.

The HVAC Systems ontology provides a semantically enriched framework for representing building energy systems, supporting interoperability, digital twin integration, and data-driven optimisation across PEDs.

2.12 Battery Systems Characteristics Ontology

The Battery Systems Characteristics Ontology defines a semantic model for representing battery-related assets and their operational characteristics within Positive Energy Districts (PEDs). Its primary purpose within the PEDvolution project is to enable standardised, interoperable, and machine-readable representation of battery systems, supporting seamless data exchange between PED platforms and Solution Tools through the Interoperability Platform.

Battery systems play a critical role in PEDs by enabling energy storage, load balancing, and flexibility services, which are essential for optimising energy consumption and integrating renewable energy sources. The ontology captures both static characteristics (e.g., capacity, weight, model) and operational parameters (e.g., voltage limits, discharge currents, temperature constraints), allowing Solution Providers to perform advanced analytics, forecasting, and optimisation services.

The ontology, illustrated in Figure 32 and Figure 33, supports energy storage optimisation, demand response, asset monitoring, and integration with simulation and digital twin environments.

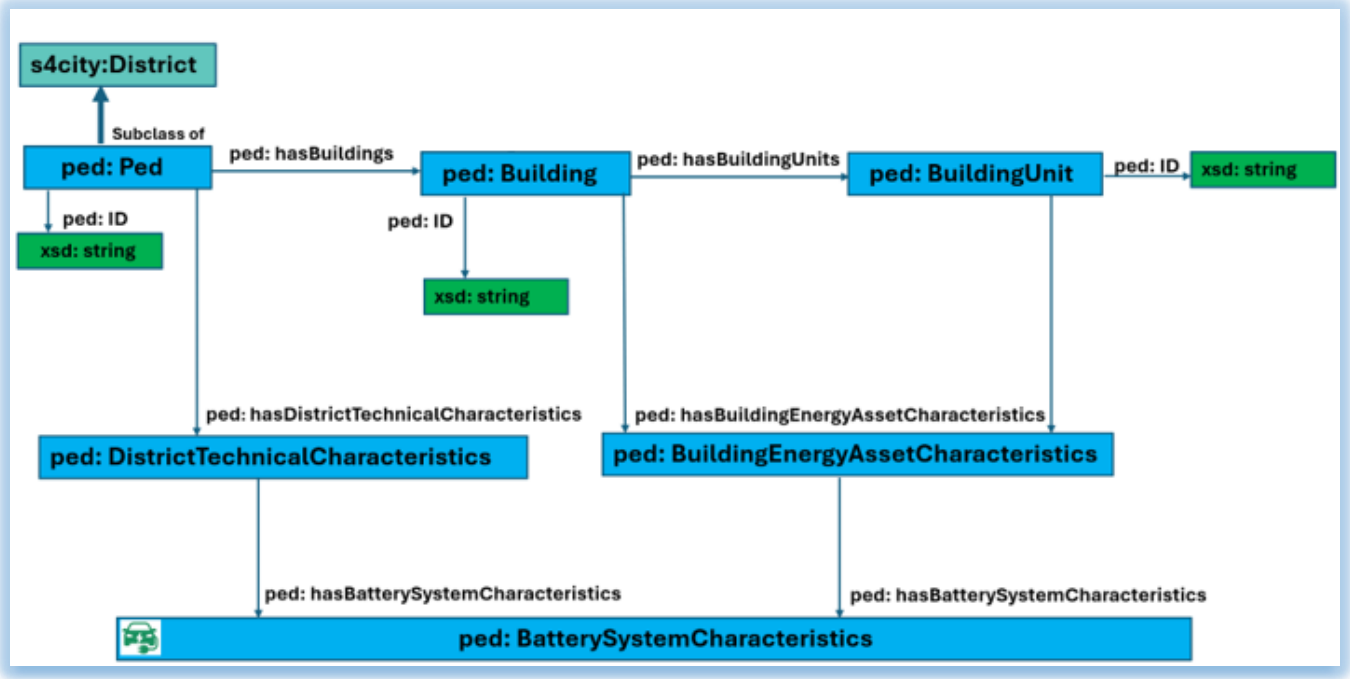


Figure 32: Semantic relationships linking PED-level and building-level entities to Battery System Characteristics within the PEDvolution Common Information Model.

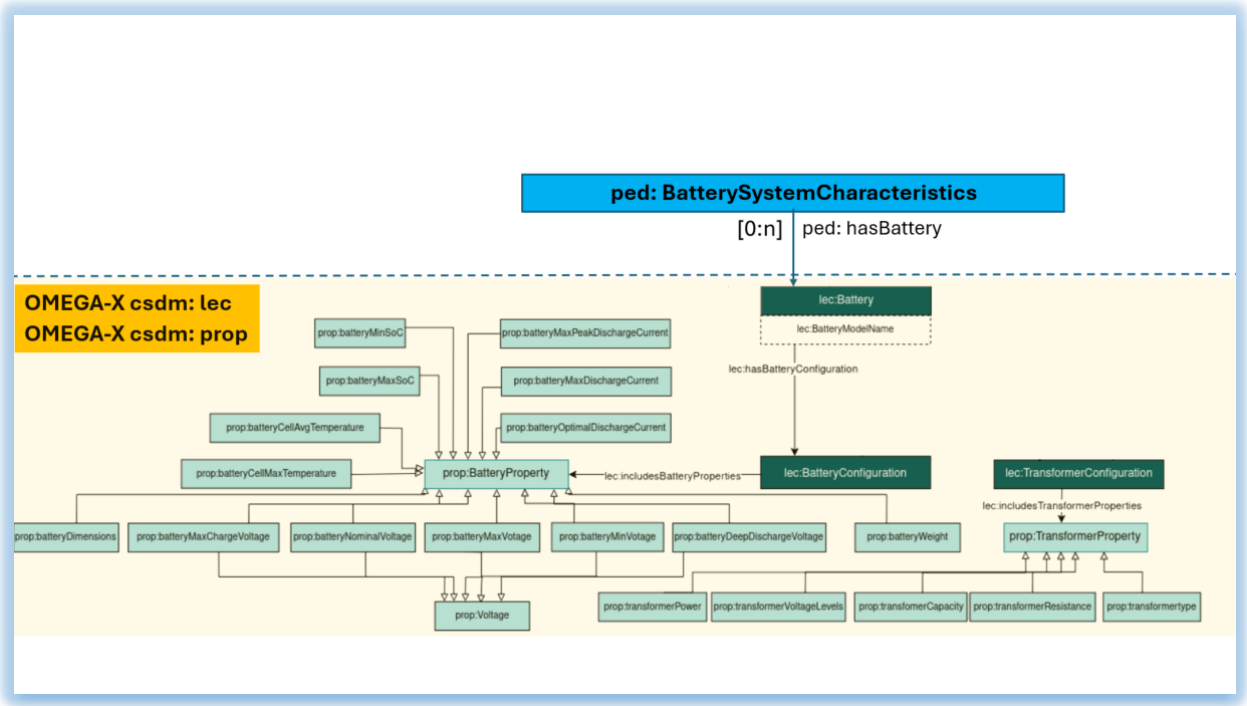


Figure 33: Semantic model linking battery systems to their configurations and properties, integrating PEDvolution ontology elements with OMEGA-X CSDM domain-specific extensions.

The Battery Systems Characteristics ontology provides a robust and extensible semantic framework for representing energy storage assets within PEDs.

2.12.1 Structure and relation to Standard Ontologies

The Battery Systems Characteristics ontology is designed to ensure interoperability by aligning with established semantic standards and domain-specific ontologies. It extends the PEDvolution Common Information Model (CIM) and integrates widely adopted concepts to enable consistent, machine-readable, and interoperable representation of battery system data.

At its core, the ontology incorporates the following standards and ontological frameworks:

- **QUDT (Quantities, Units, Dimensions and Data Types)**
  The QUDT ontology is used for the representation of quantitative values and measurement units (e.g., unit:KiloW-HR, unit:A, unit:V). It enables the standardised modelling of measurable quantities such as energy capacity, voltage, and current, ensuring semantic clarity, unit consistency, and compatibility across heterogeneous systems.
- **OMEGA-X CSDM** Local Energy Communities Ontology (lec:*).
  Classes such as lec:Battery and lec:BatteryConfiguration are used to model battery assets and their structural configurations. These concepts enable the representation of battery systems within the broader context of Local Energy Communities, supporting interoperability between PED Pilots (Data Providers) and Solution Providers.
- **OMEGA-X CSDM Property Ontology** (prop:*)

The Property ontology is used to represent battery-specific characteristics and attributes. Properties such as prop:hasPropertyValue and prop:isMeasuredIn enable the association of battery parameters with their corresponding values and units, supporting a modular and extensible representation of technical characteristics.

- **OMEGA-X CSDM** Event and Time Series Ontology (ets:*)
  Concepts such as ets:value are used to represent the actual numerical values of properties, enabling compatibility with time-series data models and supporting integration with monitoring, analytics, and real-time data processing systems.

The ontology follows a property-based modelling approach, where physical quantities are represented as separate entities, with values linked via prop:hasPropertyValue and units defined via prop:isMeasuredIn. This ensures semantic consistency, extensibility, and compatibility with external data spaces and standards.

Conceptual Structure

The conceptual structure of the Battery Systems Ontology is hierarchical and modular.

At the top level, **ped:Ped** represents the district entity.

This is linked to **ped:DistrictTechnicalCharacteristics** and **ped:BuildingEnergyAssetCharacteristics,** which aggregate battery-related technical infrastructure data.

Within this structure, **ped:BatterySystemCharacteristics** defines battery-related features at the district and building level.

The main asset is: **lec:Battery**, representing an individual battery system which is associated with ped:BatterySystemCharacteristics through the property **ped:hasBattery**.

Each battery is associated with: **lec:BatteryConfiguration**, which groups multiple battery properties.

Battery properties include capacity, voltage characteristics (nominal, minimum, maximum), current limits (peak, optimal, maximum), temperature constraints, and physical attributes such as weight. Each property is modelled as a semantic entity (e.g. prop:BatteryCapacity), linked to a numeric value (ets:value) and an associated measurement unit, enabling fine-grained representation, compatibility with analytics and AI-driven tools, and reuse across different PEDs and use cases.

An example of Battery Systems Characteristics using the PEDvolution CIM is provided in ANNEX VIII.

2.13 Building Construction Characteristics and Occupancy Patterns Ontology

The Building Construction and Occupancy Patterns Characteristics Ontology defines a structured semantic model for representing building-level physical characteristics and occupancy-related information within the PEDvolution ecosystem.

The primary objective of this ontology is to:

- Enable harmonised representation of building data across different PEDs.
- Support semantic interoperability between Data Providers and Solution Providers.

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- Provide context-rich datasets for advanced analytics, data-driven services, and energy optimisation applications.
- Facilitate integration of heterogeneous data sources into the PEDvolution ecosystem.

Within the PEDvolution project, this ontology plays a critical role in:

- Describing building geometry and structural properties (e.g., floor area, height).
- Capturing occupancy characteristics (e.g., number of occupants, household type).
- Supporting cross-domain data exchange, particularly between building, energy, and socioeconomic domains.

This ontology contributes directly to the creation of analytics-ready datasets, enabling the development and deployment of advanced data-driven services within the PEDvolution ecosystem. These include, but are not limited to:

- Energy consumption forecasting and prediction.
- Demand-response and load optimisation strategies.
- Building-level digital twins supporting simulation and real-time monitoring.

2.13.1 Structure and Relation to Standard Ontologies

The Building Construction Characteristics and Occupancy Patterns Ontology is designed following a modular, extensible, and interoperable approach, leveraging established standards and widely adopted semantic models to ensure consistency and compatibility across the PEDvolution ecosystem.

A key foundation of the ontology is the Energy ADE (Application Domain Extension), which extends standard building models (e.g., CityGML) with energy-related semantics. The use of Energy ADE enables the structured representation of building energy-related characteristics and facilitates integration with energy analytics and simulation tools.

The ontology, presented in Figure 34–Figure 41, integrates concepts from the PED domain (e.g. building units, identifiers) and the energy domain (e.g. physical properties, energy characteristics, and occupancy attributes). Leveraging the Energy ADE as a semantic backbone, it ensures consistent representation of building energy characteristics and seamless integration with simulation, analytics, digital twin, and GIS-based tools. This hybrid approach enables semantic interoperability, extensibility, and alignment with European data space architectures.

Within the Building Construction and Occupancy Patterns Characteristics Ontology, the distinction between ped:Building and ped:BuildingUnit is essential for modelling the hierarchical structure of the built environment in PEDs.

ped:Building represents the overall physical entity, capturing attributes such as construction year, cultural classification, address, geospatial location, and association with a PED. In contrast, ped:BuildingUnit represents subdivisions of a building (e.g. apartments, offices, or functional zones) and serves as the primary entity for detailed modelling and data exchange.

A building may contain multiple building units, enabling both aggregated (building-level) and granular (unit-level) modelling, which is essential for capturing occupancy-driven energy behavior and supporting fine-grained analytics.

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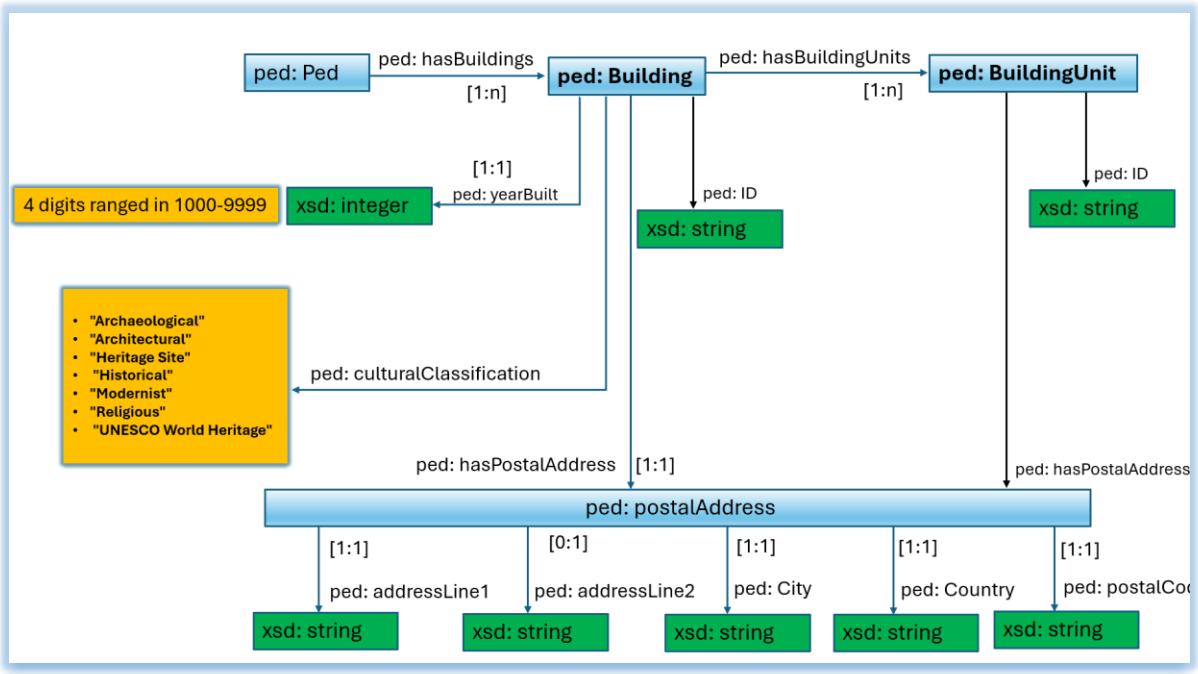


Figure 34: Conceptual model of the Building Construction and Occupancy Patterns ontology, depicting the hierarchical relationships between PED, Building, and Building Unit entities, including key attributes such as year of construction, cultural classification, and structured postal address components.

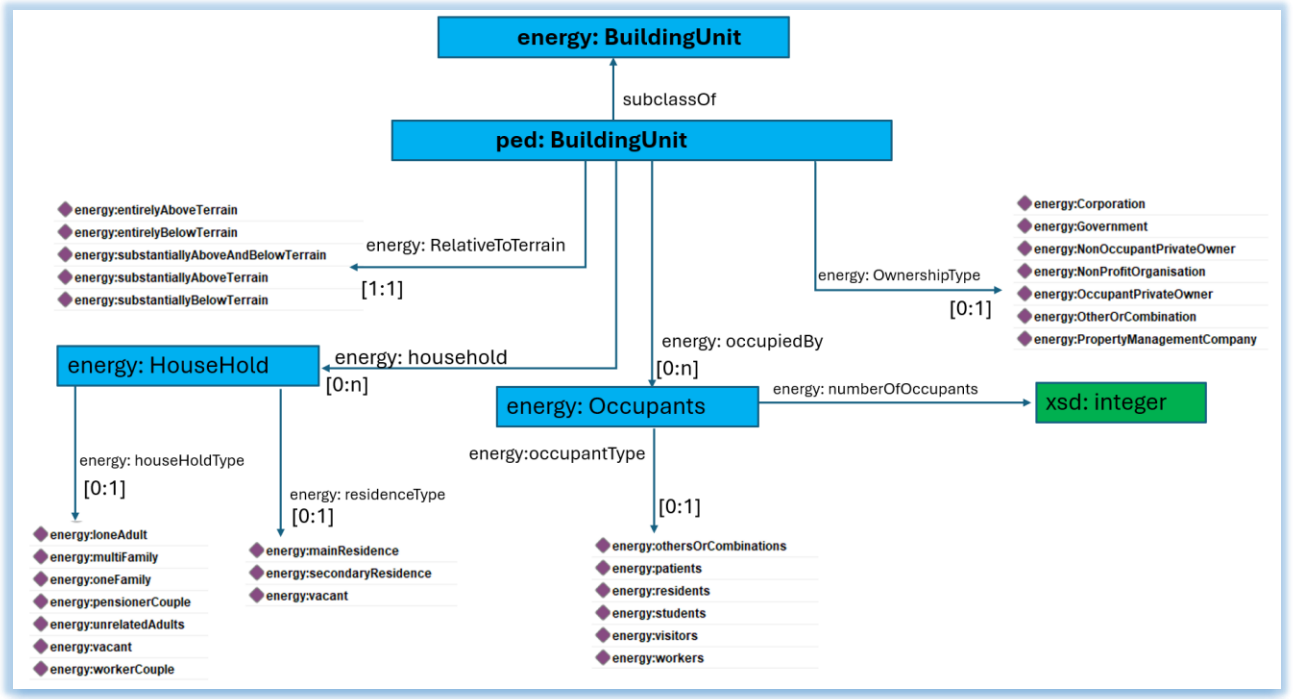


Figure 35: Semantic representation of occupancy and household characteristics within the PEDvolution Common Information Model, illustrating the relationships between ped:BuildingUnit, occupants, household entities, ownership types, residence types, and terrain-relative building classifications using Energy ADE concepts.

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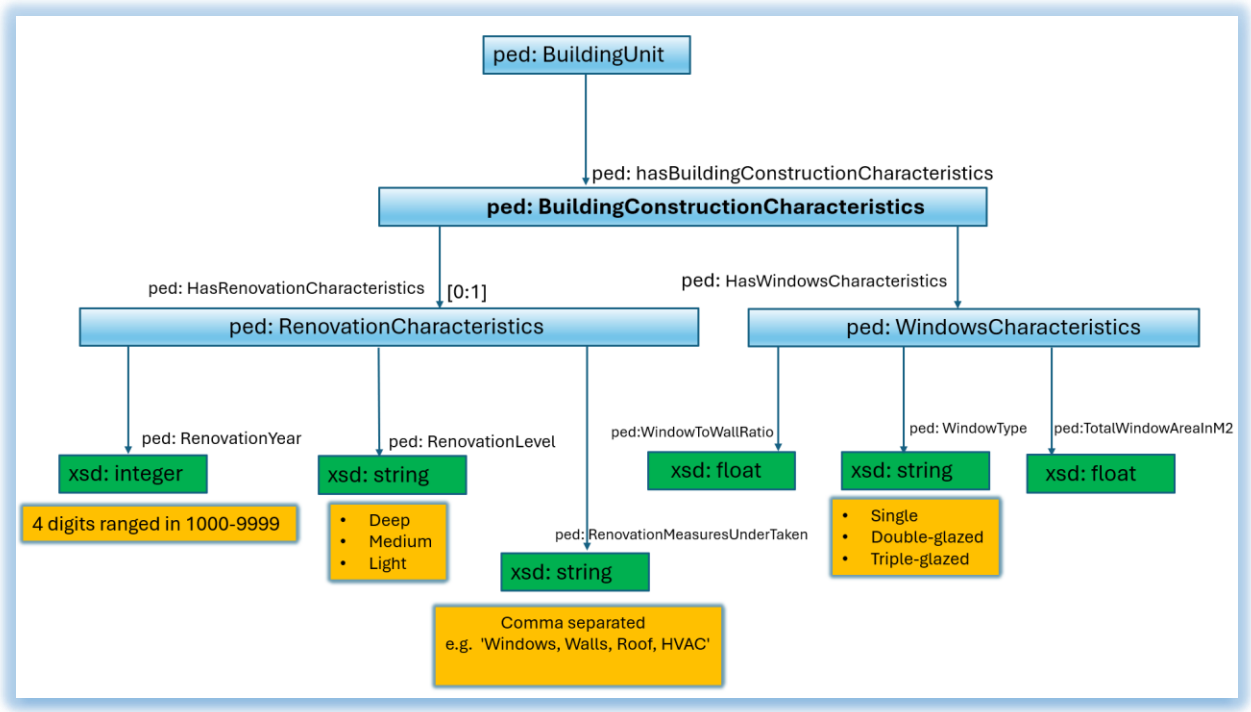


Figure 36: Semantic representation of building construction and renovation characteristics within the PEDvolution Common Information Model, illustrating the relationships between ped:BuildingUnit, building construction characteristics, renovation properties, and window-related attributes, including renovation level, renovation year, window type, and window-to-wall ratio.

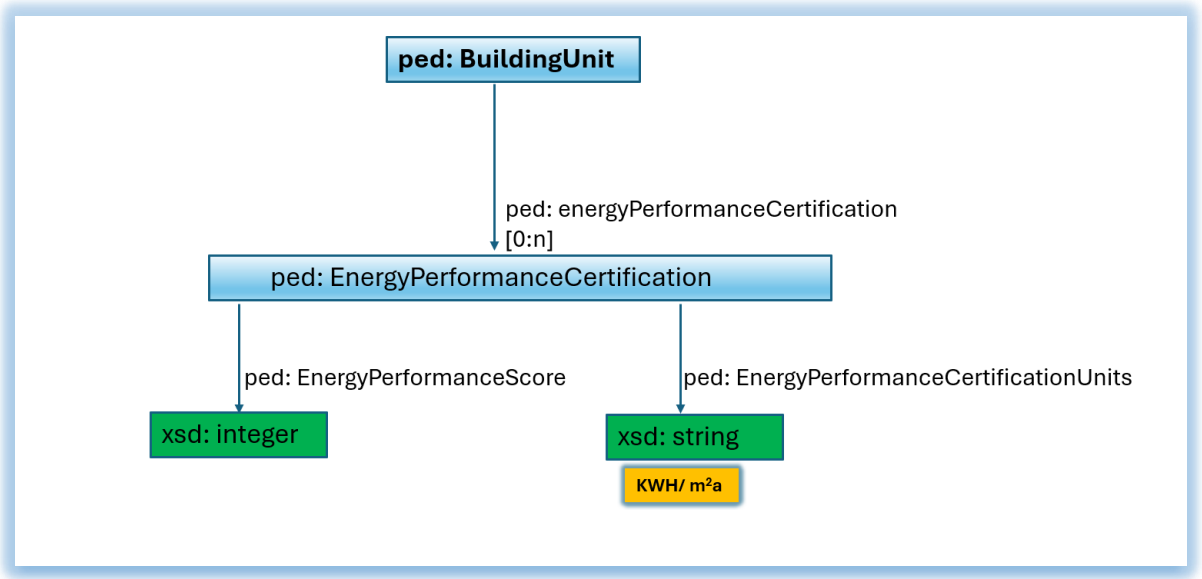


Figure 37: Semantic model of energy performance certification, showing how the ped:BuildingUnit entity is linked to energy performance certification data, including performance score (xsd:integer) and corresponding measurement units (e.g., kWh/m²a).

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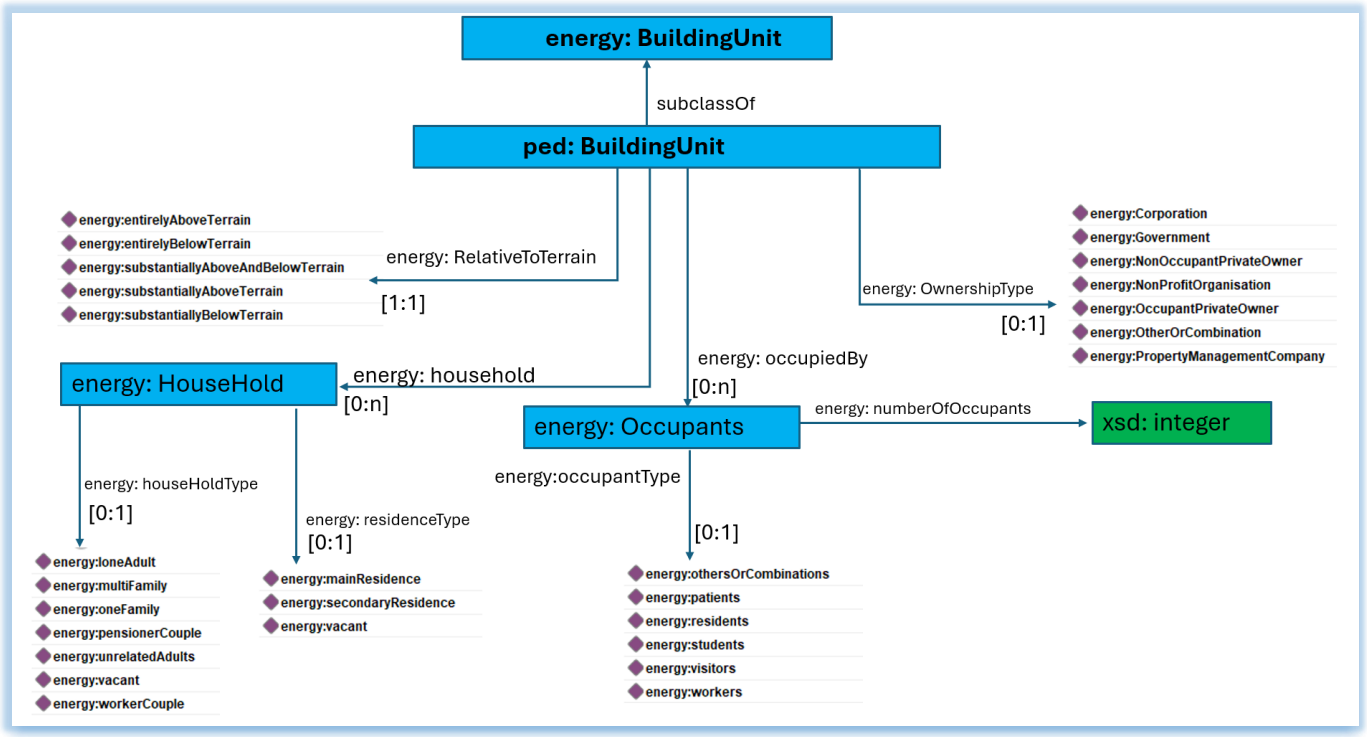


Figure 38: Semantic structure of the Building Construction and Occupancy Patterns ontology, showing the integration of PED and Energy ADE concepts for modelling building units, occupancy profiles, household types, ownership categories, and relative-to-terrain characteristics within the PEDvolution ecosystem.

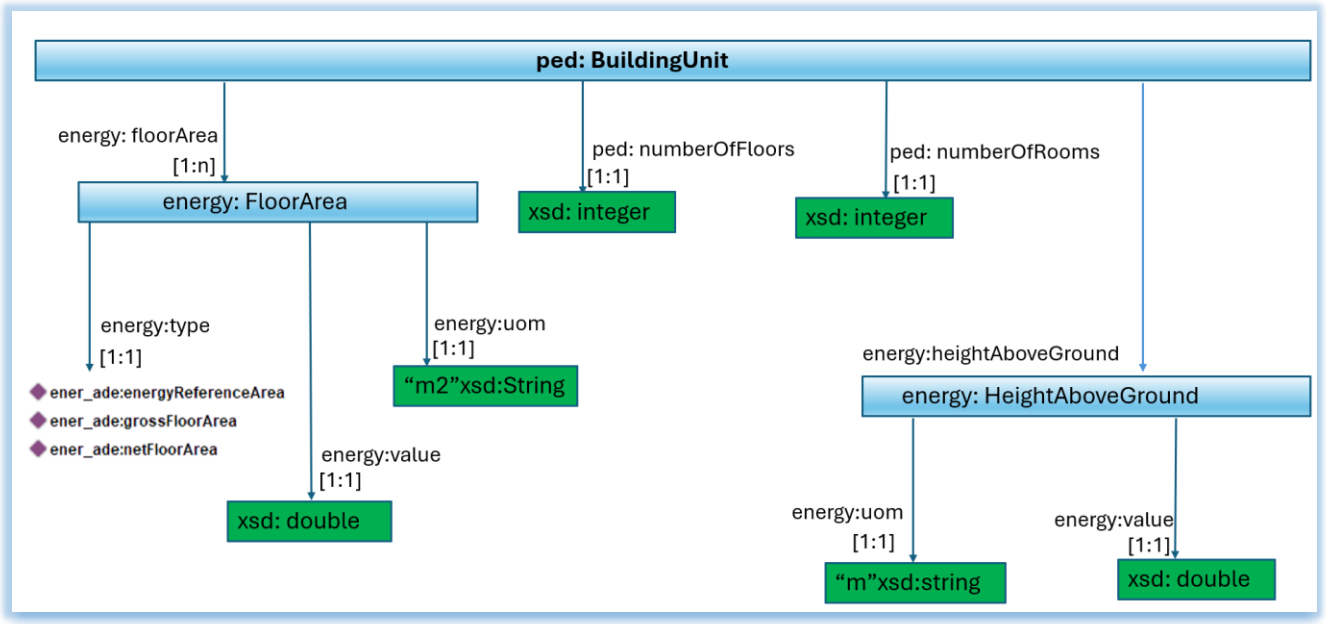


Figure 39: Conceptual model of building construction characteristics, illustrating the ped:BuildingUnit entity and its associated Energy ADE properties, including floor area, height above ground, number of floors, and number of rooms.

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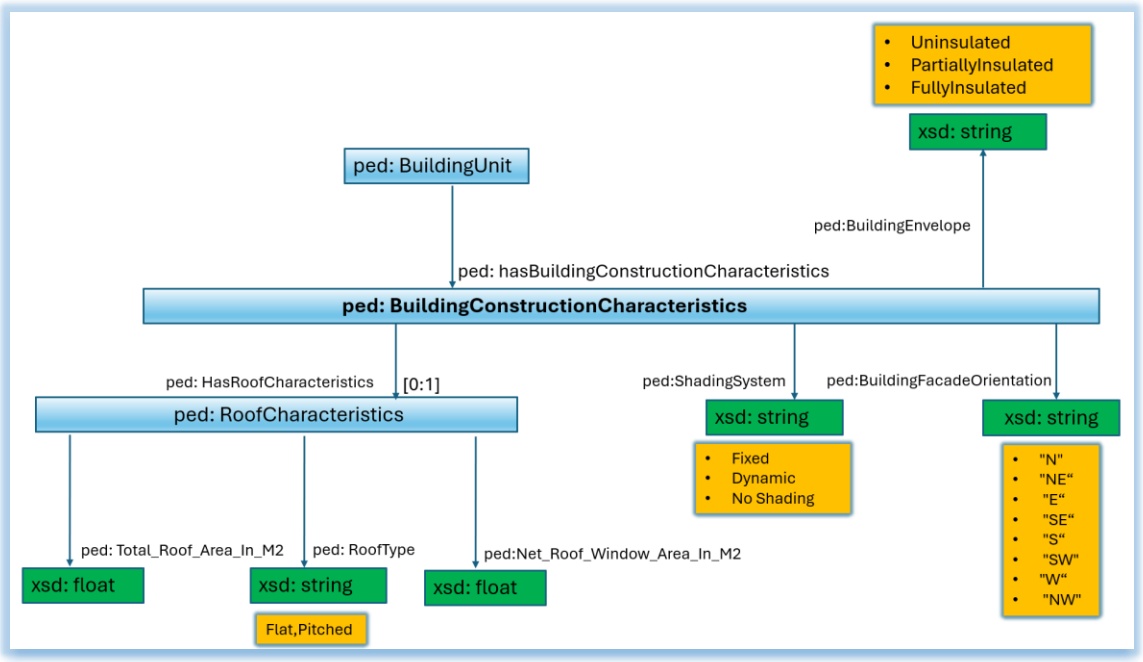


Figure 40: Semantic representation of building construction characteristics, showing the relationship between ped:BuildingUnit and construction-related attributes such as building envelope insulation level, roof characteristics (area, type, window area), shading systems, and facade orientation.

The ontology integrates geospatial concepts to represent PEDs, buildings, and building units, using geo:hasGeometry and geo:asWKT to enable interoperability with GIS platforms, digital twins, and geospatial analytics services.

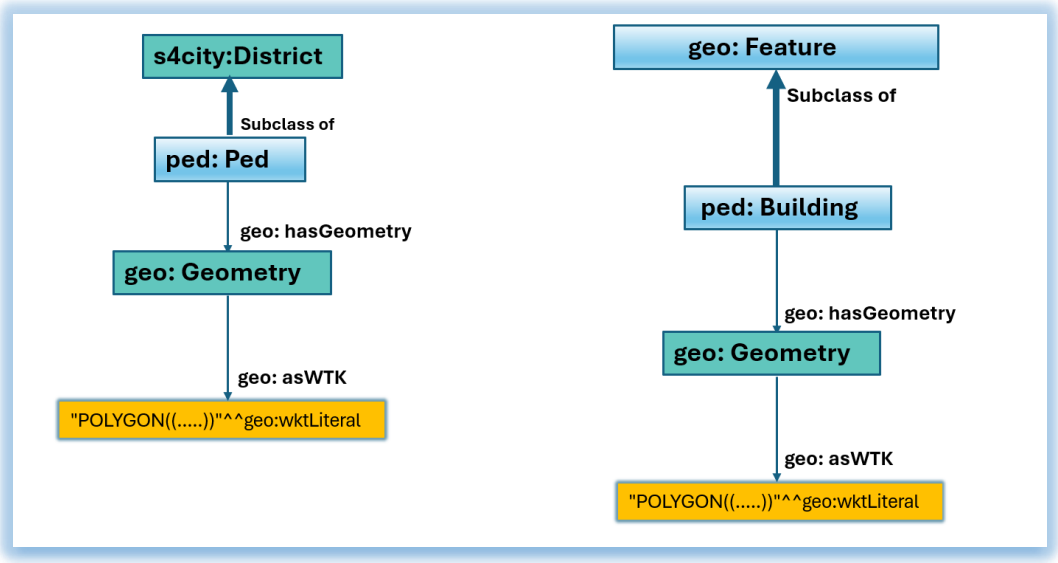


Figure 41: Geospatial representation of ped:Ped and ped:Building entities linked to spatial geometries using geo:hasGeometry and WKT literals (geo:asWKT).

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Conceptual Structure

The ontology models the building unit as a central entity enriched with both technical and socioeconomic attributes. A BuildingUnit represents an individual apartment, office, or functional subdivision within a building, while occupants or households represent the people residing in or using the unit.

Building units are characterised by attributes such as structural properties (e.g. number of floors, rooms, floor area, height), ownership and usage (e.g. ownership, residence, and household type), and occupancy characteristics (e.g. number and type of occupants).

Each BuildingUnit is linked to occupant and household entities and enriched with energy-related properties, enabling the integration of physical infrastructure with human behaviour and supporting multi-domain analytics and realistic modelling of energy demand patterns.

An illustrative example using RDF and JSON representations is provided in ANNEX IX. Within the PEDvolution ecosystem, this ontology enables interoperability, advanced analytics, and integration with digital twin environments.

2.14 Real-Time Measurements

Within the PEDvolution ecosystem, data can be broadly categorized based on their update frequency and temporal characteristics. This distinction is essential for defining appropriate data models, exchange mechanisms, and integration strategies within the Interoperability Platform.

Two primary categories of data are identified:

- **Static or quasi-static data**
  These datasets are updated infrequently, typically on an annual basis or even less often. They include information such as infrastructure characteristics, asset configurations, and technical specifications of buildings, energy systems, and district-level components. Such data has been extensively covered in the previous ontology sections (e.g., HVAC systems, district heating and cooling infrastructure, and battery systems), where the focus is on structural and descriptive representations of PED assets.

- **Real-time data**
  In addition to static or quasi-static data, the PEDvolution ecosystem incorporates dynamic datasets that are updated periodically, ranging from minutes to hours depending on the application context. These datasets capture the operational state and performance of assets and systems.

Real-time data play a crucial role in enabling:

- Monitoring of energy consumption and production.
- Real-time decision-making.
- Optimisation and control of energy systems.
- Support for advanced analytics and AI-driven services (e.g. energy consumption prediction).

Such data originates from both:

- **Residential domains** (e.g., smart meters, household devices), and
- **Industrial domains** (e.g., energy-intensive processes, industrial monitoring systems).

2.14.1 Residential Real-Time Energy Consumption Data

Within the residential domain, real-time data primarily capture the energy consumption behavior of buildings and associated devices. These datasets provide continuous insights into electricity usage, enabling monitoring, optimisation, and intelligent control of energy systems at building level.

The information model for residential real-time measurements is defined through the Energy Consumption Data ontology, which structures device-level measurements in a semantically consistent and interoperable manner. The ontology supports the representation of both instantaneous measurements (e.g., power, voltage, current) and aggregated indicators (e.g., total energy consumption).

Residential Real-Time Energy Consumption Data Conceptual Description

Real-time energy consumption data, illustrated in Figure 42, are typically generated by:

- Smart meters
- IoT-enabled devices
- Building energy management systems

Each measurement instance corresponds to a timestamped observation, associated with:

- A specific device (deviceId)
- A PED context (linkedToPED)
- A set of measured electrical parameters.

The core attributes include:

- timestamp: indicates when the measurement was recorded.
- deviceId: uniquely identifies the measuring device.
- linkedToPED: associates the measurement with a specific PED.
- powerConsumption: instantaneous active power consumption.
- totalEnergyConsumption: cumulative energy usage over time.
- voltage: electrical potential.
- current: electrical current intensity.
- online: device connectivity status.
- energy15minAverage: 15 minutes average energy consumption used for historical data.

All measurable quantities are represented as structured values comprising a numeric value and an associated measurement unit, ensuring consistency with the semantic modelling practices adopted in PEDvolution.

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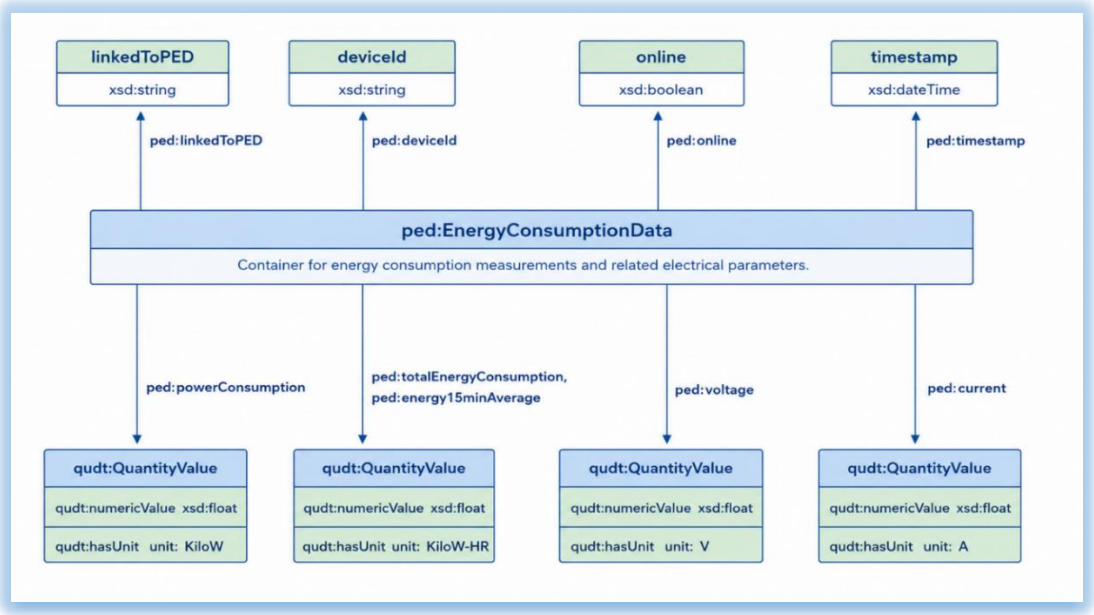


Figure 42: Semantic structure of energy consumption measurements, including device metadata, timestamping, and associated electrical parameters with standardised units.

JSON Representation Example

Figure 43, illustrates an example of a real-time energy consumption measurement in JSON format, as recorded by a smart meter installed in a residential building.


```
{
    "timestamp": "2026-05-22T06:25:43Z",
    "deviceId": "e4b3233b0e84",
    "linkedToPED": "GERMAN",
    "powerConsumption": {
        "value": 10.0,
        "unit": "W"
    },
    "totalEnergyConsumption": {
        "value": 127.7,
        "unit": "kWh"
    },
    "voltage": {
        "value": 233.1,
        "unit": "V"
    },
    "current": {
        "value": 4.0,
        "unit": "A"
    },
    "online": true
}
```


Figure 43: JSON representation of a real-time energy consumption measurement, including timestamped device-level data and associated electrical parameters (power, energy, voltage, current) linked to a PED entity.

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Relation to Ontologies and Standards

The Energy Consumption Data ontology aligns with the broader PEDvolution semantic framework and leverages:

- QUDT ontology for representing measurable quantities and units.
- PEDvolution CIM concepts for linking measurements to PED entities.
- Event-based modelling principles for representing time-dependent observations.

This ensures that real-time data:

- Can be seamlessly integrated with static asset descriptions.
- Remain interoperable across different PEDs and Solution Tools.
- Support advanced analytics and AI-driven services.

Role of residential real-time measurements within PEDvolution Ecosystem

Residential real-time energy consumption data are essential for:

- Real-time monitoring of energy usage.
- Demand-side management and flexibility services.
- AI-based optimisation of energy consumption.
- Integration with digital twins and simulation tools.

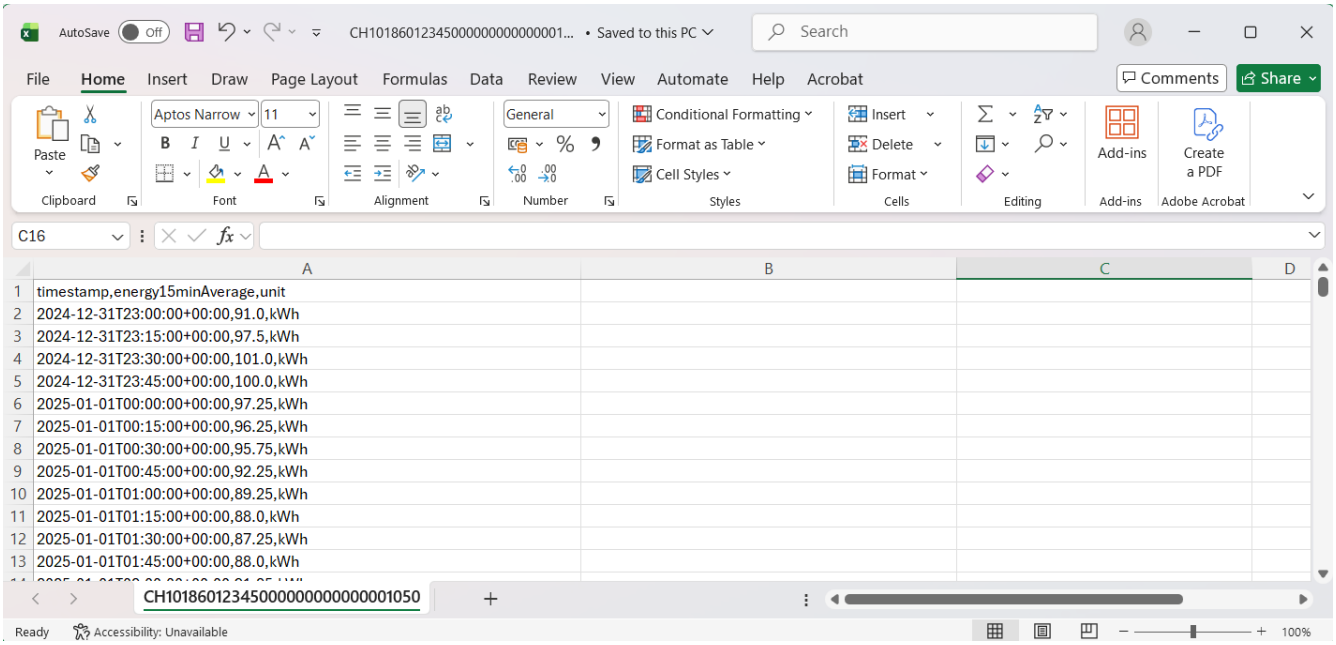
By combining real-time measurements with static asset data, PEDvolution enables a holistic and dynamic representation of energy systems, supporting intelligent decision-making and improved energy efficiency.

Historical Data of residential real-time measurements

In addition to real-time data streams, the PEDvolution CIM supports the representation and exchange of historical measurement data, typically provided in CSV format. Historical datasets consist of time-series records, where each entry includes a timestamp and the corresponding measured value, such as average energy consumption in kWh. As illustrated in the Figure 44, such data can be represented in tabular form, enabling aggregation at different temporal resolutions (e.g. 15-minute intervals) and supporting retrospective analysis, forecasting, and validation of real-time measurements.

The availability of historical data complements real-time monitoring by providing contextual information, enabling trend analysis, and supporting advanced analytics within the PEDvolution ecosystem.

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	A	B	C	D
1	timestamp,energy15minAverage,unit			
2	2024-12-31T23:00:00+00:00,91.0,kWh			
3	2024-12-31T23:15:00+00:00,97.5,kWh			
4	2024-12-31T23:30:00+00:00,101.0,kWh			
5	2024-12-31T23:45:00+00:00,100.0,kWh			
6	2025-01-01T00:00:00+00:00,97.25,kWh			
7	2025-01-01T00:15:00+00:00,96.25,kWh			
8	2025-01-01T00:30:00+00:00,95.75,kWh			
9	2025-01-01T00:45:00+00:00,92.25,kWh			
10	2025-01-01T01:00:00+00:00,89.25,kWh			
11	2025-01-01T01:15:00+00:00,88.0,kWh			
12	2025-01-01T01:30:00+00:00,87.25,kWh			
13	2025-01-01T01:45:00+00:00,88.0,kWh			

Figure 44: Tabular representation of historical energy consumption data (15-minute averages), consisting of timestamp–value pairs (kWh), supporting time-series analysis and integration with real-time measurements.

2.14.2 Industrial Real-Time Measurements

In addition to residential data, the PEDvolution ecosystem incorporates real-time measurements originating from the industrial domain, including energy production assets, industrial facilities, and large-scale energy systems such as photovoltaic (PV) plants and Combined Heat and Power (CHP) units.

These datasets capture operational performance indicators of industrial assets and are essential for monitoring, optimisation, and integration of distributed energy resources within the Positive Energy District (PED) environment.

The data model used for industrial real-time measurements is aligned with the Smart Data Models initiative, which provides standardised schemas for representing context data in interoperable smart applications. This alignment ensures compatibility with widely adopted data models and facilitates integration with external platforms and data spaces.

Conceptual Description of Industrial real-time measurements

Industrial real-time measurements are typically generated by:

- Energy production systems (e.g., PV plants, CHP units)
- Industrial monitoring systems
- SCADA and energy management platforms

Each measurement represents a timestamped observation associated with a specific asset and includes one or more measured parameters.

The core attributes include:

- **AssetId**: unique identifier of the monitored industrial asset, structured as:

  [Country Code] – [Business Entity/PED] – [Prosumer ID] – [building ID] – [Tool ID] – [device ID] – [Asset/Device Id)] – Measurement ID].

  This structure ensures uniqueness, traceability, and alignment with PEDvolution asset identification schemes.
- **Timestamp**: time at which the measurement is recorded, expressed in ISO 8601 format (YYYY-MM-DDThh:mm:ss±hh:mm) and typically normalized to UTC.
- **AssetDescription**: human-readable description of the asset, typically including asset type, name, and optionally location.
- **Items**: a list of measured parameters, each defined by a Name (measurement type, e.g. totalActivePower, aligned with Smart Data Models), a Unit, and a Value.

This flexible structure allows representation of multiple measurements per timestamp, supporting complex industrial monitoring scenarios.

Relation of industrial real-time data models to Ontologies and Standards

The industrial real-time data model is based on Smart Data Models, which:

- Provides standardised and widely adopted data structures.
- Supports interoperability across domains (energy, mobility, environment).
- Facilitates integration with external platforms and data spaces.

Within PEDvolution, these models are aligned with the CIM, integrated with dataspace-based sharing mechanisms, and compatible with real-time data processing pipelines, enabling seamless integration of industrial data into the ecosystem.

JSON Representation example of an industrial asset

Figure 45 presents a representative example of industrial real-time data, demonstrating how measurements from a Combined Heat and Power (CHP) asset are structured and exposed within the PEDvolution ecosystem .


```
{
  "AssetId": "049-001-001-B00-1-00-02",
  "Timestamp": "2025-12-18T01:53:02+01:00",
  "AssetDescription": "CHP 2",
  "Items": [
    {
      "Name": "totalActivePower",
      "Unit": "kW",
      "Value": 213.9
    }
  ]
}
```


Figure 45: JSON representation of a timestamped total active power measurement from a CHP asset in Germany (country code 049 in the AssetId), structured according to Smart Data Models specifications.

Role of industrial real-time measurements within the PEDvolution Ecosystem

Industrial real-time measurements support monitoring of energy production assets (e.g. PV systems, CHP plants), real-time balancing of production and consumption, integration of distributed energy resources, predictive maintenance, and data-driven optimisation at district and cross-PED levels.

Combined with residential real-time data, they enable a comprehensive view of energy flows, supporting advanced services such as energy forecasting, flexibility management, and cross-sector optimisation.

The adoption of Smart Data Models for industrial real-time measurements ensures interoperability with external ecosystems, while enabling PEDvolution to integrate heterogeneous data sources into a unified, semantically consistent, and real-time operational framework.

Within the PEDvolution ecosystem, industrial real-time measurements provide a robust and interoperable framework for capturing and exchanging time-series data from energy production assets. By leveraging Smart Data Models and aligning with the PEDvolution CIM, the model ensures consistency, scalability, and seamless integration across heterogeneous systems, enabling real-time monitoring, analytics, and optimisation.

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3 PEDVOLUTION'S INTEROPERABILITY PLATFORM

The PEDvolution Interoperability Platform has been designed following a *dataspace-by-design paradigm*, which embeds the core principles of European Data Spaces directly into the architectural, functional, and operational layers of the platform. Rather than treating data sharing, security, and governance as add-on features, these aspects are considered foundational design elements from the earliest stages of system conception. The design builds on the results of D7.1 [2] and incorporates functional and technical requirements gathered from PED pilots and Solution Tools.

At the core of this paradigm is the recognition that data within Positive Energy Districts is inherently distributed, owned by multiple stakeholders, and subject to varying regulatory, contractual, and operational constraints. Consequently, the platform architecture avoids centralised data aggregation and instead promotes decentralised data exchange, where data remains under the control of its original provider while being made available for authorised use through clearly defined access and usage policies.

The dataspace-by-design approach adopted in PEDvolution is characterized by the following key principles:

- **Data sovereignty**, ensuring that data providers retain full control over how their data is shared, accessed, and reused. Data sovereignty is supported by ensuring that data ownership and control remain with the original data providers, namely the PED pilots and connected asset owners. The Interoperability Platform does not impose centralised data storage; instead, data remains under the control of the data provider and is shared only when explicitly authorised. The use of dataspace technologies allows data providers to define access policies and usage constraints, ensuring that data is made available to authorised Solution Tools strictly according to agreed conditions. This design enables PED actors to retain full control over their data assets while participating in federated data exchange scenarios.
  This is critical for meeting PEDvolution's security and privacy requirements, as providers can implement granular sharing policies, ensure compliance with GDPR [21] for EU and Federal Act on Data Protection [22] for Switzerland, and adopt techniques like anonymisation and pseudonymisation to protect sensitive user data. It also fosters trust among participants, which is vital when integrating diverse stakeholders and pilots in the project.

- **Decentralization**, avoiding vendor lock-in and enabling peer-to-peer data exchange between autonomous participants. Decentralization is a fundamental architectural principle of the PEDvolution Interoperability Platform. The platform avoids the creation of a central data repository and instead enables peer-to-peer data exchange between participants. Each data provider and consumer interacts through a dataspace-based architecture, allowing multiple independent actors to participate without reliance on a single central authority. This decentralised approach improves scalability, resilience, and alignment with European Data Space principles, while allowing PED pilots and Solution Tools to operate autonomously within the federation.

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- **Usage control**, allowing data providers to specify and enforce contractual and technical constraints on data consumption. Usage control is implemented through policy-driven data access mechanisms that govern not only who can access data, but also how the data may be used. The platform supports the definition and enforcement of machine-readable usage policies that can specify constraints such as permitted purposes, temporal validity, and access conditions. These policies are enforced at runtime by the dataspace infrastructure, ensuring that data consumers comply with the conditions defined by data providers. This capability enables controlled and transparent data sharing across organizational boundaries, a key requirement for trustworthy PED data exchange.

- **Interoperability**, achieved through common semantics, standardised metadata, and aligned APIs. Interoperability is addressed at both technical and semantic levels. At the technical level, the Interoperability Platform provides standardised APIs and connector interfaces that enable seamless integration between heterogeneous systems. At the semantic level, a Common Information Model has been developed to harmonize data representations across PED pilots and Solution Tools. The CIM ensures a shared understanding of entities, attributes, and relationships, enabling consistent interpretation and cross-domain data exchange. By aligning the CIM with established standards and ontologies, the platform ensures extensibility and compatibility with external data ecosystems.

- **Trust and security by design**, integrating identity management, authentication, authorisation, and secure communication mechanisms at platform level. Trust and security are embedded as foundational elements of platform architecture. Secure communication channels, authentication mechanisms, and identity management are integrated to ensure that only trusted participants can join and interact within the dataspace. The platform supports participant verification through API key and secure data transfer, reducing the risk of unauthorised access or data misuse. By combining technical security measures with governance mechanisms and policy enforcement, the platform establishes a trusted environment for cross-organizational data exchange among PED stakeholders and external ecosystems.

Through these design choices, the PEDvolution Interoperability Platform provides a robust and future-proof foundation for secure, sovereign, and interoperable data sharing. By embedding dataspace principles into its architecture, it enables scalable collaboration between PEDs, Solution Tools, and European Data Spaces.

3.1 System Architecture

The PEDvolution Interoperability Platform serves as a data sharing and integration solution, designed as a multi-layered architecture that separates concerns across functional, implementation, deployment, and process perspectives. This layered architectural approach ensures modularity, scalability, and flexibility, enabling the platform to effectively address the heterogeneous requirements of PED pilots and Solution Tools.

The architecture follows a dataspace-aligned design, building upon established European frameworks such as the International Data Spaces Association Reference Architecture Model (IDSA-RAM) [4] and

the Gaia-X framework [5]. By leveraging these standards, the platform ensures interoperability, portability, and seamless compatibility with emerging European Data Spaces ecosystems.

In particular, the IDSA-RAM provides a comprehensive architectural framework for data spaces, defining key principles such as data sovereignty, trusted data exchange, and connector-based communication between participants. It introduces a layered model spanning business, functional, information, process, and system perspectives, enabling the consistent design and implementation of interoperable data sharing infrastructures. Within PEDvolution, these principles are concretely realised through the adoption of Dataspace Connectors, policy-based data exchange mechanisms, and standardised interaction workflows between data providers (PED Pilots) and consumers (Solution Providers).

Complementarily, the Gaia-X framework promotes the development of trusted and sovereign data infrastructures, where data sharing is governed by transparent rules, identity management mechanisms, and compliance frameworks. It emphasizes federated services, identity and trust frameworks, and interoperability standards, ensuring that participants retain full control over data access and usage while participating in a trusted ecosystem.

The Interoperability Platform operationalises these principles through the use of the Eclipse Dataspace Components (EDC) [6], which implement the connector-based architecture defined in IDSA-RAM and enables secure, policy-driven data exchange aligned with Gaia-X federation principles. In this context, EDC acts as the core enabler of decentralised data sharing, supporting contract negotiation, policy enforcement, and secure data transfer between participants.

The separation into distinct architectural layers provides clear abstraction of system responsibilities, enables independent evolution of components, simplifies integration of new services and participants, and improves system maintainability and extensibility.

Furthermore, architecture supports a federated and decentralised data exchange model, where data providers retain full control over their assets, while enabling secure, policy-driven access to authorised consumers. This approach is fully aligned with core Data Space principles, ensuring trust, data sovereignty, and controlled data sharing across organizational boundaries. Figure 46 presents the overall system architecture structured into functional, implementation, deployment, and process layers, aligned with IDSA-RAM and Gaia-X frameworks, enabling secure, sovereign, and interoperable data exchange across the PEDvolution ecosystem.

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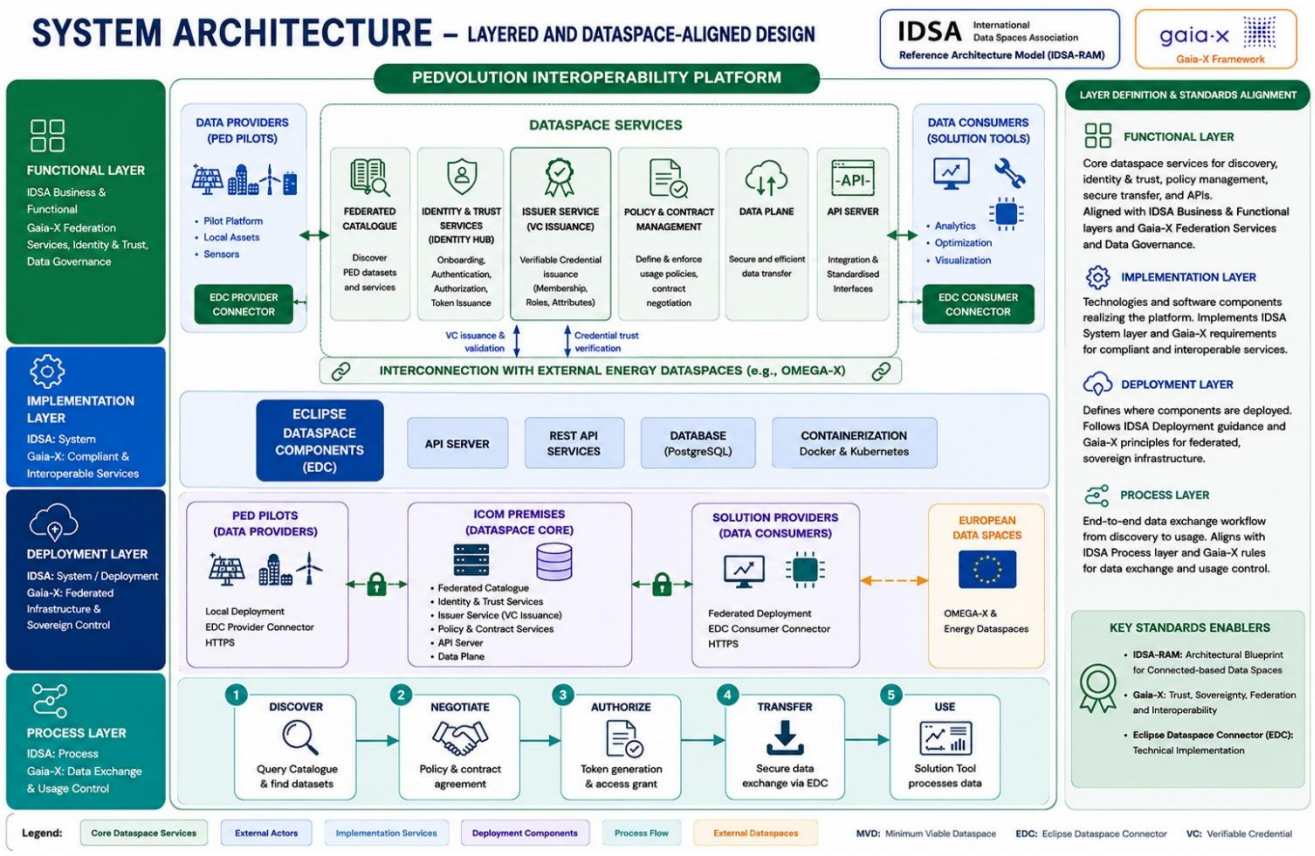


Figure 46: Overall system architecture across functional, implementation, deployment, and process layers, aligned with IDSA-RAM and Gaia-X.

3.1.1 Functional Layer

The Functional Layer of the PEDvolution Interoperability Platform supports the core operations of the dataspace, including data asset registration, discovery, and secure data exchange. It facilitates interactions between data providers and consumers while ensuring efficient and policy-compliant data sharing.

The Functional Layer orchestrates the key processes required for data asset publication, discovery, contract negotiation, and secure data transfer.

The design of the Functional Layer is based on the Minimum Viable Dataspace (MVD) approach [23], as defined by the Eclipse Foundation. The MVD provides a reference architecture for implementing data spaces using Eclipse Dataspace Components (EDC), defining the essential components required for sovereign, trusted, and interoperable data exchange. Within PEDvolution, this approach is adopted and extended to address the specific requirements of Positive Energy Districts and Solution Providers.

The Interoperability Platform follows a decentralised dataspace architecture, where participants (PED pilots, asset owners, and Solution Tools) interact through Dataspace Connectors. To facilitate integration with external systems, the platform introduces an API Server layer that provides simplified and standardised access to dataspace functionalities. Acting as the primary integration entry point, the API Server enables external systems to interact with the platform without requiring direct access to the underlying dataspace infrastructure.

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The API Server is not a native dataspace component, but a wrapper layer built on top of the APIs exposed by the underlying dataspace framework (EDC/MVD). Its primary role is to simplify interaction with the Interoperability Platform by abstracting the complexity of dataspace operations and reducing the number of steps required to execute data exchange workflows.

Dataspace Connectors act as trusted gateways managing the full lifecycle of data exchange, including asset publication, discovery, contract negotiation, and secure transfer. This decentralised interaction model ensures that data exchange occurs directly between data providers and data consumers, without requiring centralised data storage, thereby preserving data sovereignty.

The Functional Layer, as illustrated in Figure 47, comprises the key components of the PEDvolution dataspace solution, enabling interoperability between PED platforms, Solution Tools, and external stakeholders. It highlights the interaction between the API Server, Dataspace Connectors, and supporting services.

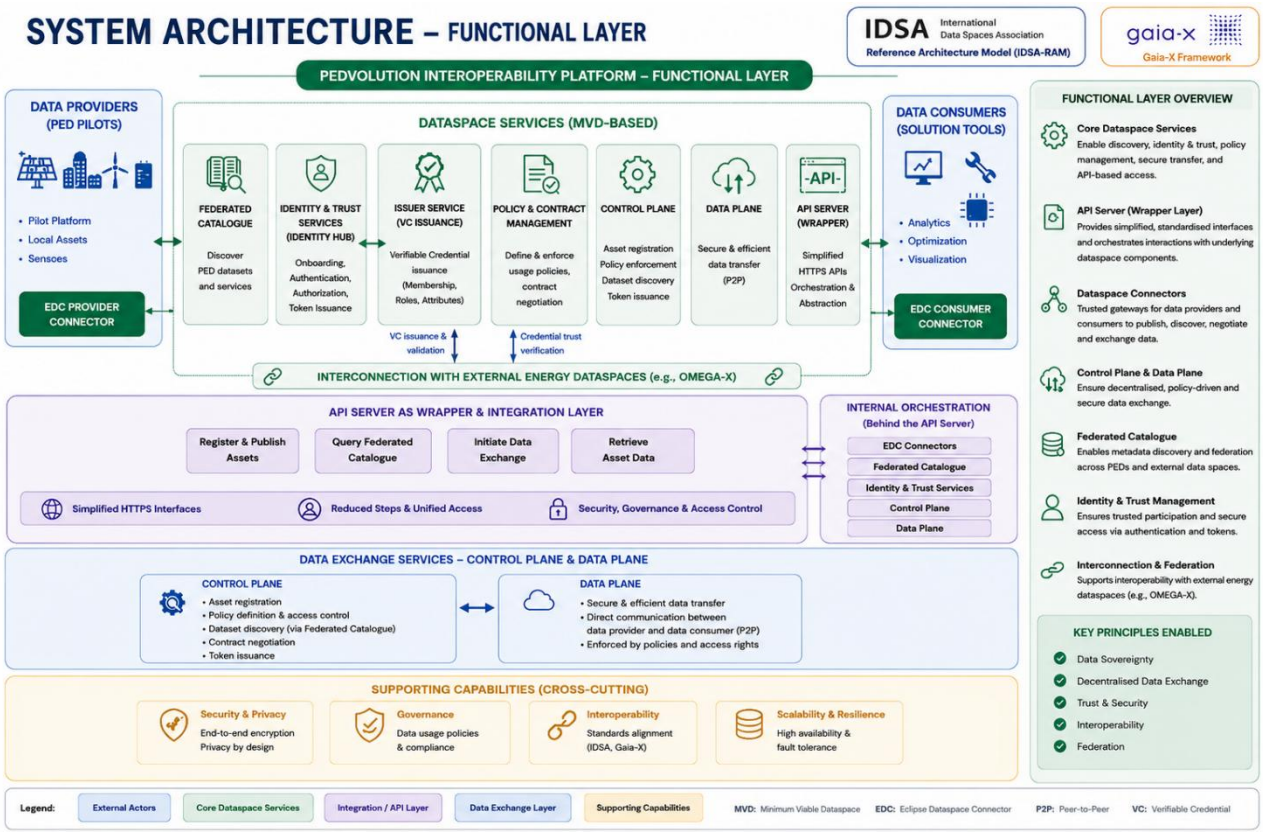


Figure 47: Functional Layer of the PEDvolution Interoperability Platform, illustrating core dataspace services for asset registration, discovery, contract negotiation, and secure data exchange via Dataspace Connectors, and highlighting the API Server as an abstraction and integration layer.

As a fundamental principle of the architecture, no data is centrally stored within the platform; all data exchanges occur directly between participants through Dataspace Connectors.

3.1.1.1 Core Functional Components and Services

API Server as an Integration and Orchestration Layer

The API Server constitutes a key supporting component of the PEDvolution Interoperability Platform, acting as the primary entry point and orchestration layer for all external interactions with the dataspace. It enables PED platforms and Solution Tools to interact with the platform through simplified and standardised HTTPS-based interfaces, without requiring direct integration with Dataspace Connectors or knowledge of internal dataspace mechanisms.

The API Server does not centralise data exchange; all data transfers remain decentralised and are executed directly between Dataspace Connectors, ensuring full alignment with data sovereignty principles.

Through its interfaces, external systems can:

- Register and publish data assets to the Federated Catalogue
- Query the Federated Catalogue
- Initiate data exchange processes
- Retrieve data in a secure and controlled manner via encrypted HTTPS communication

The API Server simplifies the interaction model by:

- Reducing the number of required API calls
- Abstracting complex processes such as contract negotiation and policy enforcement
- Providing a unified access interface across heterogeneous systems

Internally, the API Server orchestrates interactions with core dataspace components, including Dataspace Connectors, the Federated Catalogue, identity and trust management services, and Control and Data Plane mechanisms. It translates high-level API requests into dataspace operations such as asset registration and publication, discovery and querying, contract negotiation, policy validation, token-based authorisation, and secure data transfer.

Security and governance are inherently managed within the dataspace infrastructure, following a security-by-design and governance-by-design approach as defined by dataspace principles and implemented through Eclipse Dataspace Components (EDC) [6].

The API Server operates in alignment with these mechanisms by propagating requests, handling tokens, and coordinating interactions between components. The following security mechanisms are natively supported:

- Authentication and authorisation via Identity and Trust Management services
- Token-based access control, including token issuance, validation, and lifecycle management
- Policy-based usage control implemented within the Control Plane
- Secure peer-to-peer data exchange via the Data Plane

This architectural approach provides several key advantages:

- Data sovereignty by design, as control over data access remains with the provider
- End-to-end trust through identity verification, policy enforcement, and secure communication
- Alignment with European Data Spaces frameworks and principles

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Overall, the API Server acts as a critical enabler of interoperability, usability, and scalability, significantly reducing integration complexity for both data providers and data consumers.

Dataspace Connectors (Provider and Consumer)

Dataspace Connectors constitute the fundamental building blocks of the PEDvolution Interoperability Platform, enabling secure, decentralised, and sovereign data sharing between participants. Within this model, data providers (e.g. PED pilots and asset platforms) expose data assets as governed assets, while data consumers (e.g. Solution Tools) discover and access these assets through standardised and secure protocols. Participants can dynamically assume the roles of data provider, data consumer, or both, enabling flexible and bidirectional data exchange scenarios.

Data Exchange Services (Control Plane and Data Plane)

Data exchange is realised through the coordinated operation of the Control Plane and Data Plane, enabling decentralised and policy-driven data sharing between Dataspace Connectors.

The Control Plane manages asset registration, metadata and policy definition, access control, asset discovery via the Federated Catalogue, and contract negotiation, including transfer initiation and token issuance. The Data Plane is responsible for executing secure data transfer through direct peer-to-peer communication between data providers and consumers.

Policy Enforcement and Security

Integrated policy mechanisms ensure that data is shared only with authorised participants and in accordance with defined usage constraints. During contract negotiation, Dataspace Connectors evaluate the compliance of participant credentials with asset policies. Only when all policy conditions are satisfied is data access granted.

These mechanisms enforce data sovereignty, privacy protection, and regulatory compliance, ensuring that data providers retain full control over how their data is accessed and used.

Federated Catalogue Service

The Federated Catalogue serves as the primary discovery mechanism of the PEDvolution dataspace, providing a structured overview of available data assets through their associated metadata. It enables participants to discover and select relevant assets based on metadata without accessing the underlying data itself.

Within the catalogue, metadata describing data assets is published by data providers through Dataspace Connectors and made available for discovery by authorised participants. This approach ensures that data remains under the control of the provider while enabling interoperable and scalable asset discovery.

Participants can query the catalogue using a range of filtering criteria, including:

- PED identifier
- Asset type
- Time period
- Data format
- Data characteristics

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The Federated Catalogue plays a key role in the data exchange workflow, supporting the asset discovery phase prior to contract negotiation and data access. It allows Solution Providers to identify available assets and retrieve the necessary metadata required to initiate negotiation processes.

In addition, the catalogue supports federation mechanisms, allowing PEDvolution assets to be exposed beyond the project scope and discovered by external ecosystems. This includes integration with European energy dataspaces, such as OMEGA-X, thereby enabling cross-dataspace interoperability and broader data sharing opportunities.

By enabling decentralised asset discovery while preserving data sovereignty, the Federated Catalogue contributes to a scalable, interoperable, and policy-driven dataspace environment.

Identity and Trust Management (Identity Hub)

The Identity and Trust Management component, implemented through the Identity Hub, ensures that only verified and trusted participants can interact within the PEDvolution dataspace. It provides decentralised identity management based on Decentralised Identifiers (DIDs) [24] and supports the use of Verifiable Credentials (VCs) [25] as a mechanism for establishing trust between participants. The concepts of DIDs and VCs are further detailed in the Process Layer section.

Through the Identity Hub, participants are securely authenticated and authorised, enabling trusted interactions without reliance on centralised identity providers. Each participant maintains its own Identity Hub, supporting a decentralised identity management approach across the dataspace. The component supports:

- Authentication and authorisation of participants based on decentralised identifiers (DIDs)
- Validation of Verifiable Credentials (VCs) presented during interactions
- Secure issuance and management of tokens for access control
- Trust establishment between dataspace participants

The Identity and Trust Management component plays a critical role in the data exchange workflow. During contract negotiation, the Verifiable Credentials of a participant are evaluated against the access policies associated with a data asset. Only when the required conditions are satisfied is access granted, ensuring policy-compliant and secure data sharing.

Aligned with dataspace trust frameworks and the Eclipse Dataspace Components (EDC), the Identity Hub enables a secure and interoperable trust environment based on decentralised identity and credential management, supporting data sovereignty and governance-by-design principles within the PEDvolution dataspace.

Issuer Services

Issuer Services are responsible for generating and issuing Verifiable Credentials to authorised participants within the PEDvolution dataspace. These credentials encapsulate attributes such as roles, permissions, and organisational membership, and are used during contract negotiation to support policy-based access control.

Operating as an integral part of the overall trust framework, Issuer Services enable trusted identity assertion and contribute to the establishment of secure and interoperable interactions between dataspace participants.

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3.1.1.2 Interconnection with External Data Spaces

The functional layer supports interoperability with external ecosystems, such as OMEGA-X and other European Data Spaces. Through federated catalogue integration and standardised dataspace protocols, PEDvolution enables:

- Cross-dataspace data exchange.
- Exposure of data assets and services beyond the project scope.
- Participation in broader data-driven ecosystems.

3.1.1.3 Alignment with Data Space Principles

The Functional Layer operationalises key principles defined by the International Data Spaces Association and Gaia-X frameworks, including:

- Data sovereignty
- Decentralised data exchange
- Trust and security
- Interoperability
- Federation

These components correspond to the functional and process layers defined in IDSA-RAM and align with Gaia-X federation services, identity management, and trust services, ensuring compatibility with European Data Space ecosystems.

3.1.2 Implementation Layer

The Implementation Layer of the PEDvolution Interoperability Platform describes the technologies, software components, and deployment mechanisms that realise the functional capabilities of the dataspace. It translates the architectural concepts described in the Functional Layer section into a concrete and deployable solution, aligned with the Minimum Viable Dataspace (MVD) approach, which defines a baseline architecture for dataspace implementations.

The platform is implemented using the Eclipse Dataspace Components (EDC) framework, which provides a modular and extensible framework for sovereign, inter-organisational data sharing. The EDC implements the IDS Dataspace Protocol (DSP) [28], as well as protocols associated with Gaia-X, supporting interoperability across data space ecosystems. The extensible architecture of the EDC allows integration with alternative protocols and adaptation to domain-specific requirements.

Figure 48 illustrates the implementation layer of the PEDvolution Interoperability Platform, highlighting the Eclipse Dataspace Components framework and the API Server acting as a wrapper layer over the dataspace infrastructure.

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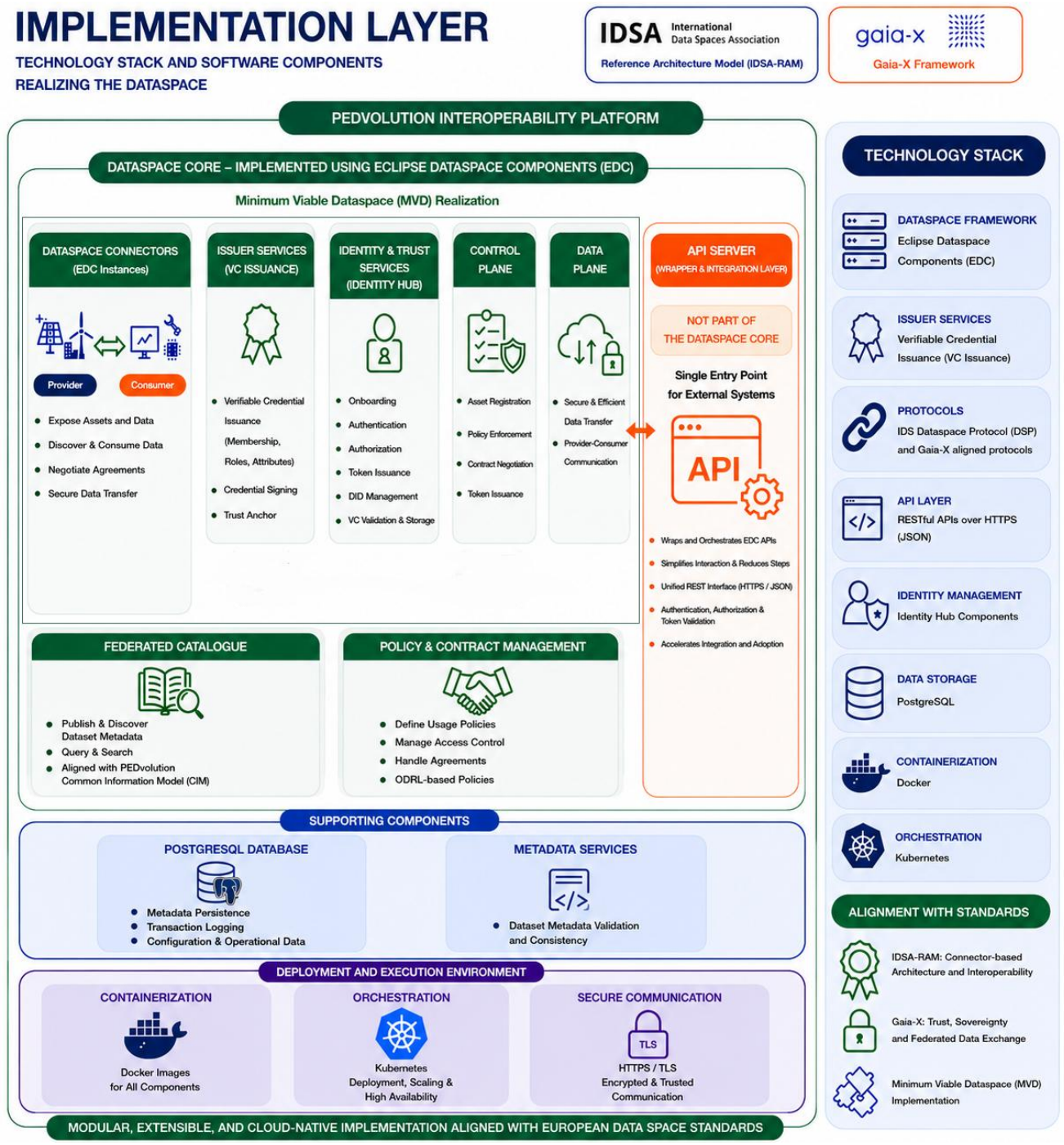


Figure 48: Implementation Layer of the PEDvolution Interoperability Platform, illustrating the technology stack based on Eclipse Dataspace Components, including core dataspace services and supporting components, with the API Server acting as an abstraction and integration layer.

3.1.2.1 Minimum Viable Dataspace (MVD) Realisation

The PEDvolution platform adopts the Minimum Viable Dataspace (MVD) approach as a practical framework for implementing dataspace infrastructures. It defines the minimum set of components required for secure, sovereign, and policy-driven data exchange with trusted participant interactions. In PEDvolution, the MVD is realised using Eclipse Dataspace Components, forming the core infrastructure for decentralised data exchange.

3.1.2.2 Core Implementation Components and Services

Eclipse Dataspace Components (EDC)

The Eclipse Dataspace Components constitute the core technological framework of the PEDvolution Interoperability Platform, implementing the connector-based architecture defined by the International Data Spaces Association Reference Architecture Model [4].

Within the platform, each participant (data provider or data consumer) operates an EDC-based connector instance, which serves as the primary interface for participating in the dataspace. External systems interact with these connectors indirectly via the API Server, which provides a simplified integration layer while preserving the underlying dataspace mechanisms.

Through the EDC connectors, participants are able to:

- Expose data assets as governed and policy-controlled resources.
- Participate in federated catalogue discovery.
- Perform contract negotiation and agreement management.
- Enable secure, policy-enforced data transfer between participants.

Identity and Trust Components (Identity Hub)

Identity and Trust services are implemented through dedicated components (e.g. Identity Hub), enabling decentralised identity management based on Decentralised Identifiers (DIDs) and supporting Verifiable Credentials (VCs) for trusted interactions between dataspace participants.

These components provide:

- Identity management for data providers and data consumers
- Authentication and authorisation mechanisms
- Credential validation and token issuance

These components help ensure that only trusted and verified participants can interact within the dataspace, supporting secure onboarding and access control aligned with dataspace trust frameworks.

Verifiable Credential Issuer Services

Within the Implementation Layer, Verifiable Credential Issuer Services are implemented as dedicated components responsible for the generation, signing, and lifecycle management of Verifiable Credentials (VCs) issued to authorised participants. These services leverage standard cryptographic mechanisms and decentralised identity frameworks to ensure the integrity, authenticity, and verifiability of issued credentials.

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Issuer Services are integrated with the Identity and Trust Management infrastructure (e.g. Identity Hub), enabling seamless issuance and validation of credentials during dataspace interactions. The issued credentials encapsulate participant attributes such as roles, permissions, and organisational membership, and are used by Dataspace Connectors during contract negotiation and policy evaluation processes.

By supporting secure credential issuance and validation, the Issuer Services contribute to the enforcement of policy-based access control and the establishment of a trusted and interoperable dataspace environment, fully aligned with Eclipse Dataspace Components (EDC) and European Data Space trust frameworks.

API Server (Wrapper and Integration Layer)

The API Server is implemented as a wrapper layer on top of the dataspace APIs exposed by the EDC framework, providing a simplified and unified interface for external systems. It is developed using RESTful services over HTTPS, supporting JSON-based communication, secure interactions, and token-based mechanisms aligned with dataspace authentication and authorisation.

By abstracting the complexity of EDC interactions, the API Server simplifies integration, reduces interaction steps, and provides a unified access interface across heterogeneous PED platforms and Solution Tools. It operates as an additional integration layer without modifying the underlying dataspace mechanisms, ensuring full compliance with dataspace principles.

Federated Catalogue and Metadata Services

The Federated Catalogue is implemented as part of the dataspace infrastructure using EDC capabilities, enabling:

- Publication of metadata describing data assets.
- Discovery of available assets across participants.
- Querying based on standardised criteria.

Metadata models are aligned with the PEDvolution Common Information Model, ensuring semantic consistency across the platform.

Data Storage and Persistence Layer

Supporting components such as PostgreSQL [29] databases are used for metadata persistence, transaction logging, and storage of configuration and operational data, ensuring reliable operation, traceability, and monitoring of dataspace activities. Each Dataspace Connector is associated with a dedicated PostgreSQL database, enabling isolation, scalability, and independent management of data exchange processes.

Consumer connector database schema

Figure 49 presents an overview of the PostgreSQL database schema used by the consumer connector within the PEDvolution Interoperability Platform. It illustrates the set of tables that support the internal operation of the Eclipse Dataspace Components (EDC), including asset management, contract negotiation, policy enforcement, identity handling, and data transfer processes.

The schema reflects the persistence layer of the dataspace, where all interactions and transactions are recorded to ensure traceability, auditability, and reliable execution of data exchange workflows. The

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provider connector follows the same database schema, ensuring consistency and interoperability between data providers and data consumers within the PEDvolution dataspace. The primary difference lies in the ownership of the database entities, where the corresponding tables in the provider connector are associated with the *provider* role instead of the *consumer*.

Schema	Name	Type	Owner
public	credential_resource	table	consumer
public	did_resources	table	consumer
public	edc_accesstokendata	table	consumer
public	edc_asset	table	consumer
public	edc_contract_agreement	table	consumer
public	edc_contract_definitions	table	consumer
public	edc_contract_negotiation	table	consumer
public	edc_credential_offers	table	consumer
public	edc_data_plane	table	consumer
public	edc_data_plane_instance	table	consumer
public	edc_edr_entry	table	consumer
public	edc_holder_credentialrequest	table	consumer
public	edc_jti_validation	table	consumer
public	edc_lease	table	consumer
public	edc_policy_monitor	table	consumer
public	edc_policydefinitions	table	consumer
public	edc_sts_client	table	consumer
public	edc_transfer_process	table	consumer
public	keypair_resource	table	consumer
public	participant_context	table	consumer

Figure 49: PostgreSQL database schema of the consumer connector, illustrating the core tables supporting asset management, contract negotiation, policy enforcement, credential handling, and data transfer processes.

Example of real-time data transfer transaction record

Figure 50 presents a database record from the consumer's PostgreSQL table *edc_transfer_process*, capturing a completed data transfer transaction for the real-time asset **zhaw-shelly-plug8-asset-id**. The record corresponds to a successful HTTP data pull operation following contract negotiation and reflects the full lifecycle of the transfer process.

It includes key metadata such as the transfer state, protocol interactions, timestamps, asset and contract identifiers, and communication details between the consumer and provider connectors. This record provides end-to-end traceability and auditability of the real-time data exchange within the PEDvolution dataspace.

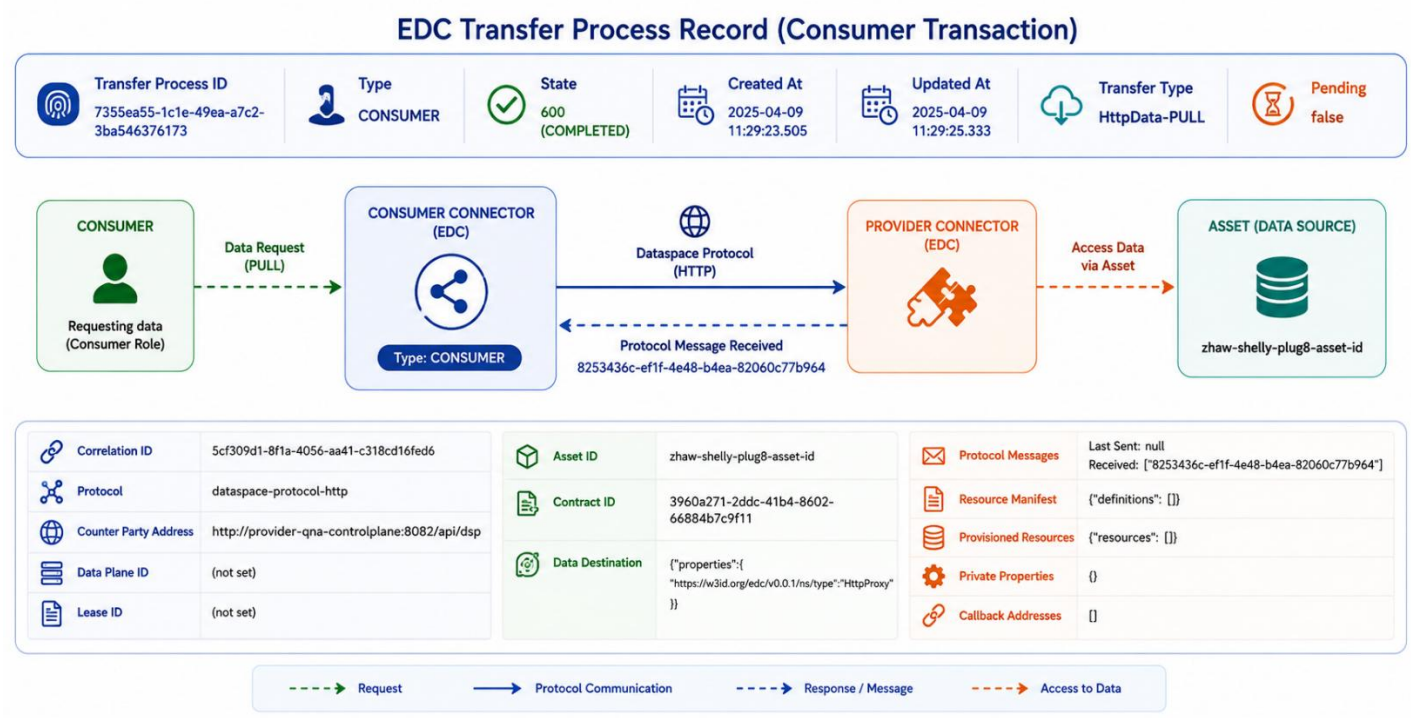


Figure 50: Visualisation of a database record from the consumer's PostgreSQL table *edc_transfer_process*, illustrating a completed real-time HTTP data pull transaction following a successful contract negotiation.

Containerisation and Orchestration

Platform components are deployed using Docker [30] containerisation and orchestrated through Kubernetes [31] environments, providing scalability, high availability, modular deployment, service isolation, and flexibility for distributed and federated deployments.

3.1.2.3 Technology Stack Overview

The PEDvolution Interoperability Platform is implemented using a modern and interoperable technology stack:

- **Dataspace Framework:** Eclipse Dataspace Components (EDC)
- **Protocols:** IDS Dataspace Protocol (DSP), Gaia-X aligned protocols
- **API Layer:** RESTful APIs over HTTPS (JSON-based)
- **Identity Management:** Identity Hub components
- **Data Storage:** PostgreSQL [29]
- **Containerisation:** Docker [30]
- **Orchestration:** Kubernetes [31]

3.1.2.4 Alignment with Data Space Standards

The implementation layer ensures alignment with European Data Space standards by adopting connector-based architectures (IDSA), implementing Gaia-X-aligned protocols, and enabling policy-driven data sharing and interoperability through standardised APIs and semantic models.

Overall, it provides a scalable and interoperable foundation for the PEDvolution dataspace, supporting secure and decentralised data exchange and enabling integration with the broader European data space ecosystem.

3.1.3 Deployment Layer

The Deployment Layer of the PEDvolution Interoperability Platform presented in Figure 51, defines how platform components are physically and logically deployed across the ecosystem, specifying hosting environments, infrastructure distribution, and secure interaction mechanisms between participants.

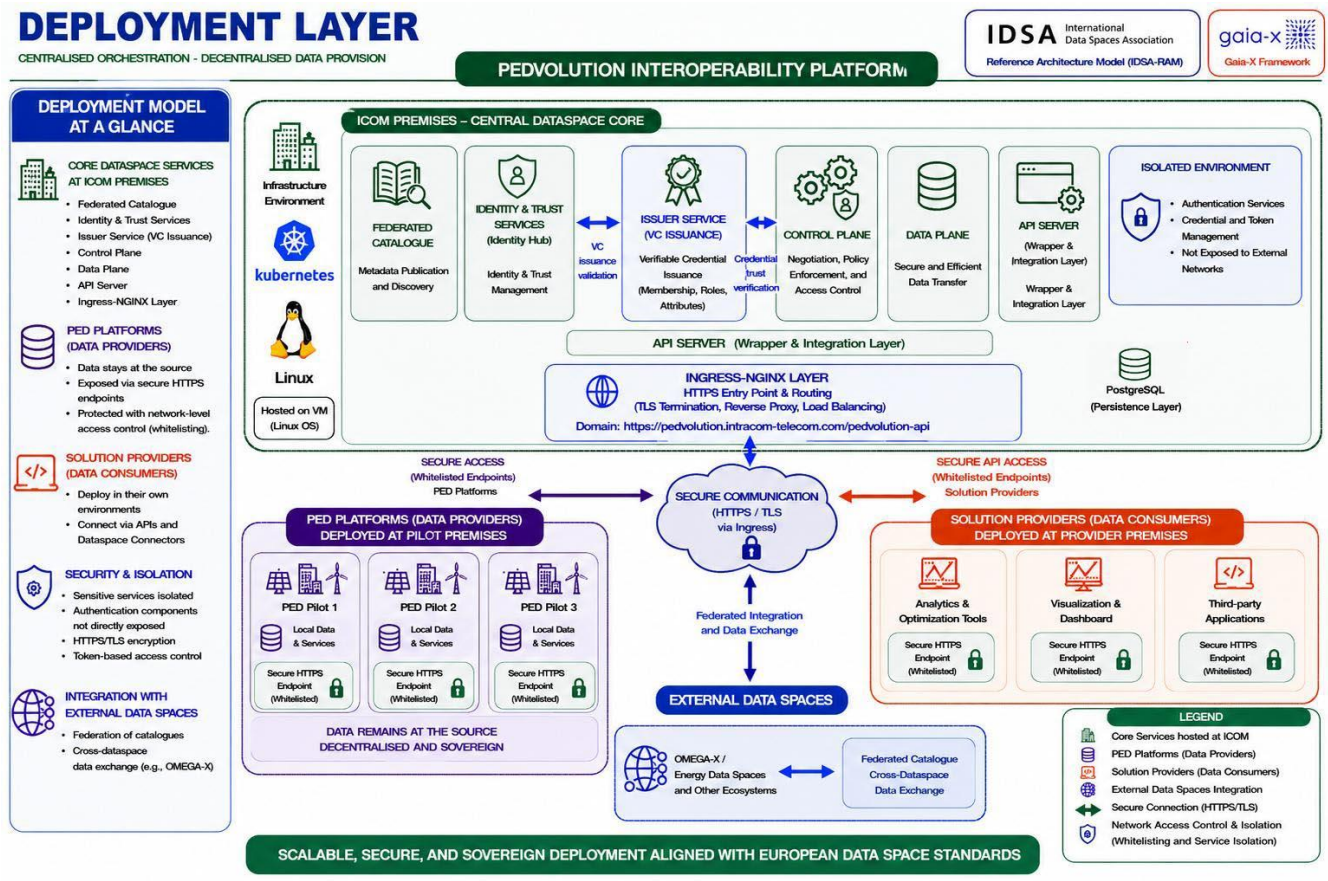


Figure 51: Deployment model of the PEDvolution Interoperability Platform, illustrating centralised orchestration at ICOM premises and decentralised data provision by PED platforms and Solution Providers.

The platform follows a centralised orchestration – decentralised data provision model, ensuring that core dataspace services are centrally managed while data remains under the control of its original data

providers (PED pilot platforms). This approach is fully aligned with data sovereignty principles and enables scalable and secure integration of heterogeneous participants.

The deployment model operationalises the implementation components described in Section 3.1.2, defining their distribution across infrastructure environments.

The platform is hosted on a virtual machine (VM) running a Linux-based operating system, leveraging containerised services orchestrated through Kubernetes [31], ensuring scalability, portability, and efficient resource management.

External access to the Interoperability Platform is provided via controlled HTTPS endpoints exposed through an Ingress layer (NGINX Ingress Controller) [32], which acts as the secure external gateway by performing TLS [33] termination, request routing, and controlled exposure of internal services.

The platform is externally accessible through the following domain:

https://pedvolution.intracom-telecom.com/pedvolution-api

3.1.3.1 Central Dataspace Core Deployment (ICOM Premises)

The core dataspace infrastructure of the PEDvolution Interoperability Platform is deployed and operated at Intracom Telecom (ICOM) premises, providing a stable, secure, and controlled environment for the orchestration of dataspace interactions.

This centralised deployment includes the following key components and services:

- Federated Catalogue
- Dataspace Connectors
- Identity and Trust Services (Identity Hub)
- Issuer Services
- Control Plane and Data Plane services
- API Server (wrapper and integration layer)
- Ingress Layer (NGINX – HTTPS entry point, TLS termination, traffic routing)
- PostgreSQL Data Storage component

Dataspace Connectors can be deployed either centrally or within participant environments, depending on integration requirements, while maintaining logical separation between data providers and data consumers. In the context of the PEDvolution project, connector instances are deployed at ICOM premises alongside the rest of the Eclipse Dataspace Components infrastructure, ensuring simplified integration and coordinated management of dataspace interactions.

These components enable data asset discovery and metadata management, identity verification and access control, contract negotiation and policy enforcement, and the orchestration of secure, policy-driven data exchange workflows.

By hosting these services centrally, the platform ensures high availability, consistent governance, and coordinated operation of the dataspace, while maintaining full alignment with data sovereignty and decentralised data exchange principles.

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3.1.3.2 PED Platforms (Data Providers)

PED pilots act as data providers, exposing their data assets through secure HTTPS endpoints within their local infrastructures. These endpoints remain under full control of PED operators, are accessible to the Interoperability Platform, and are protected through network-level access control mechanisms such as IP or domain whitelisting.

Within the PEDvolution dataspace, data providers publish their data assets through the API Server, which abstracts the underlying dataspace mechanisms and enables the registration and exposure of assets to the Federated Catalogue. This allows assets to become discoverable and accessible to authorised participants while preserving the autonomy of the data providers.

Importantly, data is not centrally stored within the platform but remains at the source and is accessed only when authorised. This design enforces data sovereignty and ensures compliance with regulatory and operational constraints.

3.1.3.3 Solution Tools (Data Consumers)

Solution Tools are deployed within the infrastructure of Solution Providers, acting as data consumers in the dataspace. They connect to the Interoperability Platform via the API Server, retrieve and process data based on authorised access, and operate independently within their environments. This decentralised approach enables flexible integration of analytics, optimisation, and visualisation services without central hosting.

3.1.3.4 Security Architecture and Network Isolation

Security is enforced through a combination of network-level controls, secure communication protocols, and architectural isolation.

Key aspects include:

- Secure communication over HTTPS using TLS encryption for all external interactions.
- Exposure of services via the Ingress layer, ensuring controlled access, TLS termination, and request routing.
- Isolation of sensitive internal services, such as authentication and authorisation components, within protected environments not directly accessible from external networks.
- Controlled exposure of APIs, ensuring that only designated endpoints are accessible to external participants.
- Use of token-based authentication and authorisation mechanisms for secure access control.

TLS certificates for secure HTTPS communication are issued and periodically renewed through a trusted Certificate Authority (e.g., DigiCert) [34], ensuring continuous validity, prevention of service disruption, and compliance with industry security best practices.

Security enforcement mechanisms, including policy validation and access control, are executed within the dataspace infrastructure (EDC Control Plane), ensuring strict enforcement of provider-defined usage constraints.

This layered security approach ensures that the platform meets strict security, privacy, and compliance requirements, while maintaining operational flexibility.

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3.1.3.5 Integration with External Data Spaces

The deployment layer supports interoperability with external data space ecosystems, enabling participation in federated environments through catalogue federation, cross-dataspace discovery and access, and exposure of PEDvolution data assets and services beyond the project scope. This enhances scalability and long-term sustainability, aligning the platform with emerging European Data Space infrastructures.

3.1.3.6 Deployment Model Characteristics

The adopted deployment model enables decentralised data ownership, centralised orchestration, scalability, security, and flexible integration of heterogeneous systems. Overall, the Deployment Layer provides a robust and scalable foundation for the PEDvolution dataspace, ensuring controlled access, interoperability, and alignment with data sovereignty principles within the European data space ecosystem.

3.1.4 Process Layer

The process layer of the PEDvolution Interoperability Platform defines the end-to-end workflows and interaction patterns that enable secure, policy-driven data exchange between data providers (PED Pilots) and data consumers (Solution Tools).

While the Functional and Implementation Layers define what services exist and how they are technically realised, the process layer focuses on how these services are orchestrated in practice, covering the complete lifecycle of data exchange operations.

Within this context, the process layer defines the operational workflows for both data publication and data consumption, specifying how participants interact with the platform through standardised API-based procedures.

The PEDvolution Interoperability Platform adopts a dataspace-driven interaction model, where data exchange is governed by standardised protocols, contract-based negotiation, and policy-driven access control. These processes are implemented using Eclipse Dataspace Components and exposed through the API Server, simplifying workflows and reducing integration complexity.

3.1.4.1 Core Operational Workflows

The platform implements two complementary workflows. Workflow 1 corresponds to the data publication process performed by PED platforms, while Workflow 2 represents the data consumption process carried out by Solution Providers.

- **Data Provider Workflow (2-step process)**
  Enables PED data providers to register and publish data assets to the Federated Catalogue, making them discoverable within the dataspace.
- **Data Consumer Workflow (3-step process)**
  Enables Solution Providers, acting as data consumers, to discover data assets, initiate contract-governed data transfer, and securely retrieve data assets from PEDs through a controlled and policy-compliant process.

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Together, these workflows operationalise the functional capabilities described in Section 3.1.1 and demonstrate the transition from identity and trust establishment to policy-driven contract enforcement and secure data exchange, reflecting the full operational lifecycle of a dataspace interaction.

3.1.4.2 Role of the API Server in the Process Layer

The API Server acts as a process orchestration layer, providing simplified HTTPS endpoints, abstracting dataspace complexity, and coordinating interactions between Dataspace Connectors, the Federated Catalogue, identity and trust services, and Control and Data Plane components. It transforms complex multi-step dataspace interactions into simplified workflows (two steps for data providers and three for data consumers), significantly reducing integration effort.

3.1.4.3 Role of Control Plane and Data Plane in the Process Layer

A fundamental aspect of the process layer is the separation between the Control Plane and the Data Plane, as defined by the EDC architecture. The Control Plane manages data governance, including asset registration, metadata management, contract negotiation, policy enforcement, and access authorisation, while the Data Plane executes secure and scalable data transfer through policy-compliant peer-to-peer communication. This separation enables clear decoupling between governance and execution, supporting independent scalability, enhanced security, and policy-driven data sharing, as illustrated in Figure 52.

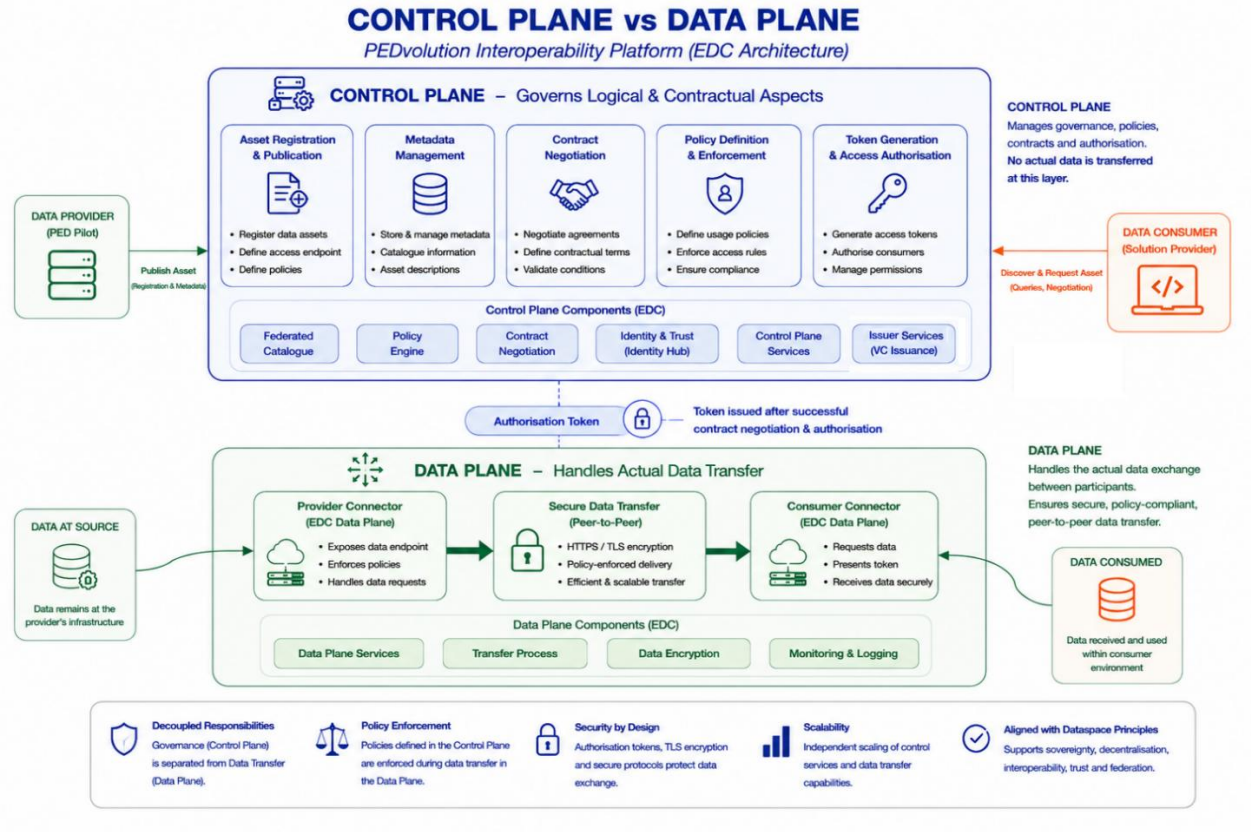


Figure 52: Architectural separation between the Control Plane and the Data Plane in the Eclipse Dataspace Components framework, illustrating the decoupling of data governance processes from data exchange execution.

3.1.4.4 Participant Onboarding, Identity, and Trust Establishment

In addition to data exchange workflows, the PEDvolution Interoperability Platform incorporates identity, trust, and contract management mechanisms, aligned with the Minimum Viable Dataspace (MVD) approach and implemented through the Eclipse Dataspace Components (EDC).

These mechanisms enable the secure onboarding of participants and establish a trusted dataspace ecosystem, where all interactions are verifiable, policy-compliant, and governed by contractual agreements.

Participants (PED platforms and Solution Providers) are onboarded into the dataspace through a policy-governed process involving registration, identity assignment, and configuration of roles and access permissions. Each participant is represented as a trusted entity, acting as a data provider, consumer, or both depending on the use case.

3.1.4.5 Trust Flow and Identity-Based Access Control

Trust in the PEDvolution dataspace follows a decentralised, verifiable model, where participants are identified through Decentralized Identifiers (DIDs) [24] and prove their roles using Verifiable Credentials (VCs) [25]. During interactions, participants resolve DIDs, present credentials, undergo policy evaluation, and establish contract agreements governing data access. This results in the following trust-driven interaction model:

Participant → DID → Verifiable Credential → Policy Evaluation → Contract Agreement → Token → Data Access

This sequence represents the trust lifecycle in dataspace environments, where identity verification and credential validation are prerequisites for policy-compliant contract establishment and controlled data access, ensuring that all interactions are authenticated, authorised, and policy-compliant.

Decentralised Identifiers (DIDs)

Each participant is associated with a Decentralised Identifier (DID) [23], serving as a unique and verifiable identity within the dataspace. DIDs provide globally unique identifiers independent of central authorities, enabling secure identification and interoperability across federated environments, in line with dataspace and Gaia-X principles.

Participants use did:web identifiers managed by the Identity Hub for authentication, contract negotiation, and token-based authorisation. A standard DID string, as illustrated in Figure 53, consists of three core components separated by colons.

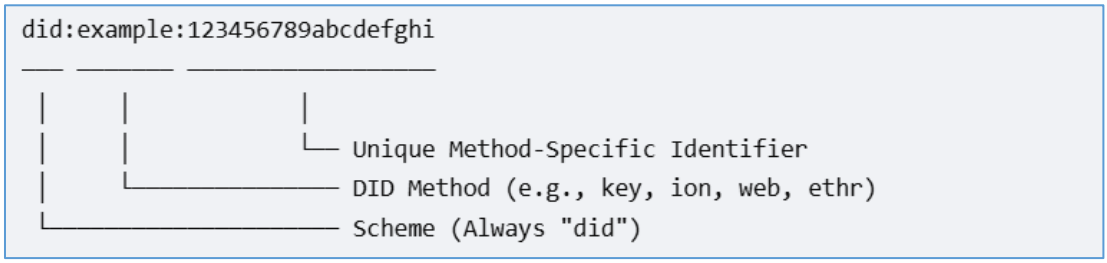


Figure 53: Anatomy of a DID

- **Scheme (did):** The prefix indicating that the string is a decentralized identifier.

- **DID Method (example):** The specific method defining how to look up, create, and manage the DID on a ledger or network.
- **Method-Specific Identifier:** The unique string generated under that specific method (often derived from a cryptographic public key).

An example of a Consumer Participant DID in the PEDvolution ecosystem:

did:web:consumer-identityhub:7083:consumer

- **did:web:** The DID method used by the Eclipse Dataspace Components (EDC). Unlike blockchain-based DIDs, did:web resolves using standard web infrastructure.
- **consumer-identityhub:7083**: This is the hostname and internal network port where the consumer's Identity Hub service is running.
- **consumer**: The sub-path or tenant indicating that this specific identity belongs to the consumer participant.

Verifiable Credentials (VCs)

To establish trust between participants, the PEDvolution Interoperability Platform leverages Verifiable Credentials (VCs) [25], which are digitally signed attestations of an entity's attributes and roles. Within the dataspace, VCs are used to verify identity, validate access rights, and support trust during contract negotiation and data exchange.

Verifiable Credentials are issued by trusted issuer services, which generate and cryptographically sign credentials attesting participant identity, roles, and attributes. These credentials are managed and presented through the Identity and Trust services (Identity Hub), ensuring that only authorised and trusted participants can interact within the dataspace. Verifiable Credentials are associated with participants identified through Decentralized Identifiers (DIDs) and are verified during interactions to enforce secure and policy-compliant data exchange.

Alignment with Dataspace Trust Frameworks

The PEDvolution platform aligns with the Minimum Viable Dataspace (MVD) approach, incorporating decentralised identity management through DIDs and Identity Hub components. While Verifiable Credentials (VCs) are not explicitly implemented as standalone services in the MVD reference, the architecture supports credential-based trust mechanisms, with Identity Hub managing credentials and connectors and control plane components validating them during interactions.

This design enables secure, decentralised, and interoperable trust establishment, aligned with Gaia-X and European dataspace frameworks.

Verifiable Credential Structure and Role in Policy Evaluation

Verifiable Credentials within PEDvolution follow the W3C Verifiable Credentials Data Model [26], where the *type* attribute defines the semantic role of each credential. Within the Minimum Viable Dataspace, implemented using Eclipse Dataspace Components (EDC), Verifiable Credentials are exchanged in the form of Verifiable Presentations (VPs). These are structured according to the W3C Verifiable Credentials Data Model and represented in JSON-LD format [27], encapsulated within JSON Web Tokens (JWT) to ensure secure, efficient and interoperable transmission.

As illustrated in Figure 54, PEDvolution supports multiple credential types representing participant roles within the dataspace.

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Figure 54: Representation of Verifiable Credential structures in PEDvolution, illustrating participant roles (e.g., MembershipCredential and DataProcessorCredential) and their use in policy-based access control during contract negotiation.

The type attribute is particularly important, as it defines the role and capabilities of the participant:

- **VerifiableCredential**: Indicates compliance with the W3C VC data model.
- **MembershipCredential**: Confirms that the participant is a trusted member of the dataspace.
- **DataProcessorCredential**: Specifies that the participant is authorized to process data under certain conditions.

These types are aligned with the Minimum Viable Dataspace (MVD) trust framework and are issued by trusted entities (issuers) within the dataspace ecosystem.

Role of Verifiable Credentials in Policy Evaluation and Negotiation

Verifiable Credentials play a central role during the contract negotiation phase (Workflow 2), where the consumer's MembershipCredential and DataProcessorCredential are evaluated against the access policies of the selected data asset. The MembershipCredential verifies the participant's membership within the trusted dataspace, while the DataProcessorCredential confirms authorisation to process the requested data.

If the credential claims satisfy the defined policies, a contract agreement is established and an access token is issued; otherwise, the request is rejected. This process ensures that data access is governed by verifiable identity and policy-compliant trust mechanisms.

Relationship Between Participants, DIDs, Connectors, and Verifiable Credentials in MVD

In Eclipse Dataspace Components, Participants, DIDs, Connectors, and Verifiable Credentials form the foundation of decentralised identity and trust. A participant may own one or more DIDs as its digital identity, depending on its roles, deployed connectors, and operational requirements. It operates connectors for data exchange and presents Verifiable Credentials to prove its attributes and rights during contract negotiation.

Contract Definition and Agreement

Data exchange in the PEDvolution dataspace is governed by contract-based mechanisms, ensuring authorised and policy-compliant access. The lifecycle includes contract definition by the provider

(specifying access conditions and policies), contract negotiation by the consumer via the Control Plane (including policy validation and credential verification), and contract agreement, where an authorisation token is issued and data access is granted under defined conditions. This approach ensures data sovereignty, policy enforcement, and traceability of all data exchanges.

Integration within Dataspace Workflows

Identity and trust mechanisms are integrated across data exchange workflows: policies and contracts are defined during asset publication, credentials are validated and agreements negotiated during data consumption, and tokens enforce access control during data transfer. The Control Plane manages identity, credentials, and contracts, while the Data Plane ensures policy-compliant data execution.

Alignment with Dataspace Frameworks

The use of DIDs, Verifiable Credentials, and contract-based data exchange ensures alignment with IDSA-RAM, Gaia-X, and Minimum Viable Dataspace (MVD) guidelines. This approach, illustrated in Figure 55, establishes PEDvolution as a trusted, interoperable, and standards-compliant dataspace ecosystem.

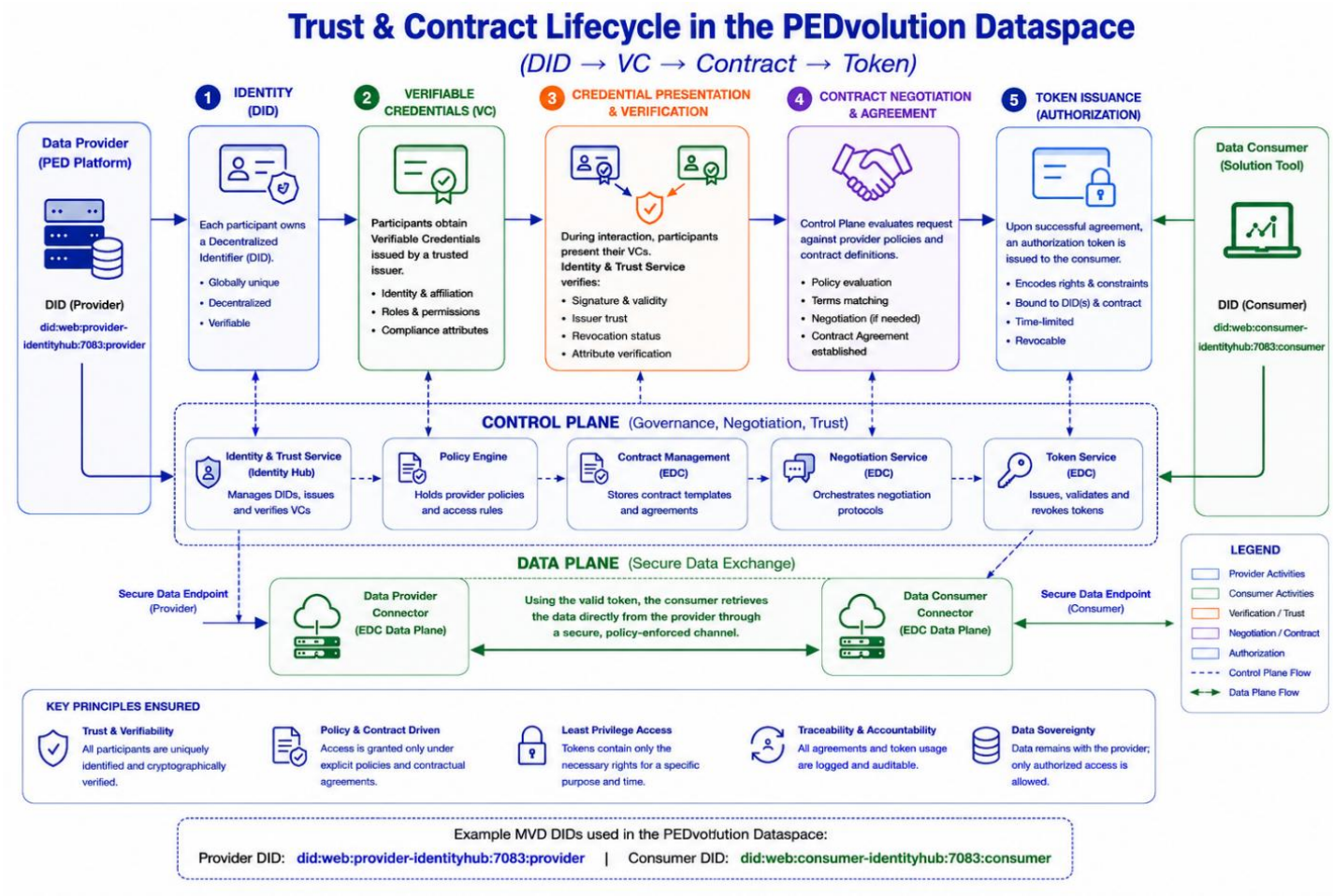


Figure 55: End-to-end trust and contract lifecycle in the PEDvolution dataspace, illustrating DID-based identity, credential verification, policy-driven contract negotiation in the Control Plane, and secure data exchange via the Data Plane with token-based authorisation.

Participant Creation and Registration in the Dataspace

Within the PEDvolution dataspace, participant onboarding follows a structured process aligned with the Minimum Viable Dataspace (MVD) approach, enabling secure and trusted participation through decentralised identity and credential-based mechanisms.

The onboarding process ensures that each participant (data provider or data consumer) is uniquely identified, authenticated, and authorised before engaging in dataspace interactions.

Step 1: Participant Identity Creation (DID Registration)

Each participant is assigned a **Decentralized Identifier (DID)**, which serves as a unique and verifiable identity within the dataspace.

- DIDs are created and managed through the Identity and Trust services (Identity Hub)
- The platform uses the did:web method to provide globally unique, domain-resolvable, and interoperable identities.

Example:

did:web:consumer-identityhub:7083:consumer

The DID forms the foundation for all subsequent trust and access control mechanisms.

Step 2: Participant Context Creation (Identity Hub Registration)

Following DID creation, a participant context is established in the Identity Hub, including metadata, roles, and authentication credentials. This enables secure interaction with dataspace services, management of participant-specific credentials, and integration with Dataspace Connectors.

Step 3: Issuance of Verifiable Credentials (VCs)

Participants receive Verifiable Credentials (VCs) issued by trusted authorities, which are digitally signed, linked to their DID, and represent roles and permissions (e.g. MembershipCredential and DataProcessorCredential). Stored in the Identity Hub, these credentials are used for contract negotiation, policy evaluation, and access authorisation.

Step 4: Connector Configuration and Dataspace Participation

Each participant operates or is associated with a Dataspace Connector (EDC), serving as the interface for data exchange. The connector is configured with endpoints, integrated with the Identity Hub for credential verification, and, for providers, registered in the Federated Catalogue. It enables participants to publish, discover, access data assets, and engage in contract negotiation workflows.

Step 5: Trust Establishment and Policy Readiness

After onboarding, participants are fully integrated into the dataspace, where DIDs provide identity, VCs establish trust and role verification, policies define access conditions, and connectors enable interaction. During data exchange (Workflow 2), credentials are presented, evaluated against policies, and used to determine access rights.

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3.1.4.6 Workflow 1: Data Provider Process (Registration & Publication)

This workflow is executed by PED platforms acting as data providers, enabling their datasets to become discoverable within the PEDvolution Interoperability Platform and the broader dataspace ecosystem.

The workflow illustrated in Figure 56, follows a dataspace-compliant publication process, where datasets are not directly exposed, but instead represented through metadata, policies, and contract-governed data offers, in full alignment with data sovereignty principles.

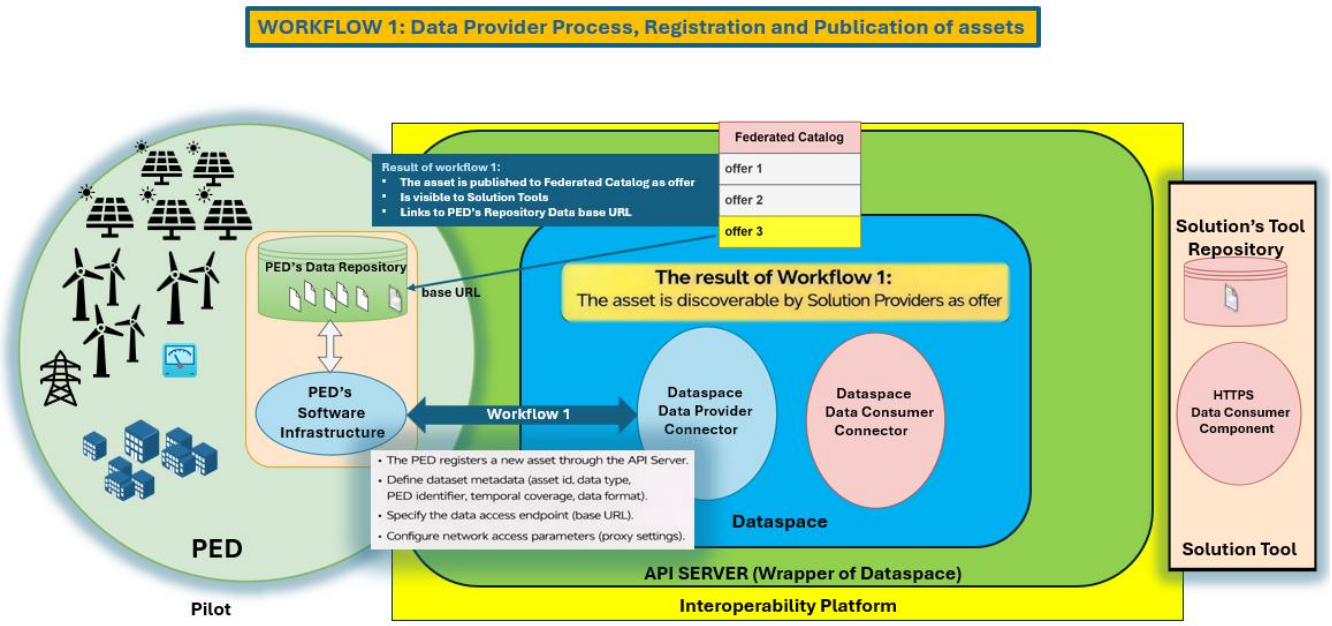


Figure 56: Data Provider workflow - Asset registration and publication process

A detailed step-by-step description of Workflow 1, including asset registration, contract definition, and policy configuration, is provided in Annex X.

3.1.4.7 Workflow 2: Data Consumer Process (Discovery & Access)

This workflow Illustrated in Figure 57, is executed by Solution Providers (Solution Tools) acting as data consumers, enabling them to discover and retrieve datasets produced in PEDs. Workflow 2 describes the data consumption process performed by Solution Providers acting as data consumers. Through this workflow, data assets are discovered via the Federated Catalogue, access is negotiated through contract-based mechanisms, and data is securely retrieved from the provider using token-based authorisation.

This workflow is implemented through three main steps: dataset discovery, contract negotiation and token issuance, and secure data retrieval.

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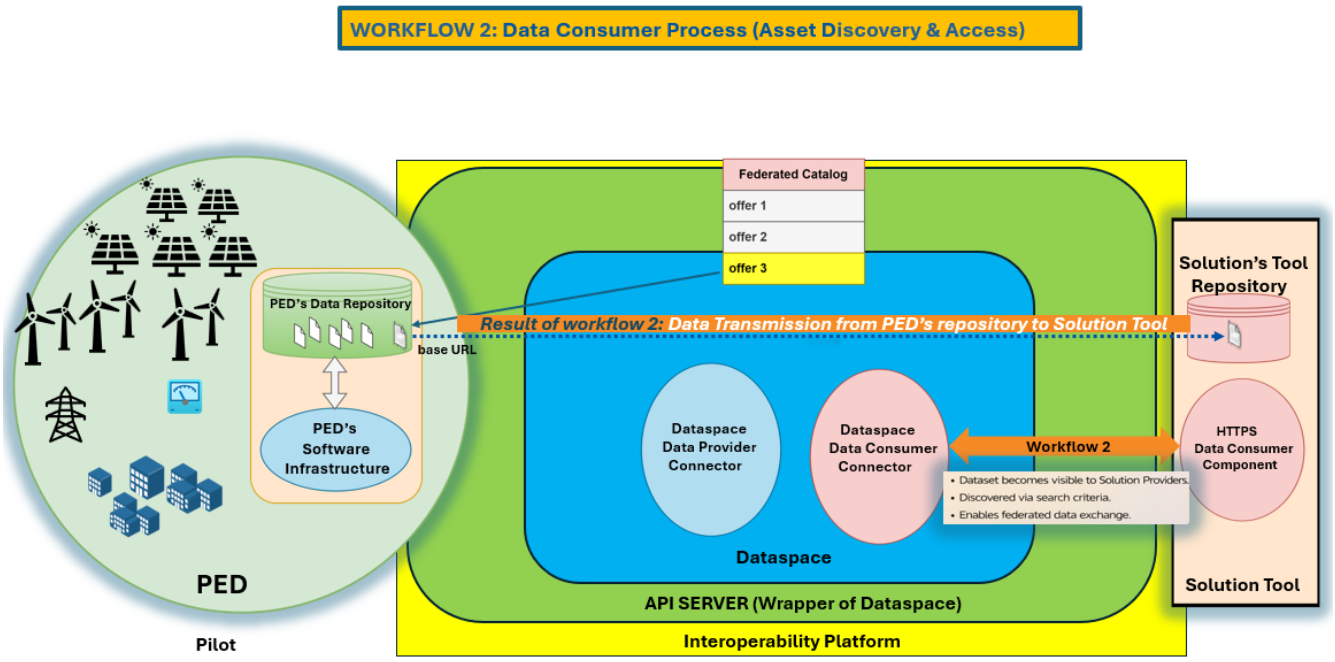


Figure 57: High-level illustration of the Data Consumer workflow

A detailed step-by-step description of Workflow 2, including the dataset discovery, contract negotiation process, and data retrieval, is provided in Annex XI.

3.2 Application Programming Interface (API) documentation

3.2.1 Overview of the API Layer

The PEDvolution Interoperability Platform exposes a set of standardised RESTful APIs through the API Server, which serves as the primary entry point for all external interactions from the PEDvolution ecosystem.

Figure 58 provides a high-level overview of the API layer, illustrating its role as an abstraction interface between external systems and the underlying dataspace infrastructure.

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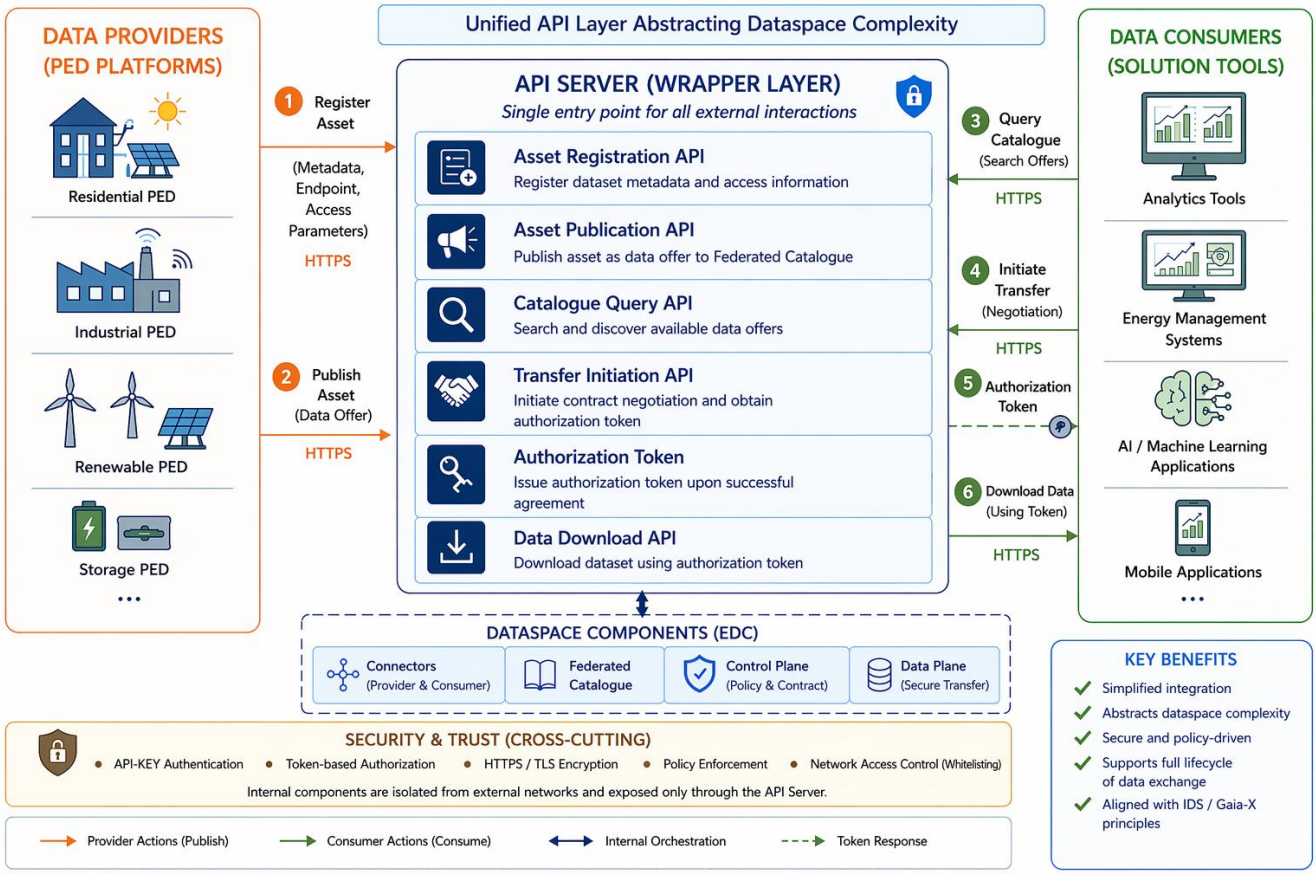


Figure 58: Overview of the API layer of the PEDvolution Interoperability Platform.

The API (Application Programming Interface) layer is designed to abstract the complexity of the underlying dataspace infrastructure, which is based on the Eclipse Dataspace Components (EDC). By encapsulating dataspace-specific mechanisms—such as connector interactions, contract negotiation, and policy enforcement, the API Server provides a simplified, consistent, and developer-friendly interface for platform integration.

Through this API layer, both data providers (PED platforms) and data consumers (Solution Tools) interact with the Interoperability Platform via standardised HTTPS interfaces, without requiring direct integration with dataspace technologies or protocols.

All APIs are exposed via secure HTTPS endpoints and support the full data exchange lifecycle, including publication and consumption workflows. The API layer enables asset registration and publication, dataset discovery via the Federated Catalogue, token generation following contract negotiation, and secure data retrieval. By providing a unified interface, it ensures interoperability across heterogeneous systems, reduces integration complexity, and supports scalable and secure participation within the PEDvolution ecosystem.

3.2.2 API design principles

The API layer of the PEDvolution Interoperability Platform, presented in Figure 59, has been designed in accordance with modern software engineering practices and dataspace-aligned principles, ensuring interoperability, scalability, security, and ease of integration across heterogeneous systems.

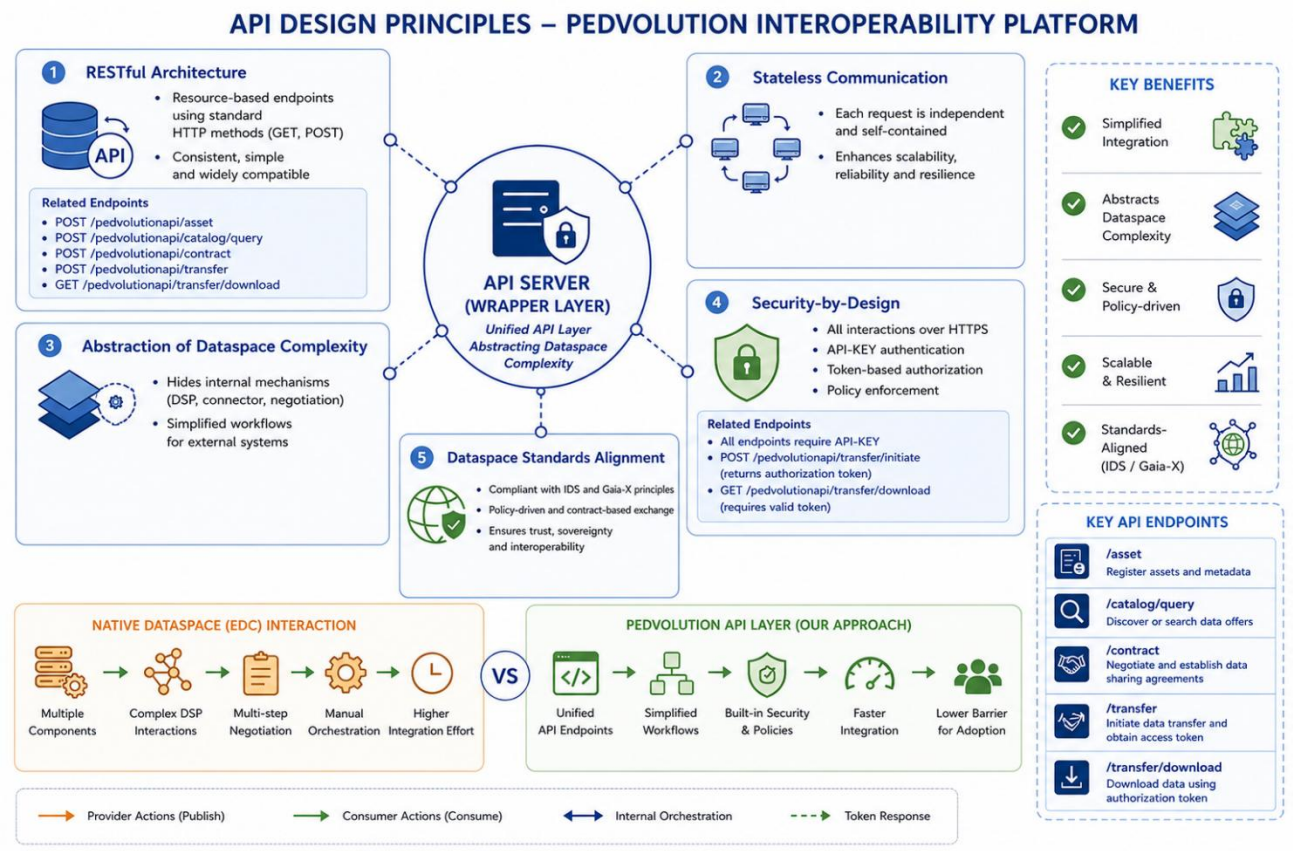


Figure 59: API design principles of the PEDvolution Interoperability Platform, demonstrating how the unified API layer simplifies complex dataspace interactions compared to native EDC approaches, enabling efficient, secure, and scalable data exchange.

The key design principles include:

- **RESTful Architecture.** The APIs follow a resource-oriented design, exposing functionalities through standardised HTTP methods (e.g., GET, POST). This approach ensures simplicity, consistency, and broad compatibility with existing systems and tools.
- **Stateless Communication.** Each API request is self-contained and independent, carrying all the necessary information for processing. This stateless model enhances scalability, reliability, and ease of deployment across distributed environments.
- **Abstraction of Dataspace Complexity.** The API Server abstracts the internal mechanisms of the dataspace infrastructure, such as Dataspace Protocol (DSP) interactions, contract negotiation, and policy enforcement. This enables external systems to interact with the platform through simplified workflows, without requiring knowledge of underlying dataspace technologies.

- **Security-by-Design.** Security is embedded as a core design principle. All interactions are performed over secure HTTPS connections and are protected through API key authentication, token-based authorisation, and policy enforcement mechanisms.
- **Alignment with dataspace standards.** The API layer supports policy-driven and contract-based data exchange, fully aligned with the principles defined by the International Data Spaces Association (IDSA) and Gaia-X. This ensures interoperability, trust, and compliance within federated data ecosystems.

Comparison with Native Dataspace (EDC) APIs

While the underlying platform leverages the Eclipse Dataspace Components (EDC), direct interaction with native EDC APIs typically requires:

- Detailed knowledge of Dataspace Protocol (DSP).
- Management of multiple low-level endpoints.
- Handling of complex contract negotiation flows.
- Direct interaction with provider and consumer connectors.
- Orchestration of control plane and data plane operations.

In contrast, the PEDvolution API layer provides a simplified and unified interface, where:

- Complex multi-step interactions are reduced to single API calls.
- Dataspace protocols are fully abstracted.
- Integration effort is significantly reduced.
- Onboarding of external stakeholders is accelerated.

By bridging advanced dataspace mechanisms with simplified API-based interaction models, the PEDvolution platform significantly lowers the barrier to entry for secure and sovereign data sharing across heterogeneous environments**.**

3.2.2.1 Performance and Scalability Considerations

The API layer has been designed to support high-performance and scalable data exchange scenarios, particularly in the context of large-scale PED deployments.

Performance Advantages

- **Reduced interaction overhead:** By consolidating multiple dataspace operations into single API calls, the platform minimizes communication latency.
- **Efficient data access patterns:** Direct peer-to-peer data transfer (via Data Plane) avoids intermediate storage and reduces bottlenecks.

Scalability Features

- **Stateless API design:** Enables horizontal scaling of API Server instances.
- **Decoupled architecture:** Separation between API layer, connectors, and data providers allows independent scaling of components.

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- **Distributed data provision:** Data remains at PED level, avoiding central bottlenecks and enabling scalable data federation.
- **Support for multiple concurrent consumers:** Multiple Solution Tools can simultaneously access datasets without impacting provider performance.

The API-driven abstraction significantly enhances system scalability by decoupling interaction complexity from data exchange operations, enabling efficient handling of large-scale, real-time, and multi-participant data sharing scenarios.

3.2.3 Authentication and Security

Security is a fundamental aspect of the PEDvolution API layer, ensuring trusted, controlled, and dataspace-compliant interactions through a multi-layered approach combining secure communication, authentication, authorisation, network isolation, and policy enforcement.

All APIs are exposed over HTTPS using TLS encryption, ensuring confidentiality, integrity, and protection against interception. Network-level access control is enforced through IP/domain whitelisting, restricting access to authorised participants and reducing the attack surface. API access requires a valid API key included in HTTP headers, ensuring that only authenticated and authorised entities can invoke platform services. Figure 60 illustrates the inclusion of the API key in HTTPS request headers.

```
POST /pedvolutionapi/catalog/offers/query HTTP/1.1
Host: pedvolution.intracom-telecom.com
Content-Type: application/json
x-api-key: YOUR_API_KEY
```

Figure 60: illustrates the inclusion of the API key within the headers of an HTTPS API request.

Token-Based Authentication and Authorisation

Secure data exchange is enforced through token-based mechanisms. During transfer initiation, the platform issues a JSON Web Token (JWT) containing identity and access information, which must be included in subsequent requests by Solution Providers. Tokens have limited validity, ensuring time-bound and controlled access. This mechanism ensures that data access is granted only after policy agreement, while maintaining authentication, traceability, and context-aware control. An example of a token payload is illustrated in Figure 61.


```
{
  "iss": "did:web:provider-identityhub:7083:provider",
  "aud": "did:web:consumer-identityhub:7083:consumer",
  "sub": "did:web:provider-identityhub:7083:provider",
  "iat": 1776765808,
  "jti": "e2e98cd5-19f6-4642-a777-610c23aee14f"
}
```


Figure 61: Decoded example of the payload of an authorisation token generated during transfer initialization process.

Description of payload token:

- **iss** (Issuer): Identity of the Data Provider
- **aud** (Audience): Intended Data Consumer
- **sub** (Subject): Token subject (provider identity)
- **iat** (Issued At): Token creation timestamp
- **jti** (JWT ID): Unique token identifier

Isolation of Internal Components and Services

Critical components of the Interoperability Platform, including Identity and Trust services, connectors, orchestration services, and the Federated Catalogue, are deployed in isolated environments and are not directly exposed to external networks. All external access is mediated through the API Server, which acts as a secure gateway, while internal communication is protected via token-based authentication with time-bound access. This approach minimises exposure of sensitive components, prevents direct access to internal services, and enhances protection against external threats.

Policy Enforcement

Policy enforcement ensures that data usage complies with provider-defined constraints, contractual agreements are respected at runtime, and unauthorised access is blocked, in line with the policy-driven data exchange model of dataspaces.

Security Sequence of Data Access

The secure data access process follows a controlled sequence:

- API request with API-KEY authentication
- Catalogue query (metadata access)
- Transfer initiation (contract negotiation)
- Authorisation token issuance
- Secure data request using token
- Data retrieval via HTTPS

This sequence ensures that no data is accessed without prior authentication, authorisation, and policy agreement.

The combination of:

- HTTPS/TLS secure communication
- API key-based authentication
- Token-based authorisation
- Network-level access control (whitelisting)
- Isolation of internal microservices
- Policy enforcement mechanisms

ensures that the PEDvolution Interoperability Platform provides a secure, trusted, and sovereign environment for data exchange, fully aligned with European dataspace standards.

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3.2.4 API Endpoints by Functionality

The PEDvolution Interoperability Platform exposes a set of APIs organized according to the functional roles of the dataspace workflows, enabling both Data Providers (PED platforms) and Data Consumers (Solution Providers) to interact with the platform in a structured and consistent manner.

The APIs are grouped into two main categories, corresponding to:

- Workflow 1: Data Provider APIs (Asset Registration & Publication)
- Workflow 2: Data Consumer APIs (Discovery, Negotiation & Data Access)

All endpoints are exposed via the API Server and are accessible through secure HTTPS communication, requiring API-KEY authentication and, where applicable, authorisation tokens.

3.2.4.1 Workflow 1: PED Data Provider APIs

The APIs in workflow 1 are utilised by PED platforms acting as Data Providers to register and publish datasets within the dataspace framework of the Interoperability Platform. These interactions are performed through the API Server using secure HTTPS requests.

The primary outcome of this workflow is that, once a dataset is successfully registered as an asset, it is published to the Federated Catalogue as a data offer. This makes the dataset discoverable and accessible to Solution Providers, enabling them to identify and select relevant data for further processing and use.

Figure 62 illustrates the two HTTPS endpoints that compose Workflow 1, supporting the asset registration and publication process within the dataspace.

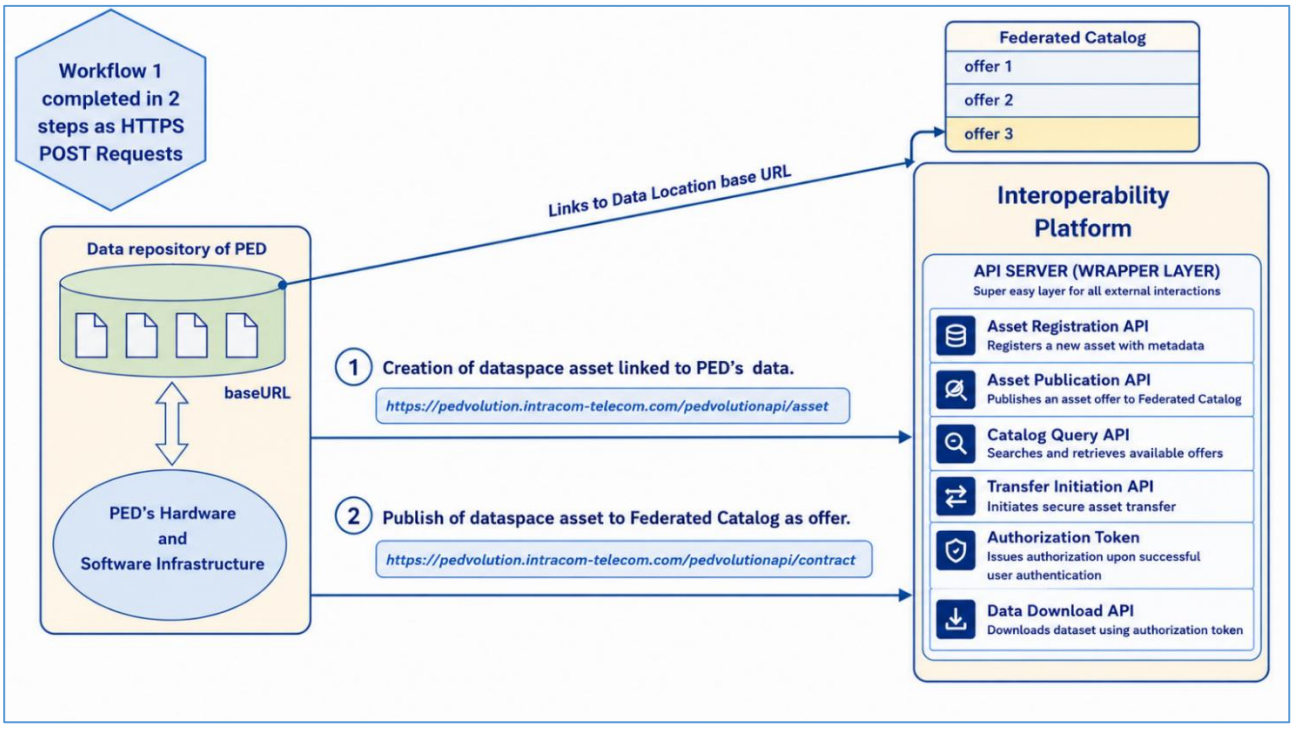


Figure 62: Illustration of the two HTTPS endpoints of Workflow 1.

The detailed description of Workflow 1, including step-by-step interactions and message exchanges, is provided in Annex XII.

3.2.4.2 Workflow 2: Solution Providers APIs

The APIs in Workflow 2 are utilized by Solution Providers acting as Data Consumers to discover, access, and retrieve datasets published by PED platforms within the dataspace of the Interoperability Platform.

These interactions are performed through the API Server using secure HTTPS requests, ensuring authentication, authorisation, and policy-compliant data access.

The primary objective of this workflow is to enable Solution Providers to:

- Discover available datasets through the Federated Catalogue.
- Initiate contract negotiation and obtain access authorisation.
- Securely retrieve data from PED platforms.

This workflow, illustrated in Figure 63, implements a policy-driven and contract-based data consumption process, aligned with dataspace principles.

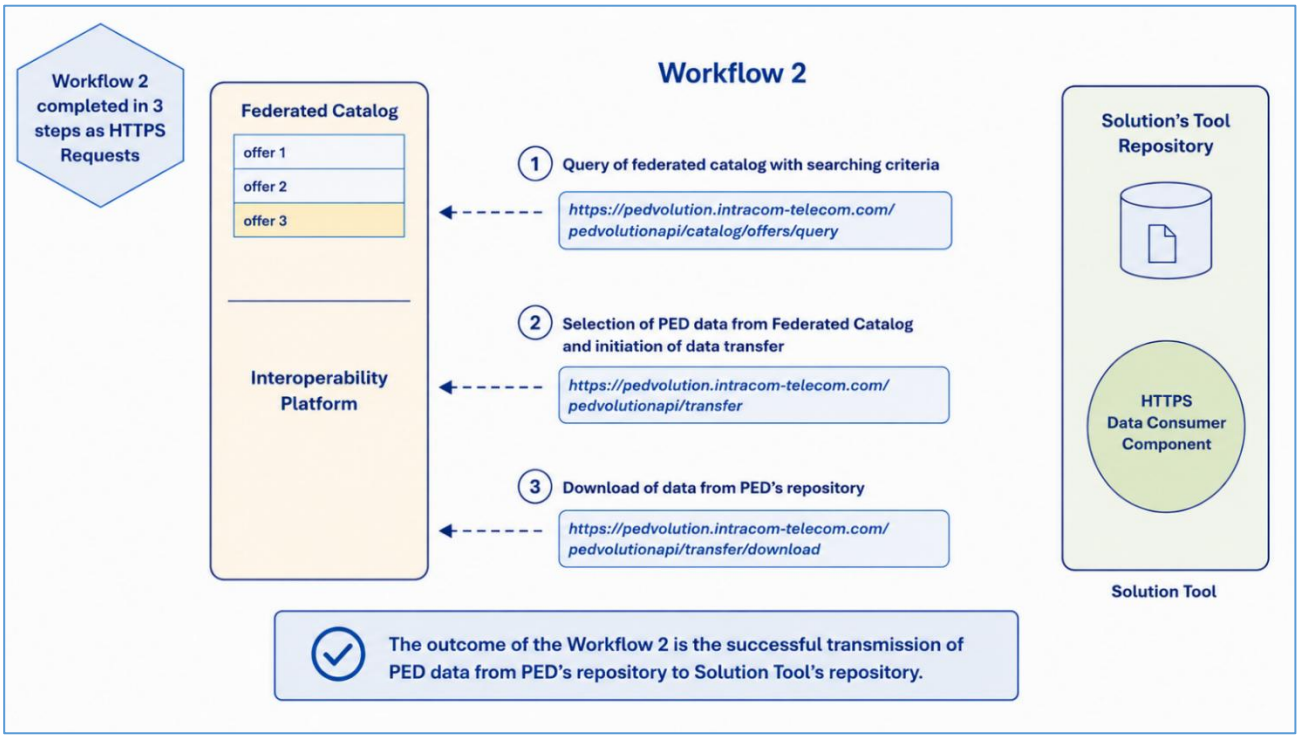


Figure 63: Illustration of the three endpoints involved in Workflow 2, supporting the data consumption process.

The detailed description of Workflow 2, including step-by-step interactions and message exchanges, is provided in Annex XIII.

4 ASSETS AND SERVICES INTEGRATION

The purpose of this chapter is to present the integration of assets produced in PEDs and services within the Interoperability Platform, focusing on how heterogeneous datasets and solution components are onboarded, exposed, and consumed through the deployed dataspace architecture.

This chapter demonstrates:

- How PED datasets (assets) are integrated and made available as data offers.
- How Solution Providers' services and tools interact with these assets.
- How the Interoperability Platform enables seamless, secure, and policy-driven integration.
- How the platform supports cross-PED and cross-domain interoperability.

The integration approach is based on the dataspace paradigm (EDC-based), where:

- Data remains at the provider side (PEDs),
- Access is governed by policies and contracts,
- Interaction is performed through standardised HTTPS APIs,
- Interoperability is achieved through semantic alignment (CIM).

This chapter builds upon the design presented in D7.1 and the market mechanisms described in D7.2, providing the final implementation and validation perspective of asset and service integration.

The integration involves two main categories of components:

1. PED Assets (Data Providers)

PED platforms act as data providers, exposing datasets such as energy consumption measurements, PV systems data, industrial real time measurements

These datasets are:

- Registered as dataspace assets to the Interoperability Platform.
- Published as data offers.
- Made discoverable to Solution Providers through the Federated Catalogue.

2. Solution Providers (Data Consumers)

Solution Providers integrate their tools and services with the platform to:

- Discover available datasets produced in PEDs.
- Retrieve data through secure APIs.
- Process and analyze data.
- Generate insights and advanced services.

Indicative Solution Tools include:

- Analytics and visualisation platforms

- Energy management systems
- Digital twin solutions

4.1 PEDvolution solutions integration

The PEDvolution Interoperability Platform enables the integration of Solution Providers' tools and services with PED datasets through a unified, API-driven, and dataspace-compliant approach. In this context, Solution Providers can:

- Access and utilise PED data.
- Develop data-driven services and applications.
- Ensure interoperability across different PEDs and domains.
- Facilitate scalable and reusable service integration.

4.1.1 Solution Providers

The integration process from Solution Providers side follows the end-to-end dataspace workflow, implemented through the API layer. This process enables the Solution Providers to securely discover, access, and consume datasets provided by PED platforms, in full compliance with dataspace principles and policy-driven data sharing mechanisms.

The integration is structured in three main steps:

The Solution Provider queries the Federated Catalogue through the API layer to discover available datasets based on specific filtering criteria (e.g., PED identifier, data type, temporal coverage).

At this stage, only metadata information is retrieved, allowing the identification and selection of relevant datasets without exposing the actual data.

- **Discovery and Selection (Workflow 2 – Step 1).** The Solution Provider queries the Federated Catalogue through the API server to discover available datasets based on specific filtering criteria (e.g., PED identifier, data type, temporal coverage). At this stage, only metadata information is retrieved, allowing the identification and selection of relevant datasets without exposing the actual data.
- **Contract Negotiation and Initialization Transfer (Workflow 2 – Step 2).** Once a dataset is selected, the Solution Provider initiates the transfer process, triggering:
  - Contract negotiation with the Data Provider.
  - Validation of access and usage policies (e.g., membership and data processing constraints).
  - Generation of an authorisation token (JWT) upon successful agreement.

  This step ensures that data access is granted only under predefined policy conditions.
- **Data Access and Consumption (Workflow 2 – Step 3).** The Solution Provider retrieves the dataset using the authorisation token obtained in the previous step. The data is accessed securely via HTTPS and consumed for further processing, analytics, and service execution within the Solution Provider platform.

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This integration workflow enables the Solution Providers to seamlessly interact with PED datasets in a secure, policy-compliant, and interoperable manner, supporting advanced energy management and decisions functionalities within the PEDvolution ecosystem.

Implementation of Integration

To facilitate the integration of Solution Providers with the PEDvolution Interoperability Platform, a set of reference Python scripts has been developed. These scripts implement the core steps of the dataspace-based data consumption workflow and serve as practical integration examples for Solution Providers. The python scripts enable Solution Providers to interact with the platform through the API layer, covering the full lifecycle of data access, from discovery to retrieval. The integration process is aligned with the APIs described in section 3.2.4.2 (Workflow 2: Solution Providers APIs).

Three python scripts implement the integration:

1) **Python Script for Federated Catalogue Query**

This script implements the Dataset Discovery step (Workflow 2 – Step 1).

It enables Solution Providers to:

- Query the Federated Catalogue.
- Apply filtering criteria (e.g., PED identifier, dataset type, temporal coverage).
- Retrieve metadata describing available datasets (data offers).

The output of this script is a list of available dataset offers matching the specified filtering criteria, from which the Solution Provider can select the dataset of interest for subsequent access.

2) **Python Script for Transfer Initiation**

This script implements the Transfer Initiation and Contract Negotiation step (Workflow 2 – Step 2).

It enables Solution Providers to:

- Initiate access to a selected dataset.
- Trigger contract negotiation with the Data Provider.
- Validate access and usage policies (require-membership, require-dataprocessor).
- Obtain an authorisation token (JWT) upon successful agreement.

This token is required for the secure retrieval of data in the next step.

3) **Data Retrieval Python script**

This script implements the Data Retrieval step (Workflow 2 – Step 3).

It enables Solution Providers to:

- Retrieve datasets from the PED using the authorisation token.
- Perform secure data access via HTTPS.
- Consume the data for further processing and analytics.

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Figure 64 illustrates the end-to-end pipeline workflow for Solution Provider integration using Python scripts, highlighting the sequence of steps from dataset discovery to secure data retrieval within the PEDvolution dataspace.

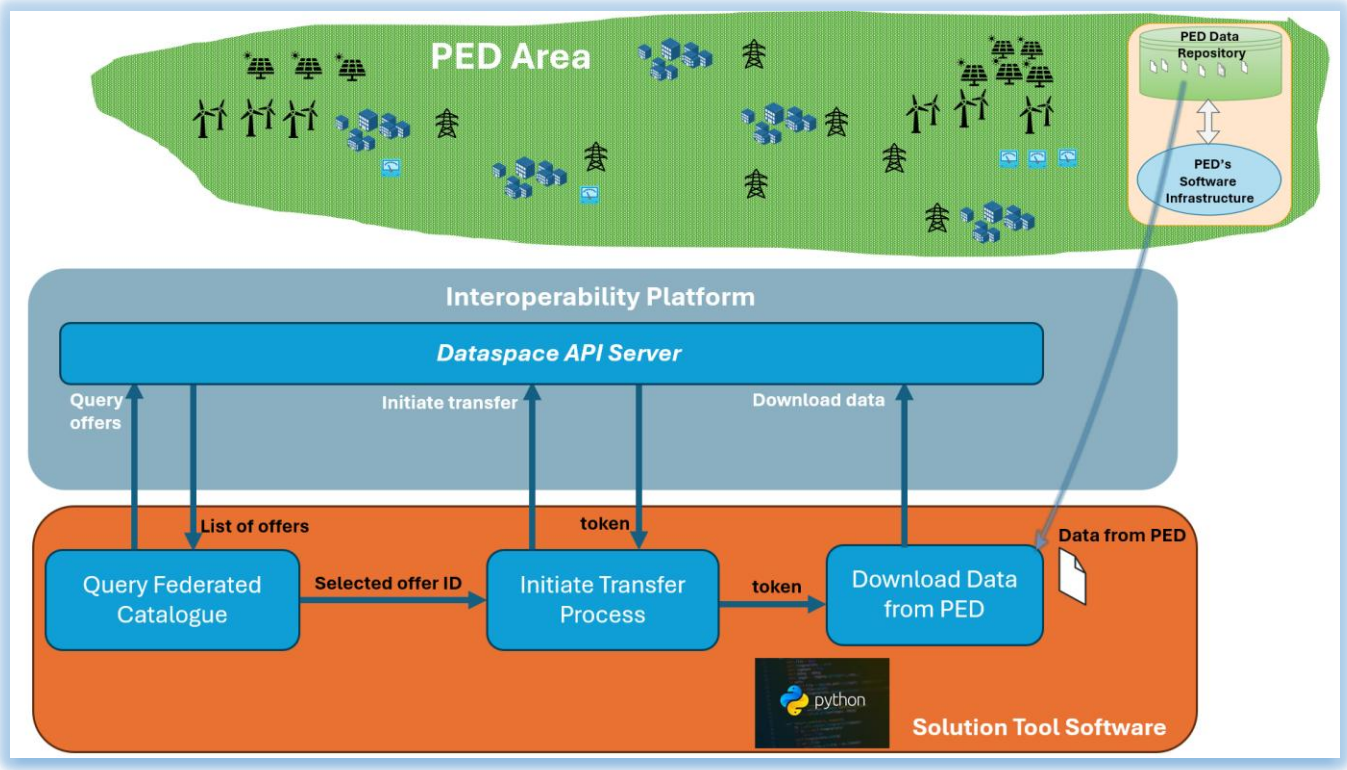


Figure 64: Pipeline workflow of Solution Provider integration using Python scripts, illustrating dataset discovery through the Federated Catalogue, selection of a data offer, initialization of transfer, token generation, and secure data retrieval from PED platforms.

This integration approach significantly lowers the technical barrier for Solution Providers, enabling rapid, secure, and standardised access to PED datasets while supporting scalable, data-driven services within the PEDvolution ecosystem.

4.2 Assets integration

4.2.1 Assets integration from SLOVENIAN PED

The SLOVENIAN PED (Residential neighbourhood Planina, Kranj, Slovenia) integrates a set of distributed industrial energy assets, including photovoltaic (PV) systems, hybrid energy storage systems, and electric vehicle charging infrastructure, into the PEDvolution Interoperability Platform.

The integration follows a dataspace-compliant approach, where datasets are exposed as dataspace assets and contract-governed data offers, enabling controlled, secure, and policy-driven data sharing within the dataspace.

4.2.1.1 Physical Assets and Data Sources

The SLOVENIAN PED infrastructure consists of the following industrial energy assets:

- **Photovoltaic (PV) systems**
  - 156 kW (SolarEdge) [35]
  - 36 kW (Solar Log) [36]
  - 34 kW (SolarEdge)
- **Hybrid Energy Storage Systems (HESS) with Photovoltaic**
  - 12 kW PV + 24 kWh storage (Deye) [37]
  - 34 kW PV + 24 kWh storage (Deye)
- **Electric Mobility Infrastructure:** Vehicle-to-grid (V2G) EV Charger (11 kW) [38].

These assets generate electrical power measurements, covering both:

- Energy production
- Energy consumption

4.2.1.2 Data Collection and Acquisition

Data collection is implemented through an edge-based architecture, ensuring reliable and near real-time data acquisition of operational energy data.

- **Edge Infrastructure:** Industrial edge devices: *Moxa UC-1222A* [39] *(Linux-based industrial PC)*.
- **Communication Protocols**
  - Device-level communication: **Modbus** [40]
  - Platform communication: **HTTPS (REST APIs)**
- **Data Flow:** *Devices → Edge Gateway (Modbus) → Aurora Platform* [39] *(REST/HTTPS)*.
- **Data Frequency:** 1-minute resolution (near real-time).

This setup aligns with the Deployment Layer, where data remains at the source and is securely exposed via APIs.

4.2.1.3 Data Storage and Management

Data is stored within the Aurora platform, which acts as the central data management system for the SLOVENIAN PED.

- **Storage Type:** Internal database (platform-managed).
- **Deployment Model:** Platform-centric (cloud deployment environment).
- **Data Characteristics:**
  - Time-series energy measurements.
  - Structured format suitable for API-based access.

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4.2.1.4 Integration with PEDvolution Interoperability Platform

The integration with the PEDvolution platform is achieved through API-based data exposure, fully aligned with the Process Layer (Workflow 1).

- **Interface Mechanism**
  - RESTful APIs (HTTPS endpoints).
  - These endpoints are registered as the baseUrl within the asset metadata during asset registration in the Interoperability Platform.
  - The registered assets are subsequently published as data offers in the Federated Catalogue.
- **Dataspace Role**
  - SLOVENIAN PED acts as a Data Provider.
  - Provides data via EDC Provider Connector abstraction (via API Server).

4.2.1.5 Security and Authentication

Assets within the SLOVENIAN PED are exposed through a multi-layered security mechanism, combining local platform authentication with dataspace-level access control.

At the Aurora platform level, access is secured using:

- SSL client certificates.
- Username/password authentication.
- Upon authentication, a time-limited token (24 hours) is issued and must be included in API requests.

However, this native security model is not directly compatible with dataspace-based token and policy enforcement mechanisms. To address this limitation, a custom Node.js [51] component has been developed as an integration and security adaptation layer. The component is deployed on the same Virtual Machine hosting the Interoperability Platform and acts as a secure intermediary (proxy layer), enabling the translation and enforcement of dataspace-level tokens and policies when accessing the Aurora platform APIs.

This component acts as a secure intermediary between the PEDvolution Interoperability Platform and the Aurora APIs, managing token handling, credential forwarding, and secure API invocation. It ensures that Aurora APIs remain protected by their native security mechanisms while being seamlessly integrated into EDC-based dataspace workflows. As a result:

- The Control Plane governs access (contracts, policies, tokens).
- The Node.js layer enforces compatibility with Aurora security.
- The Data Plane performs the actual data retrieval.

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From a dataspace perspective, the Node.js component operates within the Data Plane, executing policy-compliant data access after successful authorisation by the Control Plane.

This approach demonstrates how legacy or third-party APIs can be integrated into dataspace environments through adaptation layers, ensuring interoperability without requiring modifications to existing systems.

4.2.1.6 CIM-Aligned Data Assets

The SLOVENIAN PED provides datasets aligned with the PEDvolution Common Information Model (CIM), focusing on: ENERGY_REAL_TIME_MEASUREMENTS.

These datasets include:

- Power consumption / production values
- Timestamped measurements
- Consistent structure for interoperability

The datasets follow a structured representation aligned with the PEDvolution CIM, as described in the section 2.14 Real Time measurements .

Figure 65 illustrates a Photovoltaic Systems data asset from the SLOVENIAN PED, as represented in the Federated Catalogue and exposed as a contract-governed data offer within the dataspace.


```
{
    "id": "386-001-004-B00-1-00-01_realtime",
    "description": "PV GEK 1",
    "ped": "SLOVENIAN",
    "assetIds": [
        "assets",
        "386-001-004-B00-1-00-01"
    ],
    "characteristic": "ENERGY_REAL_TIME_MEASUREMENTS",
    "realTimeMeasurement": "yes",
    "realTimeMeasurementIndex": null,
    "timePeriodFrom": null,
    "timePeriodTo": null,
    "fullTimePeriod": "From null To null",
    "timeResolution": "EVERY_1_MIN",
    "dataFormat": "JSON",
    "details": "details of mweasurements",
    "offerIds": [
        "Mzg2LTAwMS0wMDQtQjAwLTEtMDAtMDFfcmVhbHRpbWUtY29udHJhY3Q=:Mzg2LTAwMS0wMDQtQjAwLTEtMDAtMDFfcmVhbHRpbWU=:ZWRhNzJhZDctMWZiOS00MzM1
            LTgzOGYtMzNhYjljYzQwYjA4"
    ]
},
```


Figure 65: Representation of 34kW SolarEdge Photovoltaic Systems data asset from the SLOVENIAN PED as a data offer in the Federated Catalogue.

Figure 66 presents an example of a CIM-aligned JSON structure representing a real-time energy measurement from a SLOVENIAN PED Photovoltaic asset, illustrating how operational data is standardised and exposed for interoperable data exchange within the PEDvolution dataspace.



Figure 66: JSON representation of a real-time energy measurement (total active power) from a SLOVENIAN PED Photovoltaic Systems 34kW SolarEdge asset, including timestamp, asset identifier, and structured measurement values aligned with the PEDvolution CIM.

4.2.2 Assets Integration from SWISS PED

The SWISS PED (Gemeinschaft Hard, Winterthur, Switzerland) integrates a heterogeneous set of distributed energy assets and IoT-based measurement devices into the PEDvolution Interoperability Platform, enabling the collection and exchange of real-time and aggregated energy data.

The integration reflects a multi-source, multi-platform architecture, where data is collected from various systems (cloud services, FTP servers, edge devices) and exposed as dataspace assets and contract-governed data offers, ensuring interoperability and data accessibility within the PEDvolution ecosystem.

4.2.2.1 Physical Assets and Data Sources

The SWISS PED infrastructure consists of the following energy assets and measurement devices:

- **Smart Meters (2 units):**
  - Measure total energy consumption of the PED.
  - Measure energy production from a hydroelectric power plant.
- **Smart Plugs (12 units – Shelly devices [42]):**
  - Measure energy consumption of individual household appliances.
  - Examples: refrigerators, coffee machines, washing machines, freezers.
- **Photovoltaic (PV) Monitoring Device (Moxa):** Measures energy production from PV systems.
- **Electric Vehicle Charging Infrastructure (Clemap device [43])**: Monitors energy consumption of 6 EV charging stations.

This setup enables fine-grained monitoring, ranging from:

- Device-level consumption (smart plugs)
- Building-level consumption (smart meters)
- Infrastructure-level production (PV and hydro power)
- Mobility-related energy usage (EV charging)

The SWISS PED managers decided to expose all assets under the PED identifier **"HARD"** instead of "**SWISS"**, in order to distinguish them from the assets of the other SWISS PED, Oberwinterthur.

4.2.2.2 Data Collection and Acquisition

Data collection is implemented through a distributed and heterogeneous architecture, combining cloud-based services, edge devices, and file-based data exchange.

- **Communication Mechanisms**
    - HTTP/REST (Shelly cloud → ZHAW servers)
    - FTP/FTPS [44] (energy consumption data transfer)
    - VPN-based data transfer (Moxa device)
    - TCP [45] / MQTT [46] (device-level communication, where applicable).
- **Data Flow:** Devices → Cloud / Edge Systems → ZHAW Servers → Data Processing → API Exposure.

Data Sources:

- Shelly Cloud (smart plug data)
- Stadtwerk Winterthur [47] (energy consumption data)
- Moxa device (PV production data via VPN [48])
- Clemap system (EV charging data)

Data Frequency:

- Smart Meters: 15-minute intervals
- Smart Plugs: every 1 minute
- Moxa (Photovoltaic data): every 1 minute
- Clemap (EV charging): every 1 minute

This configuration enables both:

- high-frequency monitoring (device-level)
- aggregated energy analysis (system-level).

4.2.2.3 Data Storage and Management

Data is stored across multiple systems within the SWISS PED infrastructure.

- **Storage Locations**
    - ZHAW-hosted servers (primary data storage)
    - FTPS servers (central repository for energy datasets)

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  - Shelly cloud (temporary storage for smart plug data)
- **Database and Formats**
  - **SQLite databases** (smart plug data, local processing)
  - **CSV files** (energy consumption datasets)
  - **JSON**
  - **FTPS-based storage** (File Transfer Protocol Secure, centralised data repository).
- **Deployment Model**
  - On-premises and server-based storage infrastructure, hosted by ZHAW.
  - Integrated with external cloud services (e.g., Shelly cloud).

This multi-layer storage approach reflects a hybrid data management strategy, combining:

- Local processing
- Cloud ingestion
- File-based data exchange

4.2.2.4 Integration with PEDvolution Interoperability Platform

The SWISS PED integrates with the Interoperability Platform through API-based exposure of datasets, aligned with the Process Layer (Workflow 1 – Data Provider).

- **Interface Mechanism:** HTTPS-based data exposure via web endpoints.
- **Integration Pattern:**
  - Processed datasets are exposed through secure HTTPS links.
  - These endpoints are registered as baseUrl entries in the asset metadata (dataAddress).
  - Assets are published as data offers in the Federated Catalogue.
- **Technologies Used**
  - Python (data processing and API handling)
  - NGINX (web server / reverse proxy)
  - Bash scripts (data handling and automation)
- **Network Configuration:** No specific network restrictions (open HTTPS access).

4.2.2.5 Security and Authentication

The SWISS PED integration leverages the built-in security and access control mechanisms of the PEDvolution dataspace, rather than relying on standalone security enforcement at the data source level.

Access to data assets is governed through the dataspace Control Plane, ensuring that all interactions are subject to policy-driven contract negotiation and token-based authorisation.

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Specifically:

- **Authentication and Authorisation:**
  - Access to data is controlled through the dataspace authentication mechanism.
  - Following successful contract negotiation, an authorisation token is issued to the consumer.
  - This token is required to access the data via the Data Plane.
- **Policy Enforcement:**
  - Access is restricted through predefined policies (e.g., *require-membership*, *require-dataprocessor*).
  - These policies are evaluated against the participant's Verifiable Credentials (VCs) during negotiation.
- **Endpoint Protection (baseUrl abstraction):** The actual data endpoint (baseUrl) is not exposed to consumers and remains accessible only through authorised Data Plane operations, ensuring controlled and mediated access via dataspace mechanisms.
- **Network-Level Security:** Additional protection is provided through whitelisting mechanisms, ensuring that only authorised participants and systems can interact with the platform.

Although the underlying data sources are accessible via HTTPS endpoints, direct access is not possible without passing through the dataspace control mechanisms, ensuring that:

- All access requests are authenticated.
- All interactions are authorised through policy evaluation.
- All data exchanges are governed by contract-based agreements.

This approach aligns the SWISS PED integration with dataspace security principles, ensuring controlled, secure, and policy-compliant data access despite the heterogeneous nature of the underlying infrastructure. This design ensures that security is enforced at the dataspace level, decoupling access control from the underlying data infrastructure and enabling consistent policy enforcement across heterogeneous systems.

4.2.2.6 CIM-Aligned Data Assets

The SWISS PED provides datasets aligned with the PEDvolution Common Information Model, including:

- **ENERGY_CONSUMPTION_DATA**
- **ENERGY_REAL_TIME_MEASUREMENTS**
- **EV_CHARGING_DATA**

These datasets include:

- Timestamped measurements (ISO 8601)
- Device-level and aggregated consumption data

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- Production data (PV and hydro)
- EV charging energy usage

Figure 67 illustrates an example of a data asset from the Swiss PED, as registered in the PEDvolution Interoperability Platform and published in the Federated Catalogue, using the PED identifier “HARD”, as explained previously.

The asset corresponds to historical electric energy consumption data in CSV format, collected from the Swiss PED infrastructure and exposed as a contract-governed data offer within the dataspace.

The asset metadata includes key descriptors such as:

- Asset identifier and PED reference.
- Data characteristics and temporal coverage.
- Time resolution and data format.
- The associated offer identifier enabling contract-based access.


```
{
    "id": "zhaw-partial-supply-measurement-id",
    "description": "This asset includes Electic energy consumption from HARD Ped, which is updated once a day with the data from the
        previous day.",
    "ped": "HARD",
    "assetIds": [
        "Supply-of-Electricity-Measurement-CH1018601234500000000000000113505",
        "dummyID"
    ],
    "characteristic": "ENERGY_REAL_TIME_MEASUREMENTS",
    "realTimeMeasurement": "no",
    "realTimeMeasurementIndex": null,
    "timePeriodFrom": "12-31-2024 00:00:00",
    "timePeriodTo": null,
    "fullTimePeriod": "From 12-31-2024 00:00:00 To null",
    "timeResolution": "EVERY_15_MINS",
    "dataFormat": "CSV",
    "details": "Electric Energy Data which is supplied from HARD PED",
    "offerIds": [
        "emhhdy1wYXJ0aWFsLXN1cHBseS1tZWFzdXJlbWVudC1pZC1jb250cmFjdDE=:emhhdy1wYXJ0aWFsLXN1cHBseS1tZWFzdXJlbWVudC1pZA==:NWFhOTY0MTMtMzJj
            Ny00MGZkLWE4MjQtYzM2NzZkNWUyNzU2"
    ]
}
```


Figure 67: Example representation of an energy consumption data asset from the SWISS PED, as registered in the Interoperability Platform and published in the Federated Catalogue, including metadata attributes and associated offer identifier for contract-based access.

Figure 68 presents an example of a real-time energy measurement dataset from the SWISS PED, structured according to the PEDvolution Common Information Model. The dataset corresponds to measurements collected from a device within the SWISS PED infrastructure and includes key electrical parameters such as power consumption, total energy consumption, voltage, and current.

Each measurement is associated with:

- A timestamp in ISO 8601 format.
- A unique device identifier.

- The corresponding PED reference.
- A structured measurement attributes with explicit units.

This representation demonstrates the transformation of raw device-level data into CIM-aligned, interoperable datasets, enabling consistent integration and consumption within the PEDvolution dataspace.


```
{
    "timestamp": "2026-05-22T06:25:43Z",
    "deviceId": "e4b3233b0e84",
    "linkedToPED": "HARD",
    "powerConsumption": {
        "value": 0.0,
        "unit": "W"
    },
    "totalEnergyConsumption": {
        "value": 82830.763,
        "unit": "kWh"
    },
    "voltage": {
        "value": 233.1,
        "unit": "V"
    },
    "current": {
        "value": 0.0,
        "unit": "A"
    },
    "online": true
}
```


Figure 68: Example CIM-aligned JSON representation of a real-time energy measurement from the SWISS PED, including timestamped device-level parameters and structured energy metrics enabling interoperable data exchange within the dataspace.

4.2.3 Assets Integration from GERMAN PED

The GERMAN PED (Schönbrunn village Wunsiedel, Germany) integrates a set of industrial-scale distributed energy assets, including photovoltaic (PV) systems, Combined Heat and Power (CHP) units, and heating rod systems, into the PEDvolution Interoperability Platform. In contrast to residential-oriented PEDs, the GERMAN PED focuses on industrial energy production and consumption scenarios, supporting use cases such as advanced energy optimisation, load balancing, and operational efficiency.

The integration follows a dataspace-compliant approach, where datasets are exposed as dataspace assets and contract-governed data offers, ensuring data sovereignty, secure access, and policy-driven data exchange.

4.2.3.1 Physical Assets and Data Sources

The GERMAN PED infrastructure consists of the following industrial energy assets:

- **Photovoltaic (PV) System 80 kW**
- **Heating Rod System 1 MW** [49]
- **Combined Heat and Power (CHP) systems:**

- CHP Unit 1, (manufacturer: Burkhardt [50]) - 220kW (heat power: 230 kW). The unit is operated in a heat-led mode, meaning that heat demand drives the system's operation.
- CHP Unit 2, (manufacturer: Burkhardt) - 220kW (heat power: 230 kW). The unit is operated in a heat-led mode, meaning that heat demand drives the system's operation.

CHP systems are of particular importance, as they simultaneously produce electricity and thermal energy, introducing multi-domain data characteristics that require coordinated monitoring of both energy streams.

The integration leverages the Aurora platform for data acquisition and API-based exposure, ensuring seamless interoperability with the PEDvolution Interoperability Platform.

4.2.3.2 Data Collection and Acquisition

Data collection is implemented through a distributed industrial edge architecture, enabling reliable and near real-time acquisition of operational energy data.

- **Edge Infrastructure:** Industrial edge devices: *Moxa UC-1222A (Linux-based industrial PC).*
- **Communication Protocols:**
  - Device-level communication: **Modbus**
  - Platform communication: **HTTPS (REST APIs).**
- **Data Flow:** *Industrial Assets → Edge Gateway (Modbus) → Aurora Platform (REST/HTTPS).*

Data Frequency: 1-minute resolution (near real-time).

4.2.3.3 Data Storage and Management

Data is stored within the Aurora platform, which acts as the central data aggregation and exposure system.

- **Storage Type:** Internal platform-managed database.
- **Deployment Model:** Platform-centric (cloud deployment environment).
- **Data Characteristics**
  - Time-series industrial energy data.
  - Structured format suitable for API-based access.

The generated datasets reflect industrial energy behavior, including:

- Dynamic load profiles driven by operational processes.
- Coupled electrical and thermal energy measurements (CHP systems).
- Higher variability compared to residential energy consumption patterns.

4.2.3.4 Integration with PEDvolution Interoperability Platform

The integration with the PEDvolution platform is achieved through API-based data exposure, fully aligned with the Process Layer (Workflow 1 – Data Provider).

- **Interface Mechanism:** RESTful APIs over HTTPS.
- **Integration to Interoperability Platform:**
  - Aurora platform exposes datasets via secure API endpoints.
  - These endpoints are registered as the baseUrl within the asset metadata during asset registration in the Interoperability Platform.
  - The registered assets are subsequently published as data offers in the Federated Catalogue.
- **Dataspace Role:**
  - GERMAN PED acts as a Data Provider.
  - Provides data via the EDC Provider Connector abstraction (via API Server).

4.2.3.5 Security and Authentication

The GERMAN PED adopts a multi-layered security model, combining Aurora-native authentication (SSL client certificates, credentials, and time-limited tokens) with dataspace-level policy enforcement.

Similar to the SLOVENIAN PED, a Node.js-based adaptation layer is deployed within the Interoperability Platform environment, enabling the translation of dataspace-issued tokens into Aurora-compatible authentication requests and ensuring policy-compliant data access. From a dataspace perspective, the Node.js adaptation layer operates within the Data Plane, executing policy-compliant data access after successful authorisation by the Control Plane.

4.2.3.6 CIM-Aligned Data Assets

The GERMAN PED provides datasets aligned with the PEDvolution Common Information Model (CIM), focusing on: ENERGY_REAL_TIME_MEASUREMENTS.

These datasets include:

- Timestamped measurements (ISO 8601 format).
- Electrical power values.
- Thermal energy data (CHP systems).
- Asset identifiers and metadata.
- Time resolution and contextual information.

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Figure 69 illustrates a real-time energy measurement asset from CHP Unit 1 of the GERMAN PED, as represented in the Federated Catalogue.


```
{
    "id": "049-001-001-B00-1-00-01_realtime",
    "description": "CHP 1",
    "ped": "GERMAN",
    "assetIds": [
        "assets",
        "049-001-001-B00-1-00-01"
    ],
    "characteristic": "ENERGY_REAL_TIME_MEASUREMENTS",
    "realTimeMeasurement": "yes",
    "realTimeMeasurementIndex": null,
    "timePeriodFrom": "01-27-2026 19:15:00",
    "timePeriodTo": "01-27-2026 19:30:00",
    "fullTimePeriod": "From 01-27-2026 19:15:00 To 01-27-2026 19:30:00",
    "timeResolution": "EVERY_1_MIN",
    "dataFormat": "JSON",
    "details": null,
    "offerIds": [
        "MDQ5LTAwMS0wMDEtQjAwLTEtMDAtMDFfcmVhbHRpbWUtY29udHJhY3Q=:MDQ5LTAwMS0wMDEtQjAwLTEtMDAtMDFfcmVhbHRpbWU=:ZDgzYjlmZDgtZWE5Ni00OWEw
            LTkxNDItOTQyZWExZDhhY2Ri"
    ]
}
```


Figure 69: Representation of a real-time energy asset (data offer) from CHP Unit 1 in the Federated Catalogue, including the offer ID used for contract negotiation within the metadata.

Figure 70 presents an example of a real-time measurement dataset from CHP Unit 1 of the GERMAN PED, illustrating how energy data is structured and exposed in accordance with the PEDvolution Common Information Model.


```
{
    "AssetId": "049-001-001-B00-1-00-01",
    "Timestamp": "2026-05-22T06:11:01+01:00",
    "AssetDescription": "Schönbrunn CHP 1",
    "Items": [
        {
            "Name": "totalActivePower",
            "Unit": "kW",
            "Value": 206.4
        }
    ]
}
```


Figure 70: Example JSON representation of a real-time energy measurement (total active power) from CHP Unit 1 of the GERMAN PED, aligned with the PEDvolution CIM and enabling interoperable data exchange.

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5 INTEGRATION WITH OTHER EU DATA SPACES

The PEDvolution Interoperability Platform is designed to operate not only as a standalone data exchange infrastructure but also as a federated component within the broader European Data Space ecosystem, supporting the exposure of PED data and services as interoperable, trusted, and policy-governed offerings.

This integration enables PEDvolution to:

- Participate in cross-domain data sharing.
- Interoperate with external data space initiatives.
- Support data portability and federation across platforms.
- Contribute to the development of a unified European data economy.

This integration is aligned with European initiatives such as: IDSA (International Data Spaces Association), Gaia-X framework, Energy Data Spaces (e.g., OMEGA-X), and is implemented through the extension of the PEDvolution dataspace infrastructure based on Eclipse Dataspace Components (EDC).

The integration with EU Data Spaces aims to:

- Enable exposure of PED data and services to external data space ecosystems.
- Support cross-dataspace interoperability.
- Facilitate participation in energy data marketplaces.
- Ensure secure, trusted, and policy-compliant data exchange beyond the project boundaries.
- Promote reuse of PEDvolution data and services in external ecosystems.

Integration with Energy Data Spaces (OMEGA-X)

The integration with external EU Data Spaces is demonstrated through the connection with OMEGA-X, which acts as a federation hub enabling interoperability with other EU Data Spaces. The federation model enables decentralised data exchange without requiring centralised data storage, thereby preserving data sovereignty while ensuring interoperability across data spaces. This integration serves as a reference case study demonstrating practical and scalable interoperability with European Energy Data Spaces.

In this context, PEDvolution datasets and services are exposed as dataspace assets and contract-governed data offers, which can be published in the OMEGA-X marketplace, discovered by external participants, and consumed through standard dataspace mechanisms. This integration enables cross-project interoperability, data sharing across energy ecosystems, and scalability beyond local deployments.

Market Integration and Participation

Beyond technical interoperability, the platform enables participation in energy data markets. This is achieved through:

- **Market-oriented service exposure:** PED services can be offered as data-driven services.
- **Interoperable interfaces:** Based on standard protocols and APIs.

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- **Contract-based access mechanisms:** Ensuring controlled data sharing.
- **Support for PED participation:** Enabling aggregation and higher-level service offerings.

These capabilities allow PEDvolution participants to:

- Engage with energy marketplaces.
- Offer data-driven services.
- Participate in data economy ecosystems.

Figure 71 illustrates the integration of the PEDvolution Interoperability Platform within the European Data Spaces ecosystem, highlighting the role of the OMEGA-X marketplace as a federation hub enabling indirect interoperability with multiple data spaces.

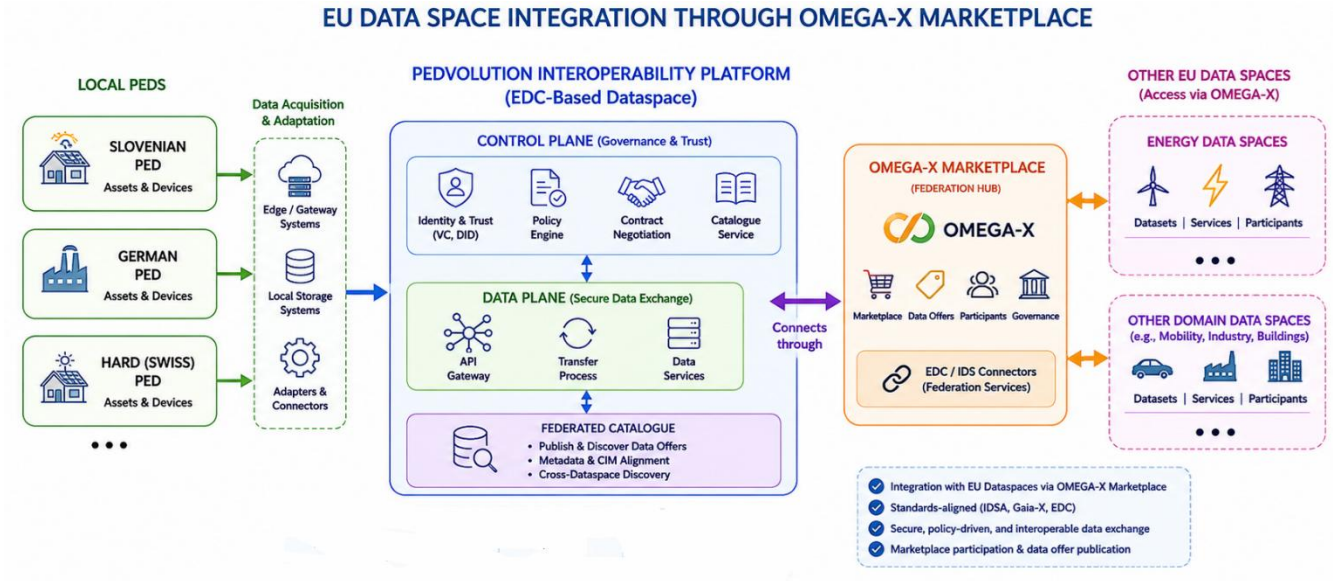


Figure 71: PEDvolution Interoperability Platform integration with the European Data Spaces ecosystem through the OMEGA-X marketplace, acting as a federation hub.

The PEDvolution Interoperability Platform has been designed to support interoperability not only within the PEDvolution ecosystem, but also across external European Data Spaces. In this context, the platform follows a dataspace-by-design approach, enabling the exposure, discovery, and controlled exchange of PED-related datasets and services through federated dataspace infrastructures.

To demonstrate this capability, the PEDvolution platform was integrated with the OMEGA-X ecosystem, which represents a federated European Energy Data Space initiative. Through this integration, PEDvolution datasets can be published as interoperable assets, enriched with metadata aligned with the Common Information Model (CIM), and made discoverable through the OMEGA-X marketplace environment. This integration enables secure and sovereign cross-platform data sharing while maintaining compliance with European dataspace principles, including decentralisation, interoperability, trust, and data sovereignty.

Figure 72 presents the OMEGA-X marketplace environment used for the federation and exposure of PEDvolution interoperable datasets and services within the broader European Data Spaces ecosystem.

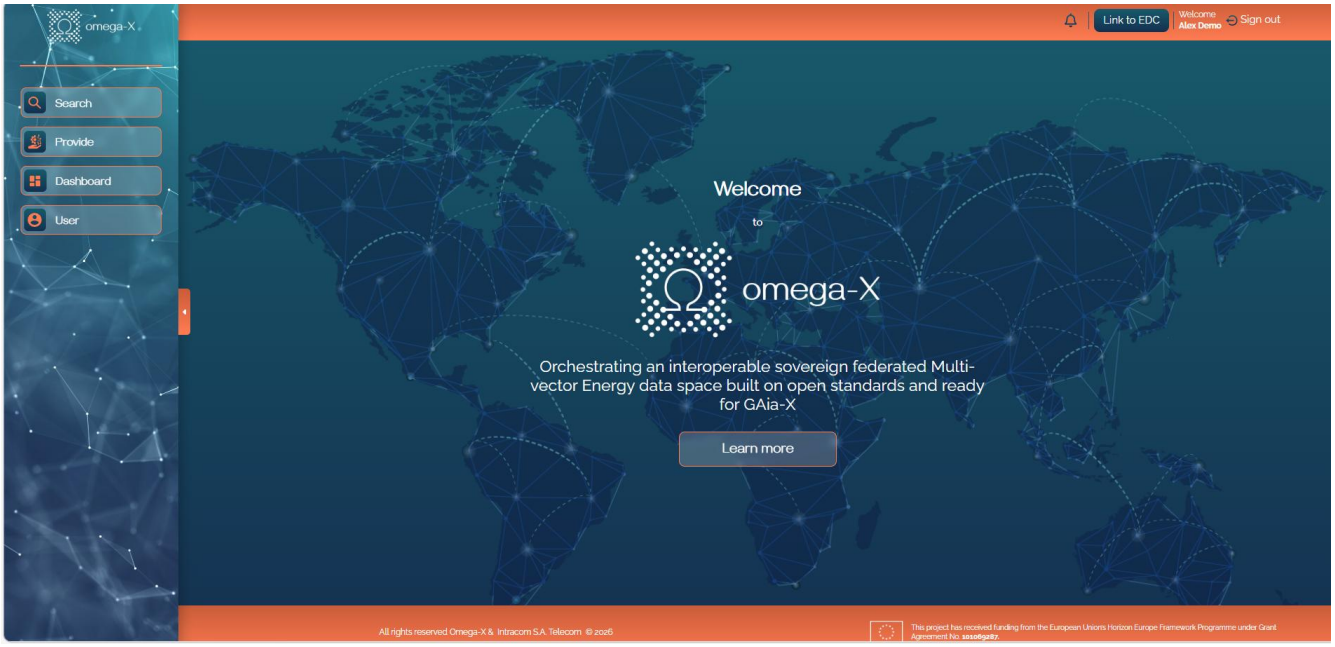


Figure 72: OMEGA-X Marketplace interface supporting the federation of PEDvolution assets and services with external European Data Spaces.

Following the successful publication of PEDvolution datasets within the OMEGA-X ecosystem, the federated marketplace environment enables the discovery, filtering, and access of interoperable PED datasets through metadata-driven mechanisms. The marketplace provides a unified interface where datasets exposed from the PEDvolution Interoperability Platform can be searched and categorised according to characteristics such as data type, PED origin, time resolution, and real-time availability.

This functionality demonstrates the practical interoperability capabilities of the PEDvolution platform and validates its integration with external European Data Spaces. Through the use of CIM-aligned metadata and dataspace technologies based on Eclipse Dataspace Components (EDC), PEDvolution assets become discoverable and reusable across organisational and sectoral boundaries while maintaining data sovereignty and controlled access policies.

Figure 73 presents the OMEGA-X marketplace interface, showcasing PEDvolution datasets published through the Interoperability Platform. The marketplace enables federated discovery of datasets through advanced filtering and search criteria, supporting cross-dataspace data sharing and access across participating entities.

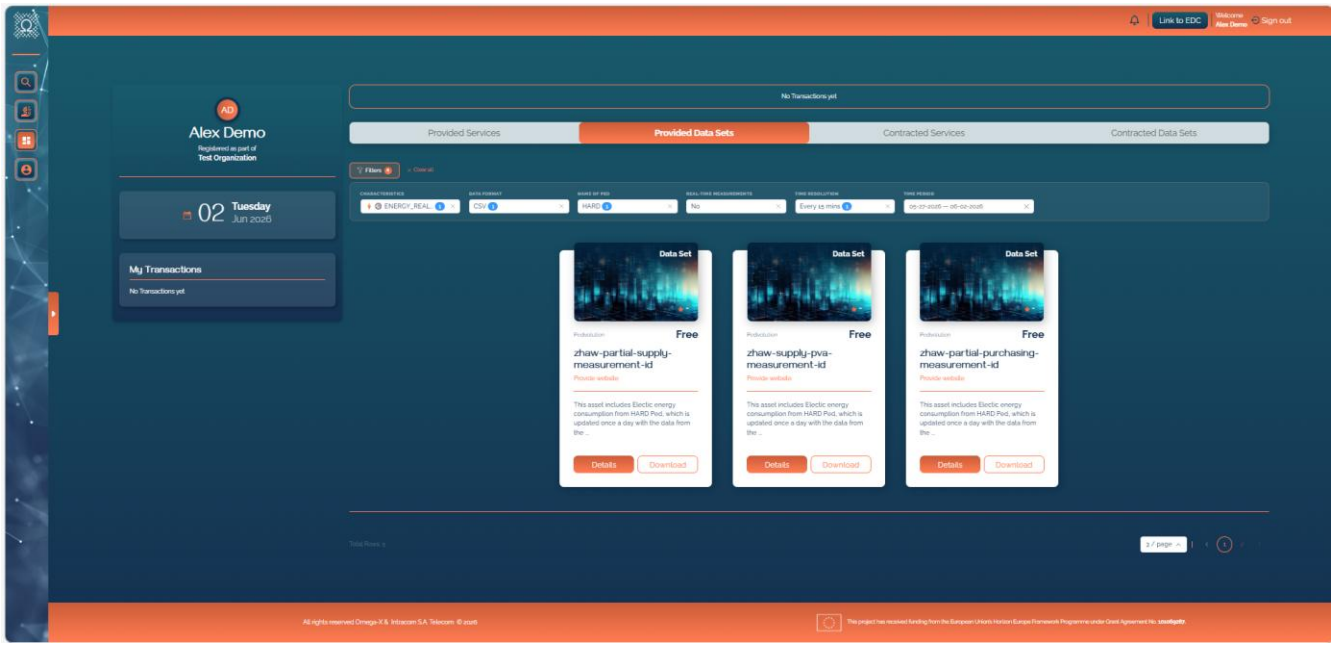


Figure 73: Figure X: OMEGA-X marketplace interface displaying PEDvolution datasets available for federated discovery, filtering, and cross-dataspace data sharing.

The OMEGA-X marketplace not only enables the discovery of PEDvolution datasets, but also provides detailed metadata views for each published asset. These metadata descriptions play a critical role in supporting interoperability, dataset discoverability, and controlled data sharing across federated European Data Spaces. Each published asset includes structured information describing the dataset category, associated PED, data format, temporal resolution and real-time measurement capabilities. Through this metadata-driven approach, the platform ensures that datasets can be consistently interpreted and reused by external systems and services participating in the dataspace ecosystem.

Figure 74 presents a detailed view of a PEDvolution dataset as displayed in the OMEGA-X marketplace. It illustrates the metadata associated with a published dataset, including dataset description, categorisation, temporal coverage, and access conditions. The selected dataset is provided in CSV format and contains historical data derived from real-time measurements collected within the PED. This view demonstrates how datasets are structured and exposed through the Interoperability Platform,

enabling transparent discovery, evaluation, and controlled access within the federated data space environment.

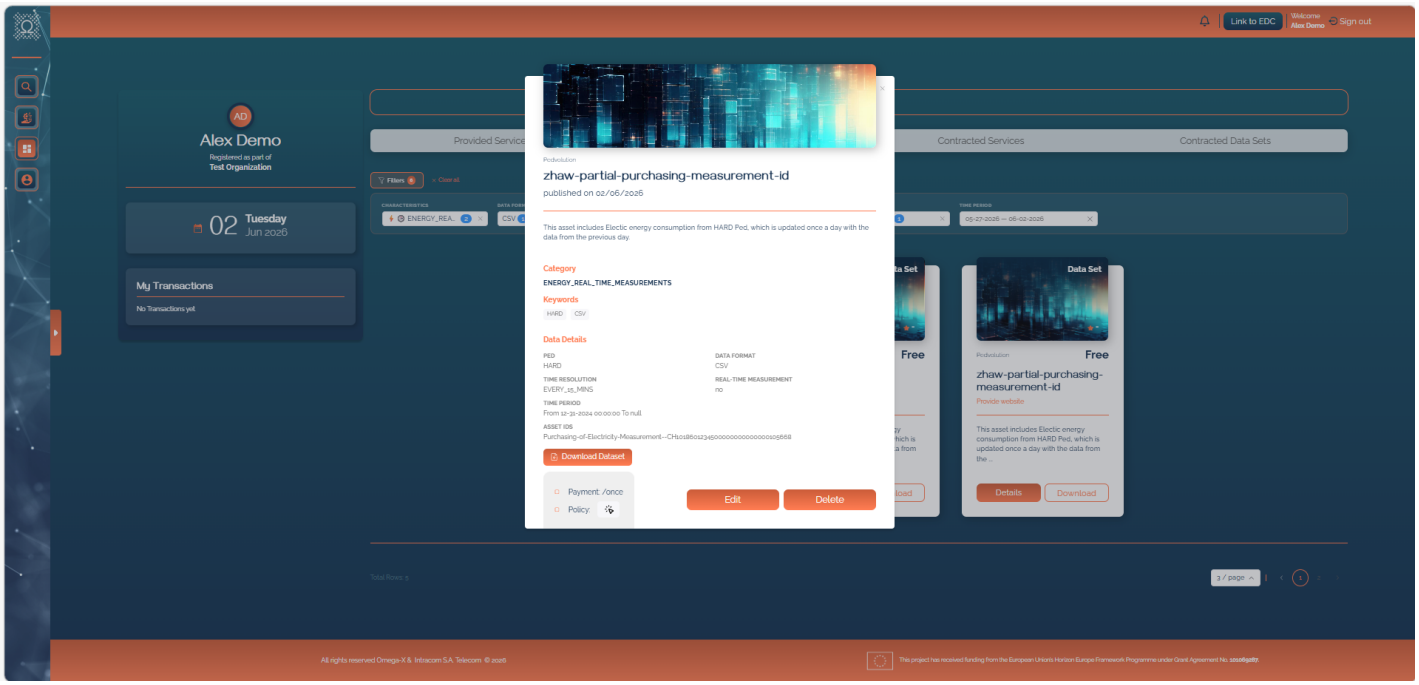


Figure 74: Detailed view of a PEDvolution dataset in the OMEGA-X marketplace, showing metadata, access conditions, and dataset management options supporting federated data sharing.

Figure 75 illustrates the data consumption process through the OMEGA-X marketplace, where a dataset published by the PEDvolution Interoperability Platform is retrieved. In this example, the selected dataset corresponds to a CSV file containing historical time-series data derived from real-time energy consumption measurements within the PED. The retrieved dataset enables further analysis, processing, and integration into external applications and services.

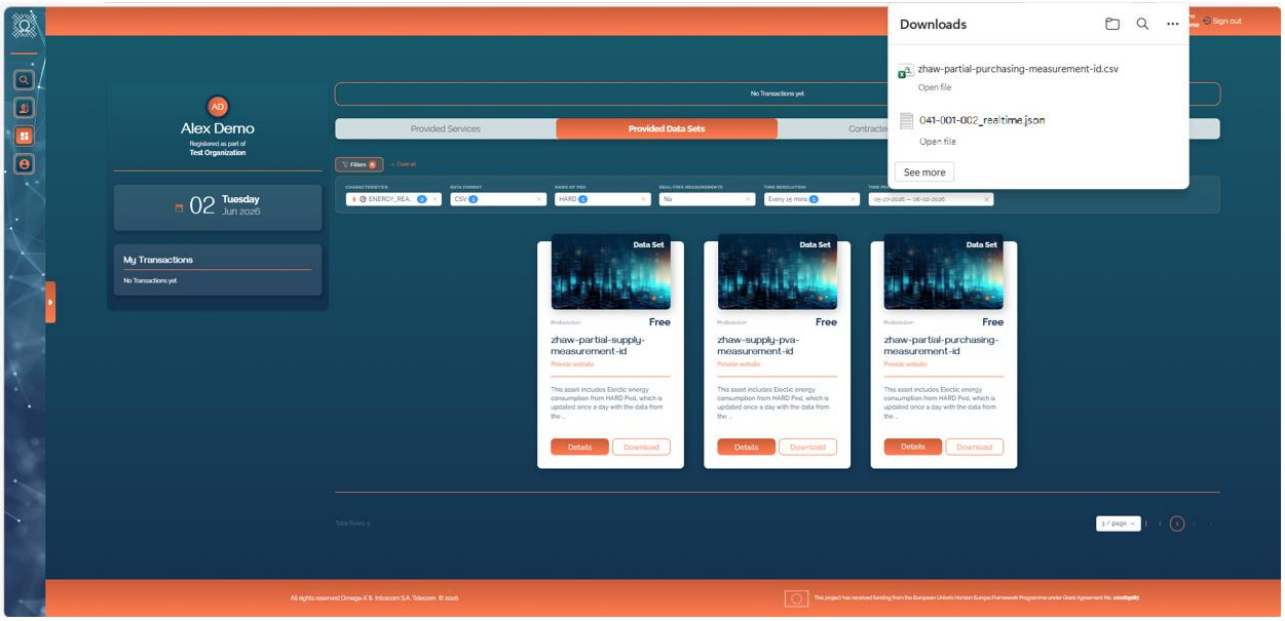


Figure 75: Retrieval of a PEDvolution dataset through the OMEGA-X marketplace, showing the download of a CSV file containing historical time-series energy consumption data.

Figure 76 presents the retrieved dataset after download from the OMEGA-X marketplace, displayed in CSV format. The dataset contains historical time-series data derived from real-time energy consumption measurements. Each record includes timestamped values representing energy consumption over defined intervals, enabling detailed analysis, validation, and integration into external applications and data-driven services.

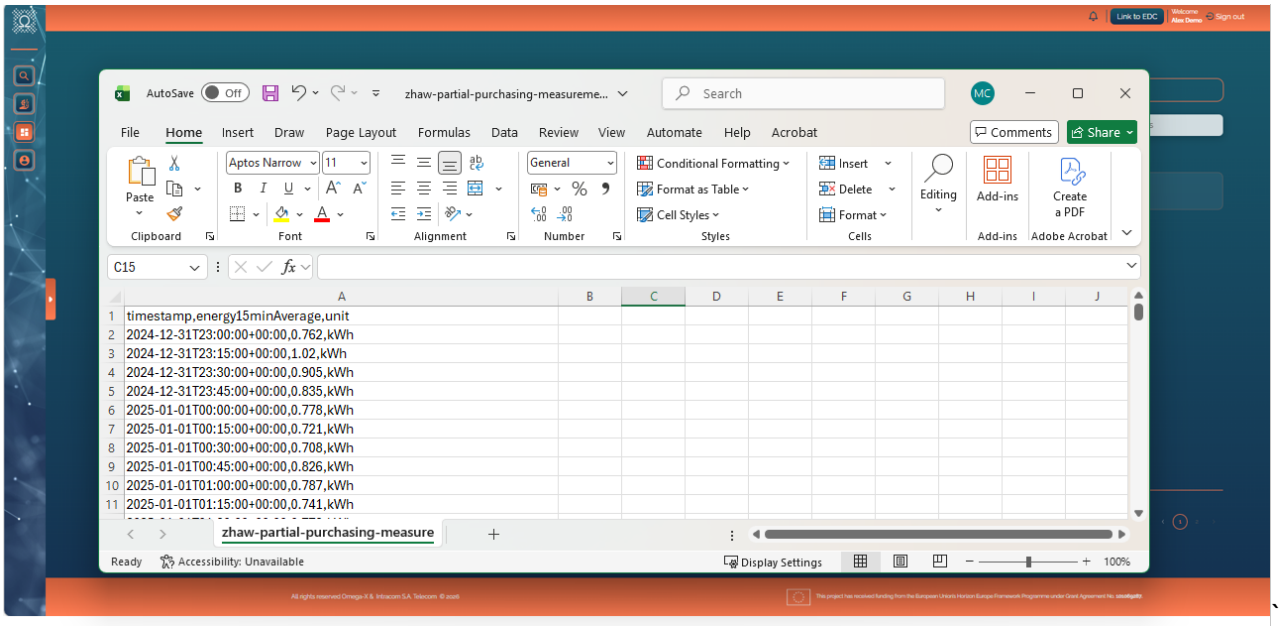


Figure 76: Example of a downloaded dataset in CSV format, showing historical time-series energy consumption measurements.

Role in the PEDvolution Ecosystem

The integration with EU Data Spaces enables PEDvolution to:

- Operate as a federated dataspace participant.
- Support cross-domain and cross-platform data exchange.
- Enable scalable deployment of PED services.
- Contribute to the European Data Space vision.

The final platform provides a cloud-native, interoperable environment where:

- Data from all PEDs can be securely exchanged.
- Services can be exposed externally.
- Interoperability is ensured across heterogeneous systems.

The integration of PEDvolution with EU Data Spaces establishes the platform as a standards-aligned, interoperable, and federated data ecosystem, enabling secure and policy-driven data exchange beyond project boundaries. By leveraging:

- Dataspace connectors
- Federation services
- CIM-aligned data models

the platform ensures compatibility with European initiatives such as IDSA, Gaia-X, and OMEGA-X, supporting the evolution of PEDvolution into a fully integrated participant in the European data economy.

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6 CONCLUSIONS

This deliverable presents the final implementation, integration, and validation of the PEDvolution Data Exchange Platform, establishing a fully operational dataspace-enabled interoperability infrastructure for secure, sovereign, and standards-based data exchange across Positive Energy Districts (PEDs).

The deliverable consolidates the work carried out in Work Package 7, translating the architectural design and specifications defined in Deliverable D7.1 and the energy market mechanisms introduced in Deliverable D7.2 into a fully implemented and validated system. The platform integrates heterogeneous data sources, Solution Tools developed in WP3–WP5, and real PED assets, enabling interoperable and policy-driven data sharing within and across PED ecosystems.

A key outcome of D7.3 is the successful implementation of a dataspace-by-design interoperability platform based on Eclipse Dataspace Components (EDC), supporting contract-based data exchange, policy enforcement, identity management, and federation with external data ecosystems. The integration with the OMEGA-X marketplace further demonstrates the platform's capability to operate within the European Data Space ecosystem, enabling cross-dataspace interoperability and marketplace-based data sharing.

The PEDvolution Common Information Model (CIM), developed and refined through stakeholder engagement and iterative validation, provides the semantic backbone of the platform. It ensures consistent representation of heterogeneous data domains, including energy systems, buildings, HVAC, EV charging, battery storage, heat recovery, and real-time measurements. The CIM enables semantic interoperability across PEDs and supports the development of analytics-ready datasets for advanced services.

Validation activities, planned in conjunction with WP9 demonstrators, will evaluate the operational maturity of the platform. These activities are expected to demonstrate end-to-end data exchange workflows, the integration of real PED assets, and the deployment of Solution Tools under real-world conditions, ultimately validating the platform's scalability, robustness, and suitability for deployment in diverse PED environments.

From a business and innovation perspective, the PEDvolution platform introduces a novel approach to data sharing in the energy domain by enabling:

- Secure and sovereign data exchange across organisational boundaries.
- Interoperable integration of heterogeneous energy systems and digital solutions.
- Participation of PEDs in emerging data-driven energy markets.
- Creation of new data-driven services and business models.

The platform provides tangible benefits for key stakeholders, including municipalities, energy operators, technology providers, and citizens, by enabling improved energy efficiency, enhanced decision-making, and increased operational transparency.

The implementation of dataspace technologies within PEDvolution also contributes to the broader European Data Strategy by demonstrating alignment with IDSA and Gaia-X principles and supporting the evolution of interoperable Energy Data Spaces.

Best practices identified during the implementation include:

- Adoption of a Common Information Model to ensure semantic interoperability.

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- Use of standardised APIs and modular architecture for scalable integration.
- Implementation of policy-driven data sharing mechanisms to ensure data sovereignty.
- Integration of real-time data streams with static asset data for enhanced analytics.

Looking forward, potential future improvements include:

- Extension of the CIM to additional domains and use cases.
- Integration with additional European and cross-sector data spaces.
- Enhancement of real-time data processing and AI-driven analytics capabilities.
- Further development of data-driven business models and marketplace functionalities.

The evolutionary roadmap of the PEDvolution platform foresees its transition from a project-based prototype to a scalable and replicable solution, capable of supporting large-scale deployment across European cities and energy communities.

In conclusion, this deliverable demonstrates that the PEDvolution interoperability infrastructure is robust, scalable, and fully aligned with EU Data Space principles. It establishes a solid foundation for enabling Positive Energy Districts to actively participate in a federated European energy data ecosystem, supporting innovation, sustainability, and digital transformation in the energy sector.

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ANNEX I: EXAMPLE OF THE ENERGY VECTORS CHARACTERISTICS ONTOLOGY USING THE PEDVOLUTION CIM

This Annex presents an illustrative example demonstrating how energy-related indicators can be semantically represented using the Resource Description Framework (RDF) and transformed into interoperable data formats suitable for integration with digital platforms and APIs. The example includes indicators such as electricity consumption, electricity production, and natural gas consumption. The example is provided solely for demonstration purposes and does not represent real operational or pilot deployment data. Furthermore, it does not expose any sensitive or personal information and is fully compliant with GDPR requirements. All identifiers, including building IDs, are synthetic and do not correspond to real buildings, ensuring that no identifiable or confidential data is disclosed. In addition, geospatial properties of buildings are not exposed, preventing the identification or localisation of real assets. This approach aligns with data protection and privacy-by-design principles adopted within the PEDvolution project.

Semantic representation (RDF Layer)

The PEDvolution CIM supports semantic data representation through the use of RDF, enabling structured and machine-readable descriptions of energy-related information. This semantic layer facilitates interoperability by allowing data to be expressed as linked entities with well-defined relationships and attributes.

```
ex:PED_Slovenian a ped:Ped ;
    ped:ID "SLOVENIAN"^^xsd:string;
    ped:hasName "Slovenian Positive Energy District"^^xsd:string;
    ped:hasBuildings ex:building_1,ex:building_2 .

ex:building_1 a ped:Building;
 ped:ID "building1@SLOVENIAN"^^xsd:string;
 ped:monthlyElectricityConsumption ex:monthlyElectricityConsumption_building_1;
 ped:electricityProduction ex:electricityProduction_building_1;
 ped:annualNaturalGasConsumption ex:annualNaturalGasConsumption_building_1;
 ped:electricitySupply:"SolarPV"^^xsd:string.


ex:monthlyElectricityConsumption_building_1 a qudt:QuantityValue ;
    qudt:numericValue "600"^^xsd:float;
    qudt:unit unit:KiloW-HR .

ex:electricityProduction_building_1 a qudt:QuantityValue ;
    qudt:numericValue "30"^^xsd:float;
    qudt:unit unit:KiloW-HR .

ex:annualNaturalGasConsumption_building_1 a qudt:QuantityValue ;
    qudt:numericValue "200"^^xsd:float;
    qudt:unit unit:KiloW-HR .


ex:building_2 a ped:Building;
 ped:ID "building2@SLOVENIAN"^^xsd:string;
 ped:monthlyElectricityConsumption ex:monthlyElectricityConsumption_building_2;
 ped:electricityProduction ex:electricityProduction_building_2;
 ped:annualNaturalGasConsumption ex:annualNaturalGasConsumption_building_2;
 ped:electricitySupply:"Grid"^^xsd:string.


ex:monthlyElectricityConsumption_building_2 a qudt:QuantityValue ;
    qudt:numericValue "900"^^xsd:float;
    qudt:unit unit:KiloW-HR .

ex:electricityProduction_building_2 a qudt:QuantityValue ;
    qudt:numericValue "50"^^xsd:float;
    qudt:unit unit:KiloW-HR .

ex:annualNaturalGasConsumption_building_2 a qudt:QuantityValue ;
    qudt:numericValue "260"^^xsd:float;
    qudt:unit unit:KiloW-HR .
```

Figure 77: Illustrative RDF representation of Energy Vectors associated with a building in the Slovenian PED using the PEDvolution CIM.

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As illustrated in Figure 77, energy vectors associated with a building can be represented using RDF triples, linking the building entity to energy consumption and production indicators. This approach enables seamless data integration, querying, and exchange across heterogeneous systems and platforms within the PEDvolution ecosystem. Figure 77 illustrates:

A PED entity (ped:Ped)

- An associated building entity
- Unit-aware measurements using QUDT (e.g., kWh)

Key modelling principles demonstrated include:

- Use of unique PED and Building identifiers (ped:ID)
- Standardised units of measurement (unit:KiloW-HR)
- Explicit relationships (ped:hasBuildings)

Transformation to JSON (Operational Layer)

Figure 78, illustrates the transformation of the RDF description into a JSON format. This transformation enables the visualisation and exchange of building-level energy indicators through lightweight interoperable data structures.

The JSON output preserves:

- Hierarchical relationships (PED → Building)
- Energy Vector indicators as structured properties
- Unit-aware metadata and measurement information

The availability of both RDF and JSON representations enables seamless integration with:

- Interoperability Platform services
- Analytics and optimisation tools
- Digital twin platforms
- Real-time monitoring applications

The Energy Vectors ontology enables interoperable, scalable, and semantically enriched energy data exchange within the PEDvolution ecosystem.

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```
{
  "Ped": {
    "id": "SLOVENIAN",
    "name": "Slovenian Positive Energy District",
    "buildings": [
      {
        "id": "building1@SLOVENIAN",
        "monthlyElectricityConsumption": {
          "value": 600.0,
          "unit": "KWh"
        },
        "electricityProduction": {
          "value": 30.0,
          "unit": "KWh"
        },
        "annualNaturalGasConsumption": {
          "value": 200.0,
          "unit": "KWh"
        },
        "electricitySupply": "SolarPV"
      },
      {
        "id": "building2@SLOVENIAN",
        "monthlyElectricityConsumption": {
          "value": 900.0,
          "unit": "KWh"
        },
        "electricityProduction": {
          "value": 50.0,
          "unit": "KWh"
        },
        "annualNaturalGasConsumption": {
          "value": 260.0,
          "unit": "KWh"
        },
        "electricitySupply": "Grid"
      }
    ]
  }
}
```


Figure 78: Illustrative JSON representation of Energy Vectors associated with a building in the Slovenian PED using the PEDvolution CIM.

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ANNEX II: EXAMPLE OF EV CHARGING ONTOLOGY USING THE PEDVOLUTION CIM

The example focuses on an EV charging station located in the Slovenian PED, demonstrating how it is semantically represented and associated with an Electric Vehicle Charging Station Pool. It illustrates how charging stations, supply equipment, and charging ports are modelled as interconnected entities using standardised RDF triples. The example also highlights the use of semantic relationships, unit-aware quantitative values (e.g., power output, battery size, and energy usage), and geospatial information for representing charging infrastructure within the PED context. The example is provided for demonstration purposes only and does not represent real operational data; all identifiers and locations are synthetic and do not correspond to real-world assets. Figure 79 presents an illustrative RDF representation of the EV Charging ontology instantiated using the PEDvolution Common Information Model.

```
ex:PED_Kranj a ped:Ped ;
    ped:ID "SLOVENIAN"^^xsd:string;
    ped:hasName "Planina Positive Energy District, Kranj Slovenia"^^xsd:string;
    geo:hasGeometry  ex:PED_Kranj_Geometry .

ex:PED_Kranj_Geometry a geo:Geometry;
    geo:asWKT "POLYGON((14.362318950747294 46.24719754144064,
    14.35914322766115 46.24182575605897, 14.359189640212804 46.24165723254174,
    14.357739247974052 46.239707137048526, 14.353852196771868 46.23850333980087,
    14.352993564566106 46.23916141890214, 14.34527557574441 46.22989854156654,
    14.348032305456314 46.22432391247975, 14.368907741442541 46.23147660165111,
    14.37736071095747 46.23919198547111, 14.362318950747294 46.24719754144064))"^^geo:wktLiteral .

ex:ElectricVehicleChargingStation_1 a ped:ElectricVehicleChargingStation;
   em:isPartOfPool ex:ElectricVehicleChargingStationPoolInKranj;
   ped:linkedToPed "SLOVENIAN"^^xsd:string;
   geo:hasGeometry ElectricVehicleChargingStation_Point;
   ped:consistsEVSupplyEquipment ex:electricVehicIeSupplyEquipment_1 .

ex:ElectricVehicleChargingStation_Point a geo:Point;
   geo:asWKT "POINT(( 14.3559, 46.2386))"^^geo:wktLiteral .

ex:ElectricVehicleChargingStationPoolInKranj a em:ElectricVehicleChargingStationPool;
   em:name "Kranj Electric Vehicle Charging Station"^^xsd:string;
   em:hasLocationAsPool ex:ElectricVehicleChargingStationPool_Point; .

ex:ElectricVehicleChargingStationPool_Point a geo:Point;
   geo:asWKT "POINT(( 14.355, 46.2386))"^^geo:wktLiteral .

ex:electricVehicleSupplyEquipment_1 a ped:ElectricVehicleSupplyEquipment;
   ped:hasElectricVehicleChargerType ped:Level1;
   em:hasChargingSpeed prop:Fast;
   ped:chargingProfile "Day"^^xsd:string;
   ped:batterySize ex:batterySize;
   ped:powerOutput ex:powerOutput;
   ped:dailyUsage  ex:dailyUsage;
   ped:hasElectricVehicleChargingPort ex:electricVehicleChargingPort_1 ; .

ex:batterySize a qudt:QuantityValue ;
    qudt:numericValue "60"^^xsd:integer;
    qudt:unit unit:KiloW-HR .

ex:powerOutput a qudt:QuantityValue ;
   qudt:numericValue "50"^^xsd:integer ;
   qudt:unit unit:KiloW .

ex:dailyUsage a qudt:QuantityValue;
    qudt:numericValue "200"^^xsd:integer ;
    qudt:unit unit:KiloW-HR .

ex:electricVehicleChargingPort_1 a ped:ElectricVehicleChargingPort;
   brick:electricVehicleConnectorType ex:Type1_CCS;
   brick:electricVehicleChargerDirectionality ex:Bidirectional;.

ex:Type1_CCS a bsh:ElectricVehicleConnectorTypeShape;
   brick:value "Type1_CCS"^^xsd:string .

ex:Bidirectional a bsh:ElectricVehicleChargingDirectionalityShape;
   brick:value "Bidirectional"^^xsd:string .
```

Figure 79: RDF representation of an EV charging station in the Slovenian PED, associated with an EV charging station pool.

GeoJSON Representation

To facilitate integration with GIS platforms and geospatial analytics tools, the RDF representation can be transformed into GeoJSON format. The following example in Figure 80 demonstrates how EV

charging infrastructure described semantically through the PEDvolution CIM can also be represented in lightweight geospatial data structures suitable for web applications, visualisation services, and digital twin platforms.


```
{
  "type": "FeatureCollection",
  "features": [
    {
      "type": "Feature",
      "geometry": {
        "type": "Polygon",
        "coordinates": [[
        [14.3623,46.2472], [14.3591,46.2418], [14.3592,46.2417], [14.3577,46.2397],
        [14.3539,46.2385], [14.353,46.2392], [14.3453,46.2299], [14.348,46.2243],
        [14.3689,46.2315], [14.3774,46.2392], [14.3623,46.2472]
]]
      },
      "properties": {
        "type": "Ped",
        "ID": "SLOVENIAN",
        "name": "Planina Positive Energy District,Kranj Slovenia"
      }
    },
    {
      "type": "Feature",
      "geometry": {
        "type": "Point",
        "coordinates": [
          14.3559,
          46.2386
        ]
      },
      "properties": {
        "type": "ElectricVehicleChargingStation",
        "ID": "ElectricVehicleChargingStation_1",
        "linkedToPed": "SLOVENIAN",
        "consistsEVSupplyEquipment": {
          "type": "ElectricVehicleSupplyEquipment",
          "ID": "electricVehicleSupplyEquipment_1",
          "chargerType": "Level1",
          "chargingSpeed": "Fast",
          "chargingProfile": "Day",
          "batterySize": {
            "value": 60,
            "unit": "kWh"
          },
          "powerOutput": {
            "value": 50,
            "unit": "kW"
          },
          "dailyUsage": {
            "value": 200,
            "unit": "kWh"
          },
          "ports": [
            {
              "id": "electricVehicleChargingPort_1",
              "connectorType": "Type1_CCS",
              "directionality": "Bidirectional"
            }
          ]
        }
      }
    },
    {
      "type": "Feature",
      "geometry": {
        "type": "Point",
        "coordinates": [
          14.355,
          46.2386
        ]
      },
      "properties": {
        "type": "ElectricVehicleChargingStationPool",
        "ID": "ElectricVehicleChargingStationPoolInKranj",
        "name": "Kranj Electric Vehicle Charging Station"
      }
    }
  ]
}
```


Figure 80: Illustrative GeoJSON representation derived from the RDF example of EV charging infrastructure using the PEDvolution CIM.

Visualisation of EV Charging Infrastructure

The following visualisation Figure 81 illustrates how semantically modelled EV charging infrastructure can be graphically represented within the PEDvolution ecosystem. Such visual representations support monitoring, interoperability validation, spatial analysis, and integration with decision-support and digital twin applications. The visualisation is based on the illustrative ontology example and is provided for demonstration purposes only.

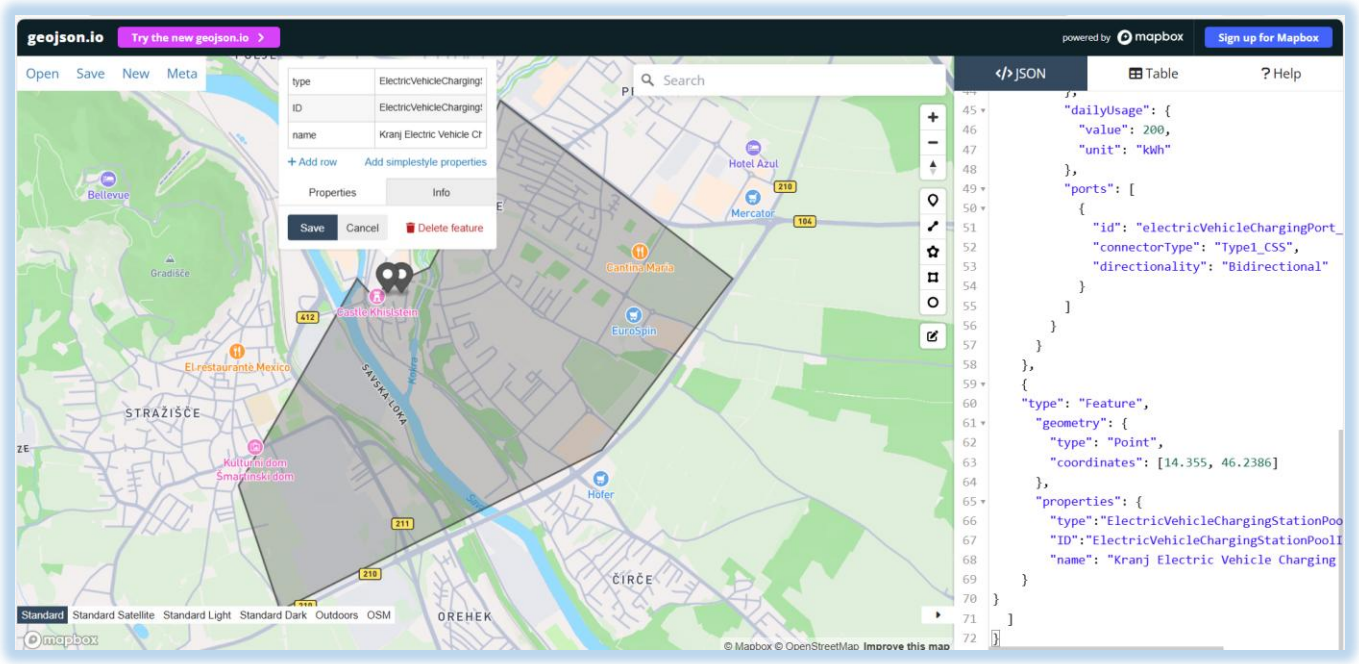


Figure 81: Illustrative visualisation of EV charging infrastructure associated with the Slovenian PED using the PEDvolution Common Information Model.

The EV Charging ontology provides a standardised and semantically enriched framework for representing electromobility infrastructure within the PEDvolution CIM. It captures both the logical structure of charging infrastructure (stations and pools) and the physical and operational characteristics of charging equipment, including performance parameters, connector types, and charging behaviour. This enables seamless integration with energy management systems, flexibility services, and digital twin platforms, supporting advanced analytics and optimisation use cases within Positive Energy Districts.

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ANNEX III: AN EXAMPLE OF HEAT RECOVERY POTENTIAL ONTOLOGY USING THE PEDVOLUTION CIM

The example illustrates how Heat Recovery Potential can be represented using the PEDvolution Common Information Model. It presents the semantic modelling of Positive Energy Districts (PEDs), industrial processes, geothermal plants, and heat-recovery-related characteristics using RDF together with geospatial ontologies for spatial representation and QUDT for quantitative measurements. The example is provided for demonstration purposes only and does not represent real operational data; all identifiers and locations are synthetic and do not correspond to real-world assets.

The instance ex:PED_Kranj (Slovenian PED) represents the district boundary and is linked to district-level technical characteristics. These characteristics include heat recovery potential information, aggregating available thermal energy sources and industrial waste heat resources within the PED.

Two heat sources are described:

- An industrial process producing recoverable waste heat, characterised by process temperature and recoverable thermal power, monitored through a steam waste meter.
- A geothermal plant providing renewable thermal capacity and temperature.

A building is also modelled within the district thermal network, providing inlet and outlet temperature information used to evaluate heat consumption and network efficiency.

All assets are georeferenced (points within the district polygon), enabling spatial queries such as identifying energy sources located inside the PED.

Operational values (temperature, capacity, waste heat) are expressed as QUDT quantities with explicit units, allowing automated processing, comparison and optimisation.

Overall, the RDF model forms a machine-readable representation of the district energy system, linking spatial context, energy production, recovery potential and consumption to support interoperability and analysis within the PEDvolution ecosystem.

Figure 82 illustrates the RDF instantiation of the Heat Recovery Potential ontology within the PEDvolution Common Information Model. It presents how different heat sources, including industrial waste heat and geothermal energy, are semantically modelled and linked to the PED context, along with associated buildings and thermal characteristics.

The figure highlights the integration of energy assets, spatial information, and quantitative measurements, enabling a unified and machine-readable representation of heat recovery potential within the district.

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```
ex:PED_Kranj a ped:PED ;
    ped:ID "Kranj"^^xsd:string;
    ped:hasDistrictTechnicalCharacteristics ex:DistrictTechnicalCharacteristicsOfKranj;
    ped:hasName "Planina Positive Energy District"^^xsd:string ;
    geo:hasGeometry  ex:PED_Kranj_Geometry .

ex:DistrictTechnicalCharacteristicsOfKranj a ped:DistrictTechnicalCharacteristics;
   ped:hasHeatRecoveryPotentialCharacteristics ex:HeatRecoveryPotentialCharacteristicsOfKranj .

ex:HeatRecoveryPotentialCharacteristicsOfKranj a ped:HeatRecoveryPotentialCharacteristics;
   ped:industrialProcesses ex:chemicalIndustrialProcesses;
   ped:geothermalPlants ex:geothermalPlant1.

ex:chemicalIndustrialProcesses a ped:IndustrialProcess;
   ped:ID "chemicalIndustrialProcesses@Kranj"^^xsd:string;
   ped:Temperature_In_Celcius ex:temperature_in_celcius_industrial_process;
   ped:Waste_Heat_In_KW ex:waste_heat_in_kw;
   ped:hasWasteMeter       ex:wasteMeter1;
   geo:hasGeometry         ex:Industrial_Kranj_Geometry .

ex:wasteMeter1 a ped:WasteMeter;
   ped:ID "wasteMeter1@chemicalIndustrialProcesses@Kranj"^^xsd:string;
   brick:hasSubstance brick:Steam.

ex:temperature_in_celcius_industrial_process  a qudt:QuantityValue ;
    qudt:numericValue "80"^^xsd:float;
    qudt:unit unit:DEG_C .

ex:waste_heat_in_kw  a qudt:QuantityValue ;
    qudt:numericValue "1500"^^xsd:float;
    qudt:unit unit:KiloW .

ex:geothermalPlant1 a ped:GeothermalPlant;
   ped:ID "geothermalPlant1@Kranj"^^xsd:string;
   ped:Capacity_In_KW ex:capacity_in_kw_geothermal_plant1;
   ped:Temperature_In_Celcius ex:temperature_in_celcius_geothermal_plant1;
   geo:hasGeometry ex:geothermalPlant_Kranj_Geometry .

ex:temperature_in_celcius_geothermal_plant1  a qudt:QuantityValue ;
    qudt:numericValue "60"^^xsd:float;
    qudt:unit unit:DEG_C .

ex:capacity_in_kw_geothermal_plant1  a qudt:QuantityValue ;
    qudt:numericValue "1000"^^xsd:float;
    qudt:unit unit:KiloW .


ex:PED_Kranj_Geometry a geo:Geometry;
   geo:asWKT "POLYGON(14.362318950747294 46.24719754144064,
                      14.35914322766115 46.24182575605897,
                      14.359189640212804 46.24165723254174,
                      14.357739247974052 46.239707137048526,
                      14.353852196771868 46.23850333980087,
                      14.352993564566106 46.23916141890214,
                      14.34527557574441  46.22989854156654,
                      14.348032305456314 46.22432391247975,
                      14.368907741442541 46.23147660165111,
                      14.377360710957447 46.23919198547111,
                      14.362318950747294 46.24719754144064)"^^geo:wktLiteral .

ex:Industrial_Kranj_Geometry a geo:Geometry;
    geo:asWKT "POINT(14.353 46.239)"^^geo:wktLiteral .

ex:geothermalPlant_Kranj_Geometry a geo:Geometry;
    geo:asWKT "POINT(14.355 46.238)"^^geo:wktLiteral .
```

Figure 82: Illustrative RDF representation of Heat Recovery Potential assets (industrial process and geothermal plant) within the Slovenian PED using the PEDvolution CIM.

Following the semantic representation in RDF, the Heat Recovery Potential data can be transformed into GeoJSON format to support geospatial interoperability and integration with GIS-based applications.

Figure 83 illustrates the GeoJSON representation of heat recovery assets, including industrial processes and geothermal plants, preserving their spatial location and associated attributes in a lightweight and widely supported data format.

```
{
  "type": "FeatureCollection",
  "features": [
    {
      "type": "Feature",
      "geometry": {
        "type": "Polygon",
        "coordinates":[[
         [14.3623,46.2472],[14.3591,46.2418],[14.3592,46.2417],[14.3577,46.2397],
         [14.3539,46.2385],[14.3530,46.2392],[14.3453,46.2299],[14.3480,46.2243],
         [14.3689,46.2315],[14.3774,46.2392],[14.3623,46.2472]
        ]]},

      "properties": {
        "type": "PED",
        "ID": "Kranj",
        "hasDistrictTechnicalCharacteristics": "DistrictTechnicalCharacteristicsOfKranj",
        "hasName": "Planina Positive Energy District"
      }
    },
    {
      "type": "Feature",
      "geometry": {
        "type": "Point",
        "coordinates": [
          14.353,46.239
        ]
      },
      "properties": {
        "type": "IndustrialProcess",
        "ID": "chemicalIndustrialProcesses@Kranj",
        "Temperature_In_Celcius": {
          "value": 80.0, "unit": "Celsius"
        },
        "Waste_Heat_In_KW": {
          "value": 1500.0,"unit": "kW"
        },
        "hasWasteMeter": {
          "ID": "wasteMeter1@chemicalIndustrialProcesses@Kranj",
          "hasSubstance": "Steam"
        }
      }
    },
    {
      "type": "Feature",
      "geometry": {
        "type": "Point",
        "coordinates": [
          14.355,46.238
        ]
      },
      "properties": {
        "type": "GeothermalPlant",
        "ID": "geothermalPlant1@Kranj",
        "Capacity_In_KW": {
          "value": 1000.0,"unit": "kW"
        },
        "Temperature_In_Celcius": {
          "value": 60.0,"unit": "Celsius"
        }
      }
    }

  ]
}
```


Figure 83: Illustrative GeoJSON representation of Heat Recovery Potential assets (industrial process and geothermal plant) within the Slovenian PED using the PEDvolution CIM.

Building upon the GeoJSON representation, the Heat Recovery Potential assets can be visualised in a spatial context to support analysis and decision-making processes.

Figure 84 presents an illustrative visualisation of the heat recovery assets within the Slovenian PED, enabling intuitive interpretation of their spatial distribution and facilitating applications such as planning, optimisation, and integration with digital twin environments.

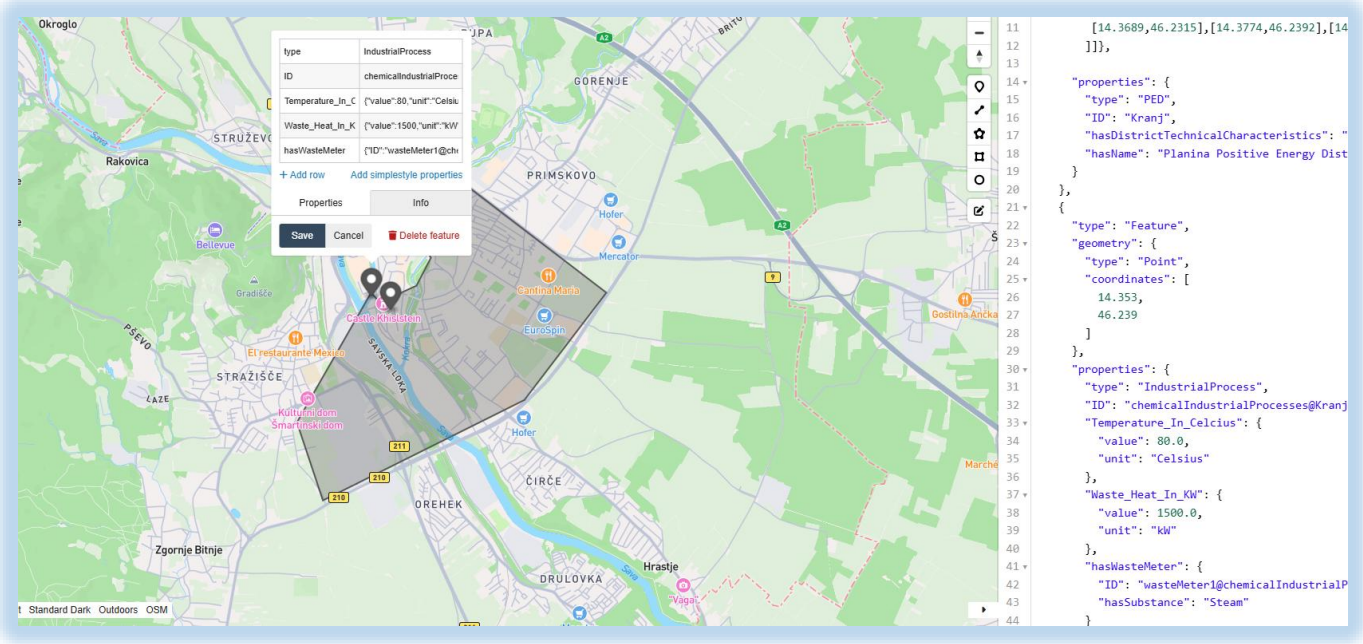


Figure 84: Illustrative spatial visualisation of Heat Recovery Potential assets (industrial process and geothermal plant) within the Slovenian PED using the PEDvolution CIM.

ANNEX IV: EXAMPLE OF THE PV SYSTEM CHARACTERISTICS ONTOLOGY USING PEDVOLUTION CIM

This ANNEX presents an example of how photovoltaic (PV) system characteristics are represented in the PEDvolution Common Information Model using RDF and standardised ontologies. As illustrated in Figure 85 , the example refers to the Slovenian Positive Energy District in Kranj, where photovoltaic system characteristics are represented at district level. At the highest level, the district is represented by the class ped:Ped, which includes identifiers, name information, and spatial geometry. In this example, the PED instance *ex:PED_Kranj* represents the Planina Positive Energy District, and its geographic boundary is described using geospatial geometry. The example is provided for demonstration purposes only and does not represent real operational data; all identifiers and locations are synthetic and do not correspond to real-world assets.

```
ex:PED_Kranj a ped:PED ;
    ped:ID "Kranj"^^xsd:string;
    ped:hasName "Planina Positive Energy District"^^xsd:string;
    geo:hasGeometry ex:PED_Kranj_Geometry .

ex:PVSystemCharacteristics_district a ped:PVSystemCharacteristics;
   geo:hasGeometry ex:pv_district_Geometry ;
   ped:Annual_Solar_PV_Output_In_MW  ex:Annual_Solar_PV_Output_In_MW;
   ped:Solar_Thermal_Capacity_in_MW  ex:Solar_Thermal_Capacity_in_MW;
   ped:Solar_PV_Installed_Capacity_In_MW  ex:Solar_PV_Installed_Capacity_In_MW;
   ped:Annual_Solar_Thermal_Output_In_MW  ex:Annual_Solar_Thermal_Output_In_MW;
   ped:PanelOrientation "45"^^xsd:integer;
   ped:installationType "Solar Park"^^xsd:string;
   ped:isControllable   "true"^^xsd:boolean .

ex:Annual_Solar_PV_Output_In_MW  a qudt:QuantityValue ;
    qudt:numericValue "50"^^xsd:float;
    qudt:hasUnit unit:MegaW .

ex:Solar_Thermal_Capacity_in_MW  a qudt:QuantityValue ;
    qudt:numericValue "10"^^xsd:float;
    qudt:hasUnit unit:MegaW .

ex:Solar_PV_Installed_Capacity_In_MW  a qudt:QuantityValue ;
    qudt:numericValue "15"^^xsd:float;
    qudt:hasUnit unit:MegaW .

ex:Annual_Solar_Thermal_Output_In_MW  a qudt:QuantityValue ;
    qudt:numericValue "17"^^xsd:float;
    qudt:hasUnit unit:MegaW .

ex:pv_district_Geometry a geo:Geometry;
    geo:asWKT "POINT((14.361351897909453 46.23525459854533 ))"^^geo:wktLiteral .

ex:PED_Kranj_Geometry a geo:Geometry ;
    geo:asWKT "POLYGON((14.362318950747294 46.24719754144064,
                        14.35914322766115 46.24182575605897,
                        14.359189640212804 46.24165723254174,
                        14.357739247974052 46.239707137048526,
                        14.3538521967718 46.23850333980087,
                        14.352993564566106 46.23916141890214,
                        14.34527557574441 46.22989854156654,
                        14.348032305456314 46.22432391247975,
                        14.368907741442541 46.23147660165111,
                        14.377360710957447 46.23919198547111,
                        14.362318950747294 46.24719754144064))"^^geo:wktLiteral .
```

Figure 85: RDF representation of PV system characteristics associated with a district-level energy asset in the Slovenian Positive Energy District (Kranj), using the PEDvolution Common Information Model.

GeoJSON Representation of the PV System Characteristics Example

The RDF example presented above can be transformed into a GeoJSON representation, enabling geospatial visualisation of PED entities and associated energy assets. GeoJSON is widely used for representing geographic features in GIS systems and web-based mapping applications, making it suitable for integrating PEDvolution data into digital twin platforms and spatial analysis tools.

The resulting GeoJSON dataset contains a **FeatureCollection** composed of two features:

1. **The PED boundary**, polygon representing the Planina PED.
2. **The PV system location**, point (or multiple points) representing district-level PV installations.

Figure 86 illustrates the geospatial representation derived from the RDF description.


```
{
  "type": "FeatureCollection",
  "features": [
    {
      "type": "Feature",
      "geometry": {
        "type": "Polygon",
        "coordinates": [[
        [14.3623,46.2472], [14.3591,46.2418], [14.3592,46.2417],
        [14.3577,46.2397], [14.3539,46.2385], [14.353,46.2392],
        [14.3453,46.2299], [14.348,46.2243], [14.3689,46.2315],
        [14.3774,46.2392], [14.3623,46.2472]
]]
      },
      "properties": {
        "ID": "Kranj",
        "type": "PED",
        "hasName": "Planina Positive Energy District"
      }
    },
    {
      "type": "Feature",
      "geometry": {
        "type": "Point",
        "coordinates": [
          14.361351897909453,
          46.23525459854533
        ]
      },
      "properties": {
        "ID": "PVSystemCharacteristics_district",
        "type": "PVSystemCharacteristics",
        "Annual_Solar_PV_Output_In_MW": {
          "value": 50.0,
          "unit": "MW"
        },
        "Solar_Thermal_Capacity_in_MW": {
          "value": 10.0,
          "unit": "MW"
        },
        "Solar_PV_Installed_Capacity_In_MW": {
          "value": 15.0,
          "unit": "MW"
        },
        "Annual_Solar_Thermal_Output_In_MW": {
          "value": 17.0,
          "unit": "MW"
        },
        "PanelOrientation": 45,
        "installationType": "Solar Park",
        "isControllable": true
      }
    }
  ]
}
```


Figure 86: GeoJSON representation of district-level PV system characteristics in the Slovenian PED (Kranj), derived from the PEDvolution CIM.

This GeoJSON representation demonstrates how semantic descriptions expressed in RDF can be transformed into geospatial datasets, enabling PEDvolution assets to be visualised and analysed using GIS tools. The transformation facilitates the integration of semantic energy asset descriptions with

spatial data infrastructures, supporting interoperability between the PEDvolution platform and external visualisation or analysis systems.

Figure 87 illustrates the visualisation of the generated GeoJSON dataset on a map where the PED boundary and the associated district-level PV system characteristics are displayed as geospatial features.

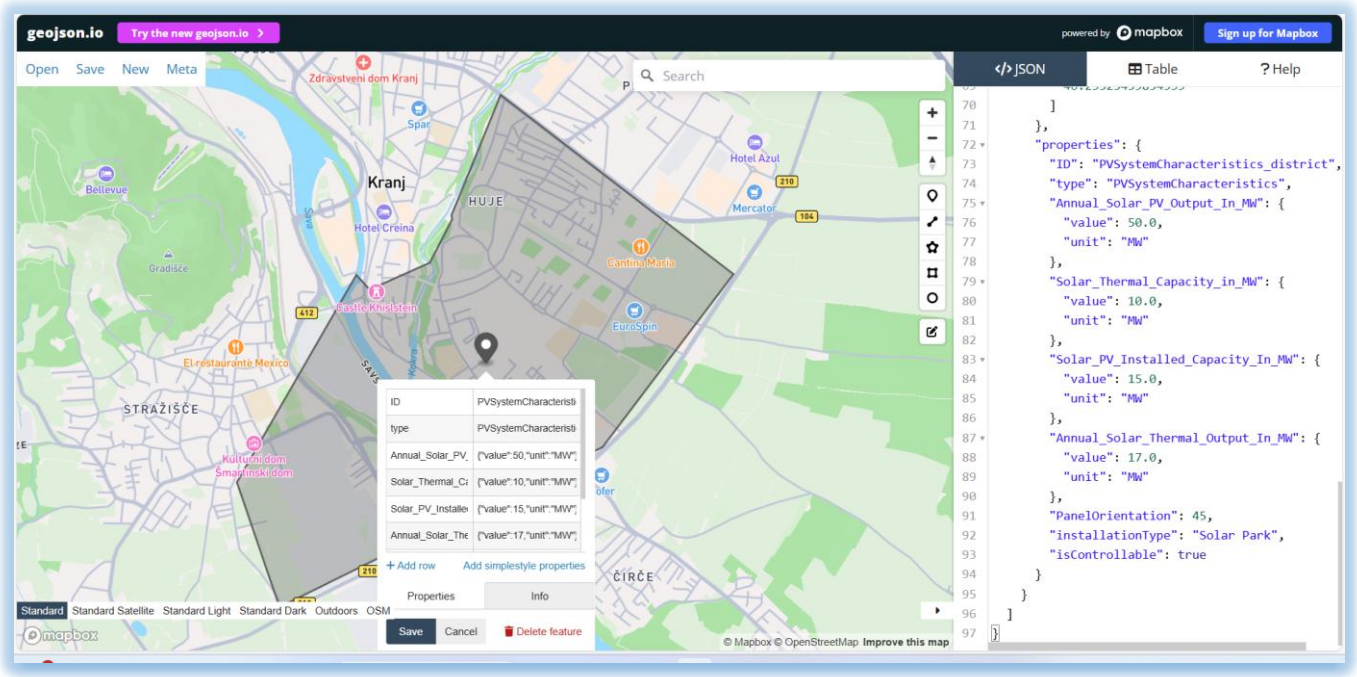


Figure 87: Visualisation of district-level PV system characteristics within the PED boundary in the Slovenian Positive Energy District (Kranj).

By modelling PV systems as energy assets, the PEDvolution Common Information Model enables their seamless integration into data-driven services and cross-domain workflows, supporting efficient, scalable, and sustainable PED operation.

ANNEX V: EXAMPLE OF THE DISTRICT ENERGY ASSETS CHARACTERISTICS ONTOLOGY USING THE PEDVOLUTION CIM

An example of the District Energy Assets ontology is presented in Figure 88, representing a Combined Heat and Power (CHP) plant located within the Slovenian PED pilot in Kranj. The example is provided for demonstration purposes only and does not represent real operational data; all identifiers and locations are synthetic and do not correspond to real-world assets.

```
ex:CHPPlant_CHPP1_Kranj a ped:CHP_Plant ;
    ped:ID "CHPPlant_CHPP1@Kranj"^^xsd:string ;
    ped:linkedToPED "SLOVENIAN"^^xsd:string ;
    ped:EnergyAssetId "CHPP1"^^xsd:string ;
    ped:Efficiency_Percentage ex:Efficiency_Percentage_CHPP1 ;
    ped:Capacity_In_KW ex:Capacity_CHPP1 ;
    ped:Thermal_Capacity_In_KW ex:Thermal_Capacity_CHPP1 ;
    ped:fuelType "Natural Gas"^^xsd:string ;
    ped:providesDistrictHeating "true"^^xsd:boolean ;
    geo:hasGeometry ex:CHPP1_Kranj_Geometry .

ex:Efficiency_Percentage_CHPP1 a qudt:QuantityValue ;
    qudt:numericValue "85"^^xsd:float ;
    qudt:hasUnit unit:PERCENT .

ex:Capacity_CHPP1 a qudt:QuantityValue ;
    qudt:numericValue "1039"^^xsd:float ;
    qudt:hasUnit unit:KiloW .

ex:Thermal_Capacity_CHPP1 a qudt:QuantityValue ;
    qudt:numericValue "1145"^^xsd:float ;
    qudt:hasUnit unit:KiloW .

ex:CHPP1_Kranj_Geometry a geo:Geometry ;
    geo:asWKT "POINT(14.35832,46.23698)"^^geo:wktLiteral .

ex:PED_Kranj a ped:PED ;
    ped:ID "Kranj"^^xsd:string ;
    ped:hasName "Planina Positive Energy District"^^xsd:string ;
    geo:hasGeometry ex:PED_Kranj_Geometry .

ex:PED_Kranj_Geometry a geo:Geometry ;
    geo:asWKT "POLYGON((14.362318950747294 46.24719754144064,
                        14.35914322766115 46.24182575605897,
                        14.359189640212804 46.24165723254174,
                        14.357739247974052 46.239707137048526,
                        14.353852196771868 46.23850333980087,
                        14.352993564566106 46.23916141890214,
                        14.34527557574441 46.22989854156654,
                        14.348032305456314 46.22432391247975,
                        14.368907741442541 46.23147660165111,
                        14.377360710957447 46.23919198547111,
                        14.362318950747294 46.24719754144064))"^^geo:wktLiteral .
```

Figure 88: RDF representation of a Combined Heat and Power (CHP) plant instance in the Slovenian Positive Energy District (Kranj), including capacity, thermal output, efficiency, and geospatial geometry defined using the PEDvolution ontology and QUDT quantities.

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In this example, the CHP plant instance ex:CHPPlant_CHPP1_Kranj is defined as an instance of the class ped:CHP_Plant. The instance includes several descriptive attributes, including:

- ped:EnergyAssetId, identifying the energy asset within the PED infrastructure.
- ped:Efficiency_Percentage, representing the operational efficiency of the CHP system.
- ped:Capacity_In_KW, describing the electrical generation capacity.
- ped:Thermal_Capacity_In_KW, describing the thermal output of the system.

These quantities are modelled using qudt:QuantityValue, allowing the representation of both numerical values and measurement units.

The asset is also linked to a specific geometry using the property geo:hasGeometry, which references a spatial representation expressed using Well-Known Text (WKT). This allows the CHP plant to be geographically located within the district energy infrastructure.

Additionally, the ontology includes the representation of the Planina Positive Energy District (PED_Kranj), which defines the district boundary as a polygon geometry.

GeoJSON Representation of the District Energy Ontology Example

The RDF representation of the district energy assets can be transformed into GeoJSON format to facilitate integration with geospatial applications and visualisation tools. In this representation as shown in Figure 89, the Positive Energy District is represented as a polygon geometry, while the CHP plant is represented as a point feature located within the district.

Each GeoJSON feature includes a properties object that stores semantic attributes derived from the RDF model. These attributes include the energy asset identifier, efficiency percentage, capacity values, fuel type, and other operational characteristics.

This transformation enables semantic energy asset data to be used in GIS platforms, web mapping applications, and spatial analytics tools, bridging the gap between semantic data models and geospatial visualisation frameworks.

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```
{
  "type": "FeatureCollection",
  "features": [
    {
      "type": "Feature",
      "geometry": {
        "type": "Polygon",
        "coordinates": [[
        [14.3623,46.2472], [14.3591,46.2418], [14.3592,46.2417],
        [14.3577,46.2397], [14.3539,46.2385], [14.353,46.2392],
        [14.3453,46.2299], [14.348,46.2243], [14.3689,46.2315],
        [14.3774,46.2392], [14.3623,46.2472]
]]
      },
      "properties": {
        "ID": "Kranj",
        "type": "PED",
        "hasName": "Planina Positive Energy District"
      }
    },
    {
      "type": "Feature",
      "geometry": {
        "type": "Point",
        "coordinates": [
          14.35832,
          46.23698
        ]
      },
      "properties": {
        "ID": "CHPPlant_CHPP1@Kranj",
        "type": "CHP_Plant",
        "linkedToPED": "SLOVENIAN",
        "EnergyAssetId": "CHPP1",
        "Efficiency_Percentage": {
          "value": 85.0,
          "unit": "%"
        },
        "Capacity_In_KW": {
          "value": 1039.0,
          "unit": "kW"
        },
        "Thermal_Capacity_In_KW": {
          "value": 1145.0,
          "unit": "kW"
        },
        "fuelType": "Natural Gas",
        "providesDistrictHeating": true
      }
    }
  ]
}
```


Figure 89: GeoJSON representation of district energy assets in the Slovenian Positive Energy District (Kranj), illustrating the PED boundary as a polygon and the CHP plant as a point feature with associated semantic attributes.

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Geospatial Visualisation of the District Energy Assets Example

The GeoJSON representation can be visualised using geospatial mapping tools. Figure 90 illustrates the spatial distribution of the Slovenian Positive Energy District and the associated CHP plant location.

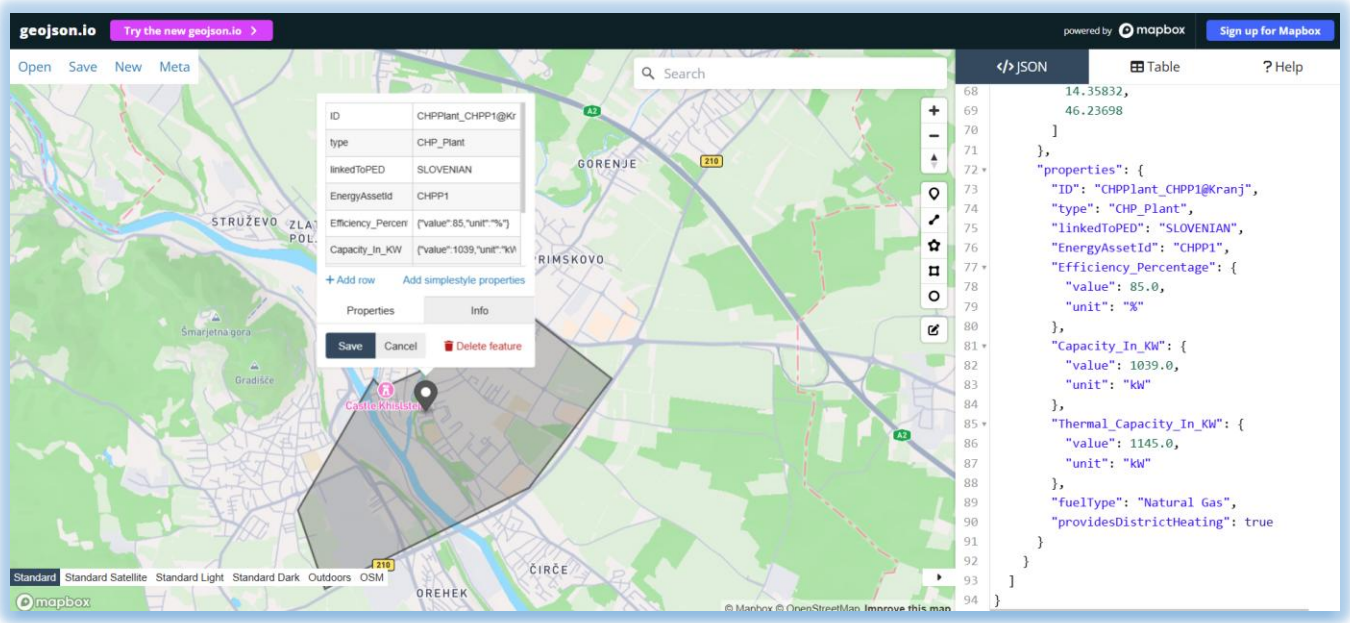


Figure 90: Geospatial visualisation of district energy assets within the Slovenian Positive Energy District (Kranj), showing the spatial relationship between the PED boundary and the CHP plant location.

The map representation enables users to easily interpret the spatial relationships between district energy assets and the overall district boundary. This visualisation supports several potential applications, including:

- District energy planning and infrastructure analysis.
- Integration with smart city dashboards.
- Visualisation of PED energy assets within digital twin platforms.
- Decision-support tools for energy system optimisation.

The District Energy Assets Ontology provides a structured and semantically consistent framework for representing district-level energy generation systems within the PEDvolution Common Information Model. By modelling energy assets at different levels of abstraction, the ontology enables the integration of heterogeneous energy infrastructures and supports interoperability across PED pilots and Solution Providers.

Through its alignment with domain-specific ontologies and geospatial representations, the ontology facilitates the integration of district energy assets into data-driven services, planning tools, and digital twin applications within the PEDvolution ecosystem.

ANNEX VI: EXAMPLE OF THE DISTRICT HEATING AND COOLING INFRASTRUCTURE ONTOLOGY USING THE PEDVOLUTION CIM

Figure 91 illustrates an example application of the District Heating and Cooling Infrastructure ontology to a PED instance (Kranj, Slovenia) using the RDF representation defined by the PEDvolution Common Information Model. The example is provided for demonstration purposes only and does not represent real operational data; all identifiers and locations are synthetic and do not correspond to real-world assets.

Key elements include:

- A PED entity (Kranj) with associated technical characteristics.
- A District Heating and Cooling Infrastructure instance.
- Linked substation(s) with:
    - Capacity
    - Efficiency
    - Costs
- A pipe network with:
    - Length
    - Heat loss
- Spatial representations using WKT geometries.

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```
ex:PED_Kranj a ped:PED ;
    ped:ID "Kranj"^^xsd:string;
    ped:hasName "Planina Positive Energy District"^^xsd:string;
    ped:hasDistrictTechnicalCharacteristics ex:DistrictTechnicalCharacteristicsOfKranj;
    geo:hasGeometry ex:PED_Kranj_Geometry .

ex:DistrictTechnicalCharacteristicsOfKranj a ped:DistrictTechnicalCharacteristics;
   ped:hasDistrictHeatingAndCoolingInfrastructure ex:DHAC_infrastructure;
   geo:hasGeometry ex:PED_Kranj_Geometry  .

ex:DHAC_infrastructure a ped:DistrictHeatingAndCoolingInfrastructure;
  ped:DHC_Network "layout_of_pipes"^^xsd:string;
  ped:pipes ex:Pipe_1;
  ped:installed_substations ex:Substation_1;
  geo:hasGeometry ex:PED_Kranj_Geometry  .

ex:PED_Kranj_Geometry a geo:Geometry;
   geo:asWKT "POLYGON((14.362318950747294 46.24719754144064, 14.35914322766115 46.24182575605897, 14.3591896

#################################################################
# Substation with costs and coordinates
#################################################################

ex:Substation_1 a ped:SubStation ;
    ped:Heat_Exchanger_Size_in_KW  ex:Substation_1_Heat_Exchanger_Size_in_KW;
    ped:Efficiency_Percentage  ex:Substation_1_Efficiency_Percentage ;
    ped:Capacity_In_KW ex:Substation_1_Capacity;
    ped:Installation_Cost_In_Euro  ex:Substation_1_Installation_Cost_In_Euro;
    ped:Operational_Cost_Per_Year_in_Euro  ex:Substation_1_Operational_Cost_Per_Year_in_Euro;
    ped:linkedToPED  "SLOVENIAN"^^xsd:string;
    geo:hasGeometry  ex:Substation_1_Geometry  .

ex:Substation_1_Heat_Exchanger_Size_in_KW a qudt:QuantityValue ;
    qudt:numericValue "150"^^xsd:float;
    qudt:hasUnit unit:KiloW .

ex:Substation_1_Efficiency_Percentage  a qudt:QuantityValue ;
    qudt:numericValue "85"^^xsd:float;
    qudt:hasUnit unit:PERCENT .

ex:Substation_1_Capacity  a qudt:QuantityValue ;
    qudt:numericValue "1039"^^xsd:float;
    qudt:hasUnit unit:KiloW .

ex:Substation_1_Installation_Cost_In_Euro a qudt:QuantityValue ;
    qudt:numericValue "124328.47"^^xsd:decimal;
    qudt:hasUnit unit:CCY_EUR .

ex:Substation_1_Operational_Cost_Per_Year_in_Euro a qudt:QuantityValue ;
    qudt:numericValue "27043.890"^^xsd:decimal;
    qudt:hasUnit unit:CCY_EUR .

ex:Substation_1_Geometry a geo:Geometry;
    geo:asWKT "POINT(14.353 46.238)"^^geo:wktLiteral .

#################################################################
# Pipe with LineString geometry
#################################################################

ex:Pipe_1 a ped:Pipe ;
    ped:Length_In_Meters  ex:Pipe_1_Length_In_Meters;
    ped:Heat_Loss_In_Pipes_in_KW_per_m  ex:Pipe_1_Heat_Loss_In_in_KW_per_m;
    ped:Total_Heat_Loss_In_KW ex:Pipe_1_Total_Heat_Loss_In_KW;
    geo:hasGeometry ex:Pipe_1_Geometry .

 ex:Pipe_1_Heat_Loss_In_in_KW_per_m a qudt:QuantityValue ;
    qudt:numericValue "50"^^xsd:float;
    qudt:hasUnit unit:KiloW .

 ex:Pipe_1_Total_Heat_Loss_In_KW a qudt:QuantityValue ;
    qudt:numericValue "50"^^xsd:float;
    qudt:hasUnit unit:KiloW .

ex:Pipe_1_Length_In_Meters a qudt:QuantityValue ;
    qudt:numericValue "5689.78"^^xsd:float;
    qudt:hasUnit unit:M .


ex:Pipe_1_Geometry a geo:Geometry ;
    geo:asWKT "LINESTRING(14.353 46.238, 14.3531 46.238, 14.354 46.238, 14.3541 46.23626)"^^geo:wktLiteral .
```

Figure 91: Example RDF representation of the District Heating and Cooling Infrastructure ontology applied to the Slovenian PED within the PEDvolution CIM.

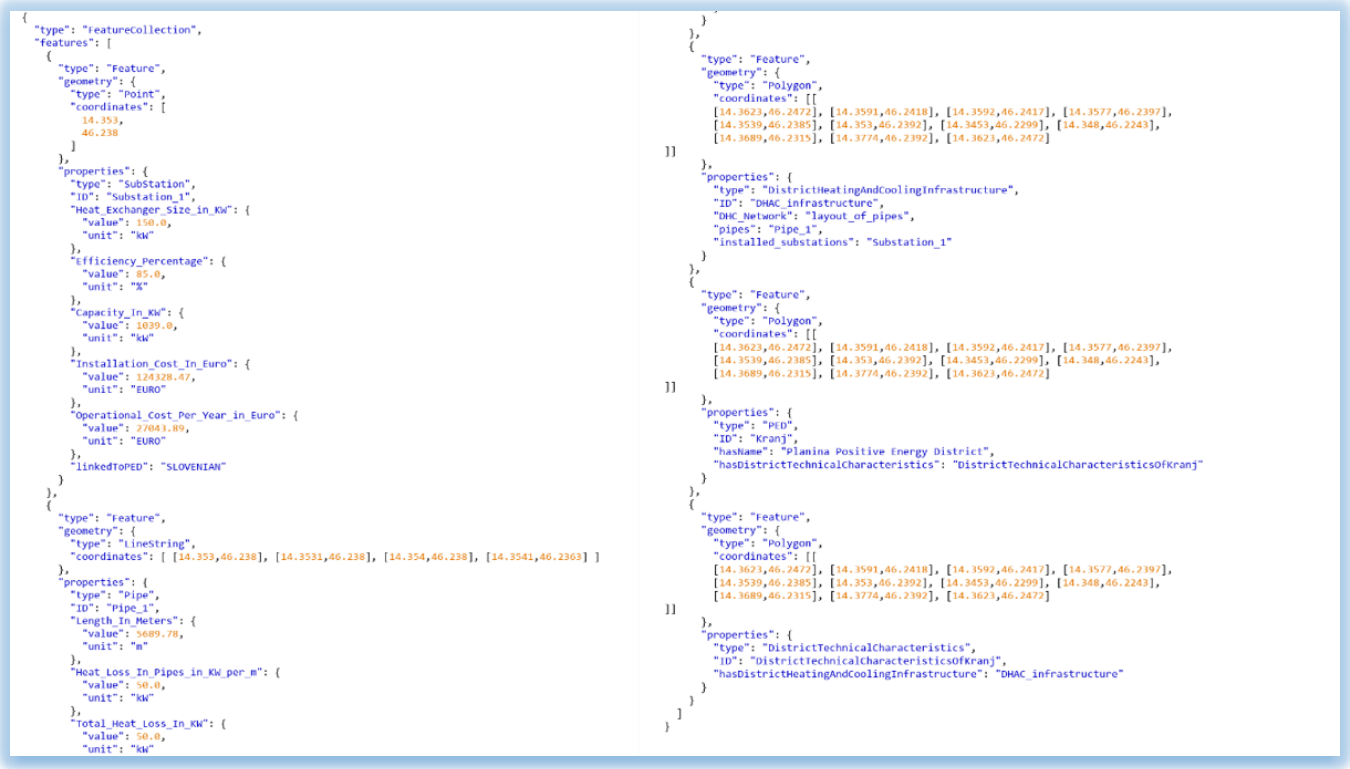
GeoJSON Representation of the DHC Ontology Example

To support visualisation and interoperability with GIS tools, the ontology is mapped into GeoJSON format. Each ontology entity is mapped to a corresponding GeoJSON feature as shown in Figure 92:

Ontology Class	GeoJSON Geometry
PED	Polygon
Substation	Point
Pipe	LineString
DHC Infrastructure	Polygon

Figure 92: Mapping of District Heating and Cooling Infrastructure ontology classes to corresponding GeoJSON geometry types for geospatial representation and visualisation.

Figure 93 illustrates the GeoJSON representation of the RDF-based District Heating and Cooling Infrastructure example.



```
{
  "type": "FeatureCollection",
  "features": [
    {
      "type": "Feature",
      "geometry": {
        "type": "Point",
        "coordinates": [
          14.353,
          46.238
        ]
      },
      "properties": {
        "type": "SubStation",
        "ID": "Substation_1",
        "Heat_Exchanger_Size_in_KW": {
          "value": 150.0,
          "unit": "kW"
        },
        "Efficiency_Percentage": {
          "value": 85.0,
          "unit": "%"
        },
        "Capacity_In_KW": {
          "value": 1039.0,
          "unit": "kW"
        },
        "Installation_Cost_In_Euro": {
          "value": 124328.47,
          "unit": "EURO"
        },
        "Operational_Cost_Per_Year_in_Euro": {
          "value": 27043.89,
          "unit": "EURO"
        },
        "linkedToPED": "SLOVENIAN"
      }
    },
    {
      "type": "Feature",
      "geometry": {
        "type": "LineString",
        "coordinates": [ [14.353,46.238], [14.3531,46.238], [14.354,46.238], [14.3541,46.2363] ]
      },
      "properties": {
        "type": "Pipe",
        "ID": "Pipe_1",
        "Length_In_Meters": {
          "value": 5689.78,
          "unit": "m"
        },
        "Heat_Loss_In_Pipes_in_KW_per_m": {
          "value": 50.0,
          "unit": "kW"
        },
        "Total_Heat_Loss_In_KW": {
          "value": 50.0,
          "unit": "kW"
        }
      }
    },
    {
      "type": "Feature",
      "geometry": {
        "type": "Polygon",
        "coordinates": [[
          [14.3623,46.2472], [14.3591,46.2418], [14.3592,46.2417], [14.3577,46.2397],
          [14.3539,46.2385], [14.353,46.2392], [14.3453,46.2299], [14.348,46.2243],
          [14.3689,46.2315], [14.3774,46.2392], [14.3623,46.2472]
]]
      },
      "properties": {
        "type": "DistrictHeatingAndCoolingInfrastructure",
        "ID": "DHAC_infrastructure",
        "DHC_Network": "layout_of_pipes",
        "pipes": "Pipe_1",
        "installed_substations": "Substation_1"
      }
    },
    {
      "type": "Feature",
      "geometry": {
        "type": "Polygon",
        "coordinates": [[
          [14.3623,46.2472], [14.3591,46.2418], [14.3592,46.2417], [14.3577,46.2397],
          [14.3539,46.2385], [14.353,46.2392], [14.3453,46.2299], [14.348,46.2243],
          [14.3689,46.2315], [14.3774,46.2392], [14.3623,46.2472]
]]
      },
      "properties": {
        "type": "PED",
        "ID": "Kranj",
        "hasName": "Planina Positive Energy District",
        "hasDistrictTechnicalCharacteristics": "DistrictTechnicalCharacteristicsOfKranj"
      }
    },
    {
      "type": "Feature",
      "geometry": {
        "type": "Polygon",
        "coordinates": [[
          [14.3623,46.2472], [14.3591,46.2418], [14.3592,46.2417], [14.3577,46.2397],
          [14.3539,46.2385], [14.353,46.2392], [14.3453,46.2299], [14.348,46.2243],
          [14.3689,46.2315], [14.3774,46.2392], [14.3623,46.2472]
]]
      },
      "properties": {
        "type": "DistrictTechnicalCharacteristics",
        "ID": "DistrictTechnicalCharacteristicsOfKranj",
        "hasDistrictHeatingAndCoolingInfrastructure": "DHAC_infrastructure"
      }
    }
  ]
}
```


Figure 93: GeoJSON representation of the RDF-based District Heating and Cooling Infrastructure ontology, illustrating PED boundaries, substations, pipes, and infrastructure characteristics.

This representation:

- Preserves semantic meaning.
- Enables direct visualisation.
- Supports integration with geospatial tools.

GeoJSON Visualisation in a Map Environment

The GeoJSON representation can be directly visualised in mapping environments as illustrated in Figure 94.

In the PEDvolution context, this enables:

- Visualisation of:
  - PED boundaries
  - Pipe networks
  - Substations
  - Infrastructure zones
- Interactive exploration of:
  - Infrastructure topology
  - Spatial relationships
  - Energy system layout

This map-based representation enhances:

- Understanding of infrastructure
- Validation of data
- Communication with stakeholders

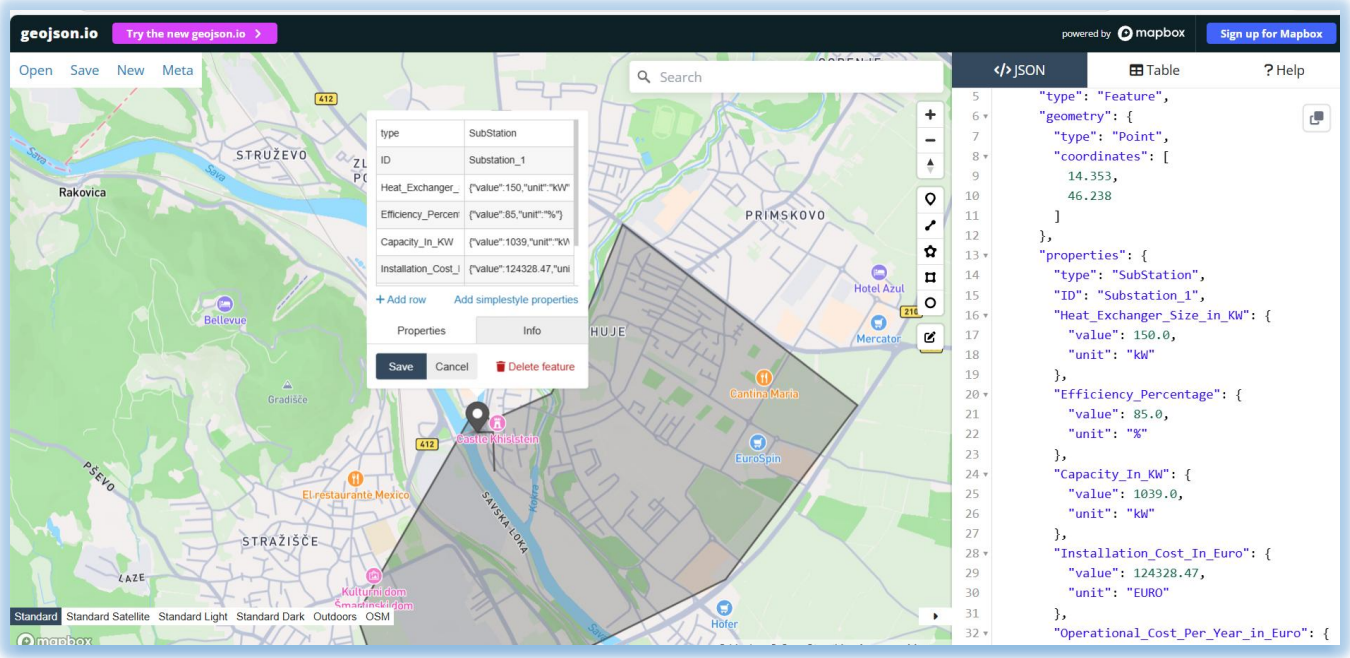


Figure 94: Visualisation of the GeoJSON representation within a map environment, illustrating the spatial representation of PED boundaries, substations, and District Heating and Cooling infrastructure components.

ANNEX VII: EXAMPLE OF HVAC ONTOLOGY REPRESENTATION USING THE PEDVOLUTION CIM

This ANNEX presents an illustrative RDF-based example of HVAC system representation using the PEDvolution Common Information Model. As illustrated in Figure 95, HVAC systems are semantically linked to buildings and energy asset characteristics within the PEDvolution CIM. The example is provided for demonstration purposes only and does not represent real operational or pilot deployment data.

At the top level:

- The PED instance represents the German Positive Energy District.
- A building (building1) is associated with the PED.
- The building includes energy asset characteristics via: ped:hasBuildingEnergyAssetCharacteristics.

Within this structure:

- HVAC characteristics are represented by: ped:HVACBuildingCharacteristics.

This entity defines:

- Number of radiators
- Heating and cooling seasonal periods
- Auxiliary heating systems.

A specific HVAC system is linked through:

- ped:hasHVAC_System

The HVAC system instance includes:

- Installation year classification
- Operating mode (heating)
- Fuel source (natural gas)
- Distribution system (floor heating)

The system includes HVAC equipment (e.g., a boiler), modelled with quantitative properties such as heating capacity and efficiency.

This RDF representation enables:

- Semantic interoperability
- Machine-readable HVAC descriptions
- Integration with analytics and optimisation tools.

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```
ex:PED_GERMAN a ped:Ped ;
    ped:ID "GERMAN";
    ped:hasName:"German PED";
    ped:hasBuildings ex:building_1 .

ex:building_1 a ped:Building;
 ped:ID "building1"^^xsd:string;
 ped:hasBuildingEnergyAssetCharacteristics ex:BuildingEnergyAssetCharacteristicsOfBuilding1.

ex:BuildingEnergyAssetCharacteristicsOfBuilding1 a ped:BuildingEnergyAssetCharacteristics;
   ped:ID "BuildingEnergyAssetCharacteristicsOfBuilding1"^^xsd:string;
   ped:hasHVACBuildingCharacteristics ex:HVACBuildingCharacteristicsOfBuilding1.

ex:HVACBuildingCharacteristicsOfBuilding1 a ped:HVACBuildingCharacteristics;
   ped:ID "HVACBuildingCharacteristicsOfBuilding1"^^xsd:string;
   ped:hasHVAC_System ex:HVAC_Heating_System10;
   ped:NumberOfRadiators "2"^^xsd:integer;
   ped:Cooling_Season_Start_Date "07-01"^^xsd:string;
   ped:Cooling_Season_End_Date "09-20"^^xsd:string;
   ped:Heating_Season_Start_Date "11-01"^^xsd:string;
   ped:Heating_Season_End_Date "15-03"^^xsd:string;
   ped:AuxiliaryHeatingSystem "Wood-burning stoves"^^xsd:string.

ex:HVAC_Heating_System10 a ped:Heating_System;
    ped:ID "HVAC_Heating_System10"^^xsd:string;
    ped:InstallationYear "Mid-aged"^^xsd:string;
    ped:HVAC_Operating_Mode "Heating"^^xsd:string;
    ped:Fuel_Source "Natural Gas"^^xsd:string;
    ped:Distribution_System "Floor Heating"^^xsd:string;
    rec:includes ex:Boiler_HVAC_Equipment;
    ped:Control_System "Basic Thermostat"^^xsd:string;
    ped:Heating_System_Type "Boiler"^^xsd:string .

ex:Boiler_HVAC_Equipment a ex:HVAC_Equipment;
 ped:ID "Boiler_HVAC_Equipment"^^xsd:string;
 ped:Heating_Capacity [qudt:numericValue "160"^^xsd:float; qudt:unit unit:KiloW];
 ped:Heating_System_Efficiency [brick:value "78"^^xsd:float; brick:hasUnit unit:PERCENT] .
```

Figure 95: RDF representation of HVAC system characteristics associated with a building in the German Positive Energy District, demonstrating semantic relationships between PED, building, HVAC systems, and equipment.

JSON Representation of the HVAC Systems Ontology Example

The RDF representation can be transformed into a JSON structure suitable for API-based data exchange and integration with Solution Providers.

Figure 96 illustrates a JSON representation derived from the RDF model:

- The PED ("GERMAN") contains a building.
- The building includes HVAC characteristics.
- A heating system is defined with operational and technical attributes.
- Equipment details (boiler) include capacity and efficiency.

Key elements include:

- Hierarchical structure: PED → Building → HVAC Characteristics → HVAC System.
- Standardised attributes aligned with the ontology.
- Quantitative values together with their associated units (kW, %).
- Embedded equipment modeling.

Example highlights:

- Heating capacity: 160 kW
- Heating efficiency: 78%
- Fuel source: Natural Gas
- Control system: Basic Thermostat

This JSON structure demonstrates how semantic RDF models can be transformed into lightweight, developer-friendly formats for:

- REST APIs
- Real-time monitoring systems
- Digital twin platforms.

```
{
  "PED": {
    "ID": "GERMAN",
    "Name": "German PED",
    "hasBuildings": [
      {
        "ID": "building1",
        "hasBuildingEnergyAssetCharacteristics": {
          "ID": "BuildingEnergyAssetCharacteristicsOfBuilding1",
          "hasHVACBuildingCharacteristics": {
            "ID": "HVACBuildingCharacteristicsOfBuilding1",
            "NumberOfRadiators": 2,
            "AuxiliaryHeatingSystem": "Wood-burning stoves",
            "Cooling_Season": {
              "StartDate": "07-01",
              "EndDate": "09-20"
            },
            "Heating_Season": {
              "StartDate": "11-01",
              "EndDate": "15-03"
            },
            "hasHVAC_System": [
              {
                "ID": "HVAC_Heating_System10",
                "InstallationYear": "Mid-aged",
                "HVAC_Operating_Mode": "Heating",
                "Fuel_Source": "Natural Gas",
                "Distribution_System": "Floor Heating",
                "includes": {
                  "ID": "Boiler_HVAC_Equipment",
                  "Heating_Capacity": {
                    "value": 160.0,
                    "unit": "kW"
                  },
                  "Heating_System_Efficiency": {
                    "value": 78.0,
                    "unit": "%"
                  }
                },
                "Control_System": "Basic Thermostat",
                "Heating_System_Type": "Boiler"
              }
            ]
          }
        }
      }
    ]
  }
}
```


Figure 96: JSON representation of the HVAC Systems ontology example derived from the RDF model, illustrating hierarchical structure and key attributes for integration with APIs and digital platforms.

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ANNEX VIII: EXAMPLE OF BATTERY SYSTEMS CHARACTERISTICS USING THE PEDVOLUTION CIM

The example illustrates the representation of a battery system deployed in the German PED. A PED entity (PED_GERMAN) is linked to its district technical characteristics, which include battery system characteristics. The battery system contains a battery asset (Battery_1) described by its configuration and operational parameters. The example is provided for demonstration purposes only and does not represent real operational or pilot deployment data.

The RDF representation, illustrated in Figure 97, defines:

- The battery model (Battery XYZ Model 2026)
- A set of battery properties such as:
  - Capacity
  - Voltage limits
  - Discharge currents
  - Temperature constraints
  - Weight

Each property is expressed using:

- A semantic class (e.g., prop:BatteryCapacity)
- A measurement unit (e.g., unit:KiloW-HR)
- A numeric value (e.g., "200")

This structured representation enables machine-readable and interoperable battery data exchange within the PEDvolution ecosystem.

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```
ex:PED_GERMAN a ped:Ped ;
    ped:ID:"German"^^xsd:string;
    ped:hasDistrictTechnicalCharacteristics ex:DistrictTechnicalCharacteristicsOfGermanPED;
    ped:hasName:"German PED" .

ex:DistrictTechnicalCharacteristicsOfGermanPED a ped:DistrictTechnicalCharacteristics;
   ped:hasBatterySystemCharacteristics ex:BatterySystemCharacteristicsOfGermanPED .

ex:BatterySystemCharacteristicsOfGermanPED a ped:BatterySystemCharacteristics;
   ped:hasBattery ex:Battery_1 .

ex:Battery_1 a lec:Battery;
 lec:hasBatteryConfiguration ex:BatteryConfiguration;
 lec:BatteryModelName "Battery XYZ Model 2026"^^xsd:string; .

ex:BatteryConfiguration a lec:BatteryConfiguration;
   lec:includesBatteryProperties ex:BatteryCapacity;
   lec:includesBatteryProperties ex:BatteryNominalVoltage;
   lec:includesBatteryProperties ex:batteryMaxOperatingVoltage;
   lec:includesBatteryProperties ex:batteryMinOperatingVoltage;
   lec:includesBatteryProperties ex:BatteryDeepDischargeVoltage;
   lec:includesBatteryProperties ex:batteryMaxPeakDischargeCurrent;
   lec:includesBatteryProperties ex:BatteryOptimalDischargeCurrent;
   lec:includesBatteryProperties ex:BatteryMaxDischargeCurrent;
   lec:includesBatteryProperties ex:batteryCellAverageTemperature;
   lec:includesBatteryProperties ex:batteryMaxTemperature;
   lec:includesBatteryProperties ex:BatteryWeight; .

 ex:BatteryCapacity a prop:BatteryCapacity;
  prop:isMeasuredIn unit:KiloW-HR;
  prop:hasPropertyValue [ets:value "200"^^xsd:integer]; .

ex:BatteryNominalVoltage a prop:batteryNominalVoltage;
  prop:isMeasuredIn unit:V;
  prop:hasPropertyValue [ets:value "200"^^xsd:integer]; .

ex:batteryMaxOperatingVoltage a prop:batteryMaxOperatingVoltage;
  prop:isMeasuredIn unit:V;
  prop:hasPropertyValue [ets:value "120"^^xsd:integer]; .

ex:batteryMinOperatingVoltage a prop:batteryMinOperatingVoltage;
  prop:isMeasuredIn unit:V;
  prop:hasPropertyValue [ets:value "20"^^xsd:integer]; .

ex:BatteryDeepDischargeVoltage a prop:batteryDeepDischargeVoltage;
  prop:isMeasuredIn unit:V;
  prop:hasPropertyValue [ets:value "20"^^xsd:integer]; .

ex:batteryMaxPeakDischargeCurrent a prop:batteryMaxPeakDischargeCurrent;
  prop:isMeasuredIn unit:A;
  prop:hasPropertyValue [ets:value "25"^^xsd:integer]; .

ex:BatteryOptimalDischargeCurrent a prop:batteryOptimalDischargeCurrent;
  prop:isMeasuredIn unit:A;
  prop:hasPropertyValue [ets:value "20"^^xsd:integer]; .

ex:BatteryMaxDischargeCurrent a prop:batteryMaxDischargeCurrent;
  prop:isMeasuredIn unit:A;
  prop:hasPropertyValue [ets:value "2"^^xsd:integer]; .

ex:BatteryMaxPeekDischargeCurrent a prop:batteryMaxPeekDischargeCurrent;
  prop:isMeasuredIn unit:A;
  prop:hasPropertyValue [ets:value "2"^^xsd:integer]; .

ex:batteryCellAverageTemperature a prop:batteryCellAverageTemperature;
  prop:isMeasuredIn unit:DEG_C;
  prop:hasPropertyValue [ets:value "47"^^xsd:integer]; .

ex:batteryMaxTemperature a prop:batteryMaxTemperature;
  prop:isMeasuredIn unit:DEG_C;
  prop:hasPropertyValue [ets:value "89"^^xsd:integer]; .

ex:BatteryWeight a prop:batteryWeight;
  prop:isMeasuredIn unit:KiloGM;
  prop:hasPropertyValue [ets:value "78"^^xsd:integer]; .

ex:batterySize a qudt:QuantityValue ;
    qudt:numericValue "60"^^xsd:integer;
    qudt:unit unit:KiloW-HR  .
```

Figure 97: RDF encoding of battery system characteristics, illustrating hierarchical relationships between PED entities, battery configurations, and property-level attributes with their associated values and units.

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JSON Representation of the Battery Systems Ontology Example

The RDF model can be transformed into a structured JSON representation, as illustrated in Figure 98, enabling integration with APIs and software systems.


```
{
  "PED_GERMAN": {
    "type": "Ped",
    "ID": "German",
    "hasName": "German PED",
    "hasDistrictTechnicalCharacteristics": {
      "BatterySystemCharacteristics": {
        "Battery": {
          "BatteryModelName": "Battery XYZ Model 2026",
          "BatteryConfiguration": {
            "BatteryCapacity": { "value": 200, "unit": "kWh" },
            "BatteryNominalVoltage": { "value": 200, "unit": "V" },
            "batteryMaxOperatingVoltage": { "value": 120, "unit": "V" },
            "batteryMinOperatingVoltage": { "value": 20, "unit": "V" },
            "BatteryDeepDischargeVoltage": { "value": 20, "unit": "V" },
            "batteryMaxPeakDischargeCurrent": { "value": 25, "unit": "A" },
            "BatteryOptimalDischargeCurrent": { "value": 20, "unit": "A" },
            "BatteryMaxDischargeCurrent": { "value": 2, "unit": "A" },
            "batteryCellAverageTemperature": { "value": 47, "unit": "Celcius" },
            "batteryMaxTemperature": { "value": 89, "unit": "Celcius" },
            "BatteryWeight": { "value": 78, "unit": "kg" }
          }
        }
      }
    }
  }
}
```


Figure 98: JSON representation of the RDF-based ontology into a hierarchical JSON structure, preserving semantic relationships and enabling efficient data exchange and processing.

This JSON structure:

- Simplifies data consumption by Solution Providers.
- Preserves semantic meaning.
- Enables lightweight integration with APIs and software platforms.
- Facilitates interoperability with analytics and monitoring systems.

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This transformation demonstrates how semantically rich RDF models can be converted into lightweight, developer-friendly formats, enabling seamless integration with APIs, analytics platforms, and real-time monitoring systems within the PEDvolution ecosystem.

Overall, the ontology plays a key role in enabling data-driven optimisation and intelligent energy management within Positive Energy Districts, while supporting interoperability with external data spaces and integration with analytics platforms, digital twins, and energy optimisation services within the PEDvolution ecosystem.

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ANNEX IX: EXAMPLE OF BUILDING CONSTRUCTION AND OCCUPANCY PATTERNS USING THE CIM ONTOLOGY

As illustrated in Figure 99, the example represents a building unit located in the German PED, using RDF format. The example is provided for demonstration purposes only and does not represent real operational or pilot deployment data.

The building unit:

- Consists of 2 floors and 4 rooms.
- Has a floor area of 125.50 m².
- Has a height of 6.20 meters.
- Is privately owned.
- Is occupied by 3 residents.
- Corresponds to a main residence (single-family household).

This RDF representation demonstrates:

- The integration of building and occupancy data.
- The linkage between building entities and household entities.

```
ex:Unit_A102 a ped:BuildingUnit ;
 ped:ID "BuildingUnit_in_German_PED"^^xsd:string;
 ped:numberOfFloors 2^^xsd:integer;
 ped:numberOfRooms 4^^xsd:integer;

 energy:floorArea [energy:type "grossFloorArea"^^xsd:string;
                   energy:value "125.50"^^xsd:double;
                   energy:uom "m2"^^xsd:string ] ;

 energy:heightAboveGround [energy:value "6.20"^^xsd:double;
                           energy:uom "m"^^xsd:string ] ;

 energy:ownershipType "OccupantPrivateOwner"^^xsd:string;
 energy:occupiedBy [energy:occupantType "residents"^^xsd:string;
                    energy:numberOfOccupants 3^^xsd:integer] ;

 energy:houseHold [energy:residenceType "mainResidence"^^xsd:string;
                   energy:houseHoldType "oneFamily"^^xsd:string] .
```

Figure 99: RDF representation of a Building Construction and Occupancy Patterns ontology instance, illustrating the semantic description of a ped:BuildingUnit with associated construction, ownership, and occupancy attributes.

JSON Representation of the Building Construction and Occupancy Patterns Ontology Example

The ontology can also be represented in JSON format, as illustrated in Figure 100, to facilitate integration with web-based applications and APIs.

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The JSON structure:

- Preserves the semantic relationships defined in RDF.
- Organizes the data into hierarchical objects.
- Enables easy consumption by frontend systems and analytics tools.


```
{
  "buildingUnit": {
    "ID": "BuildingUnit_in_German_PED",
    "numberOfFloors": 1,
    "numberOfRooms": 4,

    "floorArea": {
      "type": "grossFloorArea",
      "value": 125.50,
      "unit": "m2"
    },

    "heightAboveGround": {
      "value": 6.20,
      "unit": "m"
    },

    "ownershipType": "OccupantPrivateOwner",

    "occupiedBy": {
      "Occupants":  {
        "occupantType": "residents",
        "numberOfOccupants": 3
    }
  },


  "household": {
    "residenceType": "mainResidence",
    "houseHoldType":"oneFamily"

  }

}
}
```


Figure 100: Example JSON representation of a building unit within the PEDvolution ontology, demonstrating the mapping of construction characteristics (e.g., floor area, height) and occupancy-related attributes (e.g., number of occupants, household type) into a structured, API-ready format.

Within the PEDvolution ecosystem, this ontology provides a semantically enriched framework for linking building physical characteristics with occupancy-related attributes, enabling interoperability, advanced analytics, and integration with digital twin environments.

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ANNEX X: DETAILED DESCRIPTION OF WORKFLOW 1 (DATA PROVIDER PROCESS)

Workflow 1 describes the data publication process performed by PED platforms acting as data providers. This workflow is implemented through two main steps: data asset registration and contract definition with asset publication. Through this workflow, data assets are registered, associated with access and usage policies, and published as data offers in the Federated Catalogue, making them discoverable within the dataspace. Access to these assets is governed by contract definitions and policy-based constraints, ensuring secure, controlled, and sovereign data sharing.

Step 1: Data Asset Registration

In the first step, the Data Provider prepares the dataset for sharing to Data Consumers, by registering it as a data asset via the API Server, which acts as a wrapper layer over the underlying dataspace infrastructure.

In dataspace terminology, a data asset represents the metadata description of a dataset, including its structure, semantics, and access conditions.

This step is handled by the Control Plane and includes:

- Definition of asset metadata such as:
  - Unique asset identifier
  - Data category (e.g. Battery Systems, Photovoltaic data)
  - PED identifier
  - Temporal coverage and resolution
  - Data format (e.g. JSON, CSV, GeoJSON)
- Specification of the data access endpoint (base URL) indicating where the dataset is physically hosted.
- Configuration of secure access parameters (e.g., proxy settings).
- Registration of the data asset via the API Server, which internally forwards the request to the Dataspace Connector.

At this stage:

- The dataset remains fully under the control of the provider.
- No data is transferred or exposed externally.
- Only the metadata are registered and managed within the dataspace.

Step 2: Contract Definition and Asset Publication to the Federated Catalogue

Following registration, the Data Provider publishes the data asset as a data offer in the Federated Catalogue.

This step is also managed by the Control Plane and includes:

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- Creation of a contract definition specifying:
    - Access conditions
    - Usage policies
    - Contractual terms governing data access and processing
- Association of policies with the data asset.
- Publication of asset metadata to the Federated Catalogue.

This enables:

- Dataset discoverability by authorized participants (having the appropriate Verifiable Credentials).
- Filtering and querying by Solution Providers based on metadata criteria.
- Participation in federated data exchange scenarios.

Policy-Driven Access Constraints (Predefined Policies)

Within PEDvolution, contract definitions incorporate predefined policy constraints, which are evaluated during the negotiation phase (Workflow 2).

Specifically:

- **"require-membership" policy**: Ensures that only participants holding a valid **MembershipCredential** can access the data asset.
- **"require-dataprocessor" policy**: Ensures that only participants with a valid **DataProcessorCredential** are authorised to process the data.

These policies are configured at dataspace initialization and enforced by the Control Plane Policy Engine.

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Figure 101 illustrates an example of a contract definition created during the asset publication process, where the contract is explicitly linked to a data asset identified by the unique identifier UniqueAssetID, defining the access and usage policies applied to that asset.



```
{
    "accessPolicyId": "require-membership",
    "contractPolicyId": "require-dataprocessor",
    "assetsSelector": {
        "operandLeft": "https://w3id.org/edc/v0.0.1/ns/id",
        "operator": "=",
        "operandRight": "UniqueAssetID",
        "@type": "Criterion"
    },
    "@context": {
        "@vocab": "https://w3id.org/edc/v0.0.1/ns/",
        "edc": "https://w3id.org/edc/v0.0.1/ns/",
        "odrl": "http://www.w3.org/ns/odrl/2/"
    },
    "@id": "UniqueContractID",
    "@type": "ContractDefinition"
},
```


Figure 101: Example of a contract definition generated during asset publication, including policy bindings and access conditions.

To enforce access control within the dataspace, predefined policies are applied to data assets. Figure 102 presents the membership policy (*require-membership*), which ensures that only participants with a valid MembershipCredential can access the data.



```
{
"@context": [
    "https://w3id.org/edc/connector/management/v0.0.1"
],
"@type": "PolicyDefinition",
"@id": "require-membership",
"policy": {
    "@type": "Set",
    "permission": [
        {
            "action": "use",
            "constraint": {
                "leftOperand": "MembershipCredential",
                "operator": "eq",
                "rightOperand": "active"
            }
        }
    ]
}
}
```


Figure 102: Predefined membership policy (require-membership) in the PEDvolution Project.

In addition to membership validation, further constraints are applied to govern data processing permissions. Figure 84 illustrates the contract policy (*require-dataprocessor*), which ensures that only authorised entities are permitted to process the data in accordance with defined policies.

```
{
"@context": [
    "https://w3id.org/edc/connector/management/v0.0.1"
],
"@type": "PolicyDefinition",
"@id": "require-dataprocessor",
"policy": {
    "@type": "Set",
    "obligation": [
        {
            "action": "use",
            "constraint": {
                "leftOperand": "DataAccess.level",
                "operator": "eq",
                "rightOperand": "processing"
            }
        }
    ]
}
}
```

Figure 103: Predefined contract policy (*require-dataprocessor*) enforcing data processing permissions within the PEDvolution dataspace.

Interpretation of the Contract Definition

The resulting contract definition expresses that:

- Access to the data asset is restricted to trusted dataspace participants.
- Participants must satisfy both membership and data processing requirements.
- All access requests will be evaluated against these policies during negotiation.

This ensures that:

- Data is accessed only by authorised and trusted entities
- Usage complies with provider-defined constraints
- Data governance rules are enforced consistently across the dataspace.

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Outcome of Workflow 1

At the completion of Workflow 1:

- The data asset is published as a discoverable data offer in the Federated Catalogue.
- Data sovereignty is fully preserved, as:
    - The actual data remains at the provider's infrastructure (PED).
    - The data access endpoint is not directly exposed to consumers without prior authorisation and token-based access control.
- Only dataset metadata are shared.
- Access to the dataset will require subsequent contract negotiation, as described in Workflow 2.

ANNEX XI: DETAILED DESCRIPTION OF WORKFLOW 2 (DATA CONSUMER PROCESS)

This workflow is implemented through three main steps: dataset discovery, contract negotiation and token issuance, and secure data retrieval.

Step 1: Dataset Discovery (Catalog Query)

The consumer queries the Federated Catalogue via the API Server using criteria such as:

- PED identifier.
- Data category (e.g., real-time measurements, battery systems data, PV Systems data).
- Time range and time resolution.
- Asset identifiers.
- Data format (e.g. JSON, CSV, GeoJSON).

The Federated Catalogue returns through the API Server a list of matching data offers.

Step 2: Transfer Initiation (Contract Negotiation and Token Issuance)

During this phase:

- Consumer presents Verifiable Credentials.
- Credentials are verified by Identity services.
- Claims are extracted and evaluated.
- Policies (e.g. *require-membership*, *require-dataprocessor*) are evaluated by the Control Plane policy engine.

If policies are satisfied:

- Contract agreement is created.
- Access token is issued.

If not:

- Negotiation is rejected.

Figure 104 presents the end-to-end contract negotiation process within the PEDvolution dataspace, illustrating how participant credentials are evaluated against asset-specific access and usage policies. The figure highlights the interaction between the Consumer (Solution Provider), the Provider (PED Platform), and the underlying dataspace infrastructure, including identity services, control plane policy enforcement, and data plane execution.

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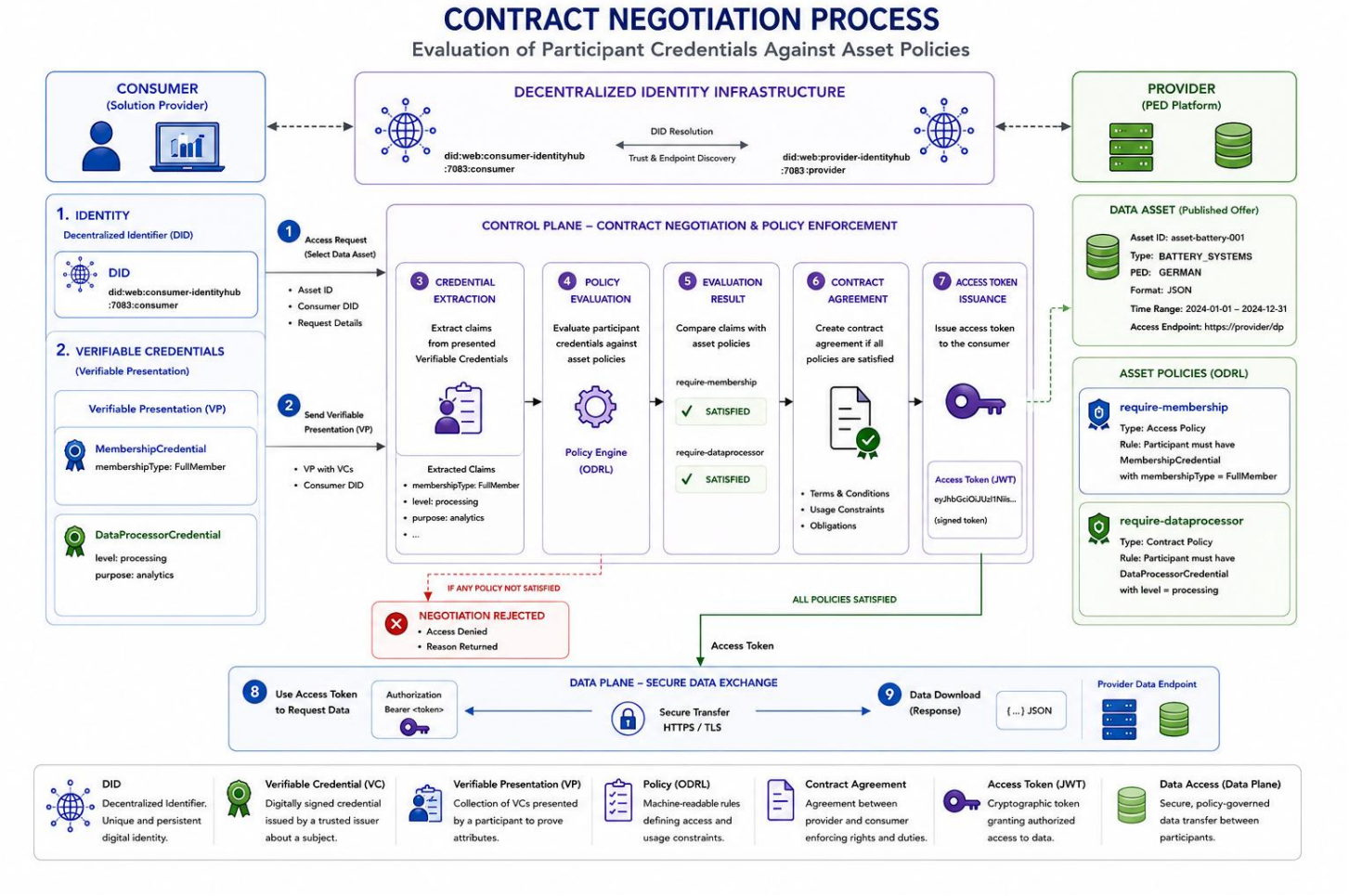


Figure 104: Contract negotiation process in the PEDvolution dataspace, illustrating credential verification, policy evaluation, contract agreement, and access token issuance, leading to secure data exchange between consumer and provider.

Step 3: Data Retrieval (Secure Transfer)

The consumer downloads the selected dataset using the authorisation token retrieved in the previous step.

This step is executed in the Data Plane and using the issued token, the consumer:

- Accesses the data directly from the provider.
- Retrieves data via secure HTTPS communication.

The data is delivered in a structured format (e.g., JSON), enabling direct integration into Solution Tools.

Security and Governance

All workflows are governed by:

- Token-based authorisation
- Policy-driven access control

- Secure HTTPS/TLS communication
- network-level access control (e.g., whitelisting)

These mechanisms ensure:

- Data sovereignty
- Controlled data access
- Secure interaction between data providers and data consumers

Alignment with Dataspace Principles

The defined workflows fully align with key dataspace principles:

- **Data sovereignty**, data remains under provider control.
- **Decentralization**, peer-to-peer data exchange.
- **Trust**, identity verification and policy enforcement.
- **Federation**, shared catalogue across participants (Data providers and Solution Providers).

Overall, the process layer demonstrates how PEDvolution operationalises dataspace principles through concrete, standardised, and policy-driven workflows, ensuring secure, interoperable, and scalable data exchange across heterogeneous participants.

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ANNEX XII: DETAILED DESCRIPTION OF WORKFLOW 1

Workflow 1 is implemented through two core HTTPS API endpoints, which enable PED platforms to register and publish datasets within the dataspace of the Interoperability Platform:

1. **Asset creation (registration)**

   Registers PED data as a dataspace asset within the Interoperability Platform by creating the corresponding metadata representation and defining access parameters.

   Endpoint: POST https://pedvolution.intracom-telecom.com/pedvolutionapi/asset

2. **Contract creation and asset publication (data offer creation)**. Creates the contract definition for the registered asset and publishes it to the Federated Catalogue as a data offer. This process makes the dataset discoverable and accessible to Solution Providers under defined access policies.

   Endpoint: POST https://pedvolution.intracom-telecom.com/pedvolutionapi/contract

Together, these endpoints implement the complete data provider workflow, enabling seamless onboarding and exposure of PED datasets within the PEDvolution ecosystem.

Step 1. Creation of a Dataspace Asset

Endpoint: POST https://pedvolution.intracom-telecom.com/pedvolutionapi/asset

Overview

This endpoint enables PED platforms to register a dataset as a dataspace asset within the Interoperability Platform.

The created asset represents the metadata description of the dataset, including:

- Semantic information (e.g., dataset type, PED origin)
- Temporal and structural characteristics
- Technical access parameters (e.g., data endpoint, network proxy settings)

This step constitutes the first stage of the data provider workflow, preparing the dataset for subsequent publication to the Federated Catalogue.

Request Body Structure

The request body contains a set of fields describing the dataset.

Key considerations:

- Some fields are mandatory

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- Field values depend on:
    - The type of data
    - The data format
    - Whether the dataset represents real-time or non-real-time data

Figure 105 illustrates the JSON structure of the Create Asset API request body, highlighting the available fields and indicative values that may be used to define a dataspace asset within the PEDvolution platform.

```
{
  "assetId":"A unique ID",

  "properties": {
          "ped": "SLOVENIAN or GERMAN or HARD",

          "characteristic": "HEAT_RECOVERY_POTENTIAL or ENERGY_PRICES or PV_SYSTEM_CHARACTERISTICS or  HVAC_SYSTEMS or
            DISTRICT_HEATING_AND_COOLING_INFRASTRUCTURE or ENERGY_REAL_TIME_MEASUREMENTS or DISTRIC_ENERGY_ASSETS or
            BUILDING_STOCK_CHARACTERISTICS_AND_OCCUPANCY_PATTERNS or EV_CHARGING_MEASUREMENTS or ENERGY_VECTORS or
            ENERGY_CONSUMPTION_DATA",

          "dataFormat": "JSON or CSV or GEOJSON",

          "assetIds": [
              "asset id 1",
              "asset id 2"

          ],

          "timePeriodFrom": "MM-DD-YYYYTHH:MM:SS",

          "timePeriodTo": "MM-DD-YYYYTHH:MM:SS",

          "timeResolution": "EVERY_1_MIN or EVERY_5_MINS or EVERY_1_HOUR",

          "details": "A short text",

          "realTimeMeasurement": "yes or no",

          "description": "A short decription"
      },

      "dataAddress": {
          "type": "HttpData",
          "proxyPath": "true or false ",
          "proxyQueryParams": "true or false",
          "baseUrl": "https://xxxxxxxxxx/yyyyy/zzzzzz"
      }
}
```

Figure 105: Illustrative JSON schema for dataspace asset creation, presenting all request fields along with indicative and possible values for each parameter used in the API request body.

Field Description

- **assetId**
    - **Description:** Unique identifier of the dataspace asset.
    - **Notes:** Must be unique per request and used to reference the dataset within the dataspace.
    - **Mandatory:** Yes

- **ped**
  - **Description:** Identifies the PED (Positive Energy District) where the data originates. For the Swiss PED, assets are exposed using the identifier "HARD", as defined by the PED managers, in order to distinguish them from assets of other Swiss PEDs (e.g. Oberwinterthur).
  - **Possible values:** SLOVENIAN, GERMAN, HARD
  - **Mandatory:** Yes

- **characteristic**
  - **Description:** Defines the dataset category and semantic domain.
  - **Possible Values:** HEAT_RECOVERY_POTENTIAL, ENERGY_PRICES, PV_SYSTEM_CHARACTERISTICS, HVAC_SYSTEMS, DISTRICT_HEATING_AND_COOLING_INFRASTRUCTURE, ENERGY_REAL_TIME_MEASUREMENTS, HEATING_REAL_TIME_MEASUREMENTS, DISTRICT_ENERGY_ASSETS, EV_CHARGING_MEASUREMENTS, ENERGY_CONSUMPTION_DATA, ENERGY_VECTORS, BUILDING_CONSTRUCTION_CHARACTERISTICS_AND_OCCUPANCY_PATTERNS
  - **Mandatory:** Yes

- **dataFormat**
  - **Description:** Specifies the format of the dataset.
  - **Possible values:** JSON, CSV, GEOJSON
  - **Mandatory:** Yes

- **timePeriodFrom / timePeriodTo**
  - **Description:** Defines the temporal coverage of the dataset.
  - **Formats:** MM-DD-YYYY or MM-DD-YYYYTHH:MM:SS
  - **Mandatory:** Required for real-time datasets, optional for non-real-time datasets

- **details / description**
  - **Description:** Optional fields providing additional dataset information.
  - **Mandatory:** No

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- **timeResolution**
  - **Description:** Defines the temporal resolution of real-time data.
  - **Possible values:** EVERY_1_MIN, EVERY_15_MINS, EVERY_1_HOUR
  - **Mandatory:** Only for real-time datasets

- **realTimeMeasurement**
  - **Description:** Indicates whether the dataset represents real-time data.
  - **Values:** "yes" or "no"
  - **Mandatory:** Yes

- **assetIds**
  - **Description:** List of identifiers representing the assets involved in the dataset.
  - **Example:** ["household1", "household2"]
  - **Mandatory:** No

- **baseUrl**
  - **Description:** URL where the dataset is stored within the PED infrastructure.
  - **Mandatory:** Yes

- **Technical Fields (dataAddress configuration)**
  - **type:** Must be "HttpData" (mandatory)
  - **proxyPath:** "true" or "false" (mandatory)
  - **proxyQueryParams:** "true" or "false" (mandatory)

  These fields define how the data endpoint is accessed via the dataspace.

The asset creation endpoint constitutes the foundational step of the data provider workflow, enabling structured, policy-aware, and interoperable registration of PED datasets within the PEDvolution dataspace.

Response of the Create Asset API Request

The Create Asset API returns structured responses indicating the outcome of the request. These responses include both successful execution messages and error messages, depending on the validity of the request.

- **Successful Response**
  Upon successful execution, the API returns a response confirming the creation of the dataspace asset. The successful response is illustrated in Figure 106.


```
{
    "@type": "IdResponse",
    "@id": "ID of Asset",
    "createdAt": 1777018213314,
    "@context": {
        "@vocab": "https://w3id.org/edc/v0.0.1/ns/",
        "edc": "https://w3id.org/edc/v0.0.1/ns/",
        "odrl": "http://www.w3.org/ns/odrl/2/"
    }
}
```


Figure 106: Example of a successful API response indicating the creation of a dataspace asset, including the assigned asset ID, creation timestamp, and semantic context aligned with EDC standards.

Description:

- @type: Indicates the response type (IdResponse).
- @id: Unique identifier assigned to the created asset.
- createdAt: Timestamp of asset creation.
- @context: Defines the semantic context aligned with EDC and ODRL standards.

This response confirms that the dataset has been successfully registered as a dataspace asset and is ready for publication in the Federated Catalogue.

- **Error Response – Duplicate assetId (HTTP 409 Conflict)**

  If the provided assetId is already in use, an error response is returned as illustrated in Figure 107.


```
{
    "timestamp": "2026-04-24T08:25:36.146+00:00",
    "status": 409,
    "error": "Conflict",
    "path": "/pedvolutionapi/asset"
}
```


Figure 107: Example of an HTTP 409 (Conflict) error response indicating that the provided assetId is already in use and must be unique within the dataspace.

Description:

- Indicates that the asset identifier must be unique.

- The request is rejected to prevent duplication within the dataspace.

- **Error Response – Invalid Request Body (HTTP 400 Bad Request)**
  If the JSON structure of the request body is invalid or incomplete, the API returns error response as illustrated in Figure 108.


```
{
    "timestamp": "2026-04-24T08:28:06.753+00:00",
    "status": 400,
    "error": "Bad Request",
    "path": "/pedvolutionapi/asset"
}
```


Figure 108: Example of an HTTP 400 (Bad Request) error response indicating that the request payload is invalid, typically due to missing mandatory fields or incorrect JSON structure.

Description:

Indicates malformed or incorrect request payload. Typically caused by:

- Missing mandatory fields
- Incorrect data types
- Invalid JSON structure

Step 2. Contract creation and asset publication (data offer creation).

Endpoint: POST https://pedvolution.intracom-telecom.com/pedvolutionapi/contract

This endpoint enables Data Providers (PED platforms) to create a contract definition and publish a previously registered dataspace asset to the Federated Catalogue as a data offer.

This step constitutes the second stage of the data provider workflow, following asset registration. It establishes access policies and usage conditions under which the dataset can be shared with Data Consumers (Solution Providers).

Once completed, the dataset becomes:

- Discoverable via the Federated Catalogue
- Accessible under defined policies
- Available for contract negotiation and secure data exchange

Request Body Structure

The request body defines the contract configuration and policy binding associated with the dataspace asset. Figure 109 illustrates an example of the body of a contract creation HTTPS Request.

```
{
    "contractId": "UNIQUE ID OF CONTRACT",
    "accessPolicyId": "require-membership",
    "contractPolicyId": "THE ID OF THE CONTRACT TO BE USED IN THE PEDVOLUTION PROJECT",
    "assetsSelectorId": "THE ID OF ASSET TO BE PUBLISHED"
}
```

Figure 109: Example of the request body for a contract creation HTTPS request.

Field Description

- **contractId**
  - **Description:** Unique identifier of the contract definition.
  - **Purpose:** Used to reference the data offer within the dataspace.
  - **Mandatory:** Yes
- **accessPolicyId**
  - **Description:** Defines the access control policy applied to the dataset.
  - **Purpose:** Specifies the conditions under which a Data Consumer can access the data.
  - **Mandatory value:** require-membership. This value means that participants such Data Consumers that are recognized members of the dataspace are allowed to access the dataset. A participant is considered a member of the dataspace if is authenticated through the Identity and Trust Management through the Dataspace Connector. This policy is the default access policy of the PEDvolution project created automatically on the startup of API Server.

The access policy is illustrated in Figure 110.

```
{
    "@context": [
        "https://w3id.org/edc/connector/management/v0.0.1"
    ],
    "@type": "PolicyDefinition",
    "@id": "require-membership",
    "policy": {
        "@type": "Set",
        "permission": [
            {
                "action": "use",
                "constraint": {
                    "leftOperand": "MembershipCredential",
                    "operator": "eq",
                    "rightOperand": "active"
                }
            }
        ]
    }
}
```

Figure 110: JSON representation of the access policy used in the PEDvolution project.

Structure Breakdown

- **@context:** Defines the semantic vocabulary used in the policy enabling interoperability between dataspace connectors.
- **@type:** Declares that this object is a policy definition.
- **@id:** Unique identifier of the access policy and used in the API call to create the contract.
- Inside policy block the permission defines a set of permissions that must be satisfied. These permissions are defined inside constraint block where the actual rule is defined: A Data Consumer is permitted to use the dataset only if it possesses a valid and active membership credential within the dataspace.

- **contractPolicyId**
  - **Description:** Defines the policy governing the contractual agreement between Data Provider and Data Consumer.
  - **Purpose:** Ensures that data usage complies with agreed rules during contract negotiation.
  - **Mandatory value:** require-dataprocessor. This contract policy is the default policy of the PEDvolution project, automatically created during the startup of the API Server to address the project's requirements. The policy is illustrated in Figure 111.



```
{
    "@context": [
        "https://w3id.org/edc/connector/management/v0.0.1"
    ],
    "@type": "PolicyDefinition",
    "@id": "require-dataprocessor",
    "policy": {
        "@type": "Set",
        "obligation": [
            {
                "action": "use",
                "constraint": {
                    "leftOperand": "DataAccess.level",
                    "operator": "eq",
                    "rightOperand": "processing"
                }
            }
        ]
    }
}
```

Figure 111: Illustration of the contract policy used in the PEDvolution project.

Structure Breakdown

- **@context:** Defines the semantic vocabulary used in the policy enabling interoperability betweendataspace connectors.
- **@type:** Declares that this object is a policy definition.
- **@id:** Unique identifier of the policy and used in the API call to create the contract

- **Inside policy block the obligation** defines a set of rules that must be satisfied. These rules are defined inside constraint block where is defined how the data should be used: The dataset can only be accessed and used by a Data Consumer if the access purpose corresponds to "*data processing*".

Response of the Create Asset API Request

The Create Asset API returns structured responses indicating the outcome of the request. These responses include both successful execution messages and error messages, depending on the validity of the request.

- **Successful Response**
  Upon successful execution, the API returns a response confirming the creation of the dataspace asset, as illustrared in Figure 112.


```
{
    "headers": {
        "Date": [
            "Fri, 24 Apr 2026 13:26:31 GMT"
        ],
        "Content-Type": [
            "application/json"
        ],
        "Content-Length": [
            "207"
        ]
    },
    "body": {
        "@type": "IdResponse",
        "@id": "plug4ID-contract",
        "createdAt": 1777037192004,
        "@context": {
            "@vocab": "https://w3id.org/edc/v0.0.1/ns/",
            "edc": "https://w3id.org/edc/v0.0.1/ns/",
            "odrl": "http://www.w3.org/ns/odrl/2/"
        }
    },
    "statusCode": "OK",
    "statusCodeValue": 200
}
```


Figure 112: Example of a successful API response indicating the creation of a contract with ID plug4ID-contract.

- **Error Response – Internal Server Error (HTTP 500)**
  Returned when an unexpected server-side error occurs during request processing. In the current implementation, this response may also be returned when the provided contractId is already in use or when the request payload is invalid, typically due to missing mandatory fields or incorrect JSON structure. An example of such a response is illustrated in Figure 113.

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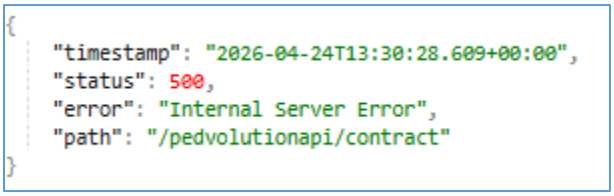


Figure 113: Example of an HTTP 500 error response indicating an internal server error during request processing.

HTTP Request Headers

All API requests to the PEDvolution Interoperability Platform are transmitted over secure HTTPS connections and must include the appropriate HTTP request headers to ensure correct formatting, authentication, and secure access to the API endpoints.

An example of the required headers is presented in Figure 114:

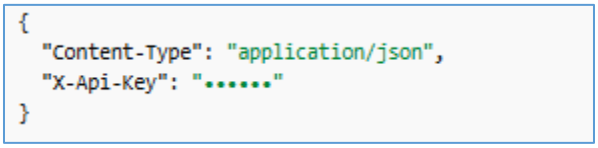


Figure 114: Example of HTTP request headers used for secure API access over HTTPS.

The standardised response mechanisms facilitate robust integration, enabling developers to reliably detect and handle both successful operations and error conditions during asset registration.

ANNEX XIII: DETAILED DESCRIPTION OF WORKFLOW 2

Workflow 2 is implemented through three core HTTPS APIs.

1. Dataset Discovery (Catalogue Query)

This endpoint enables Solution Providers to retrieve available datasets from the Federated Catalogue based on specific filtering criteria.

Endpoint: GET https://pedvolution.intracom-telecom.com/pedvolutionapi/catalog/offers/query

The Solution Provider queries the catalogue to identify datasets of interest using metadata filters such as:

- PED identifier
- Dataset category (*characteristic*)
- Temporal coverage (*timePeriodFrom*, *timePeriodTo*)
- Data format
- Asset identifiers
- Time resolution
- Real-time measurement flag

At this stage, only metadata information is returned, ensuring that no actual data is exposed without prior authorisation and contract agreement.

Request Body Structure

The request body contains the search criteria used to query the Federated Catalogue.

The following fields can be used as filters:

- characteristic
- timePeriodFrom, timePeriodTo
- dataFormat
- ped
- assetIds
- timeResolution
- realTimeMeasurement

Example query

Figure 115, presents the dataset discovery process through the Federated Catalogue, where a query is executed via the PEDvolution API using filtering parameters (e.g., PED identifier). The returned response

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includes structured metadata describing available datasets, supporting semantic discovery and enabling subsequent contract negotiation and data access workflows.

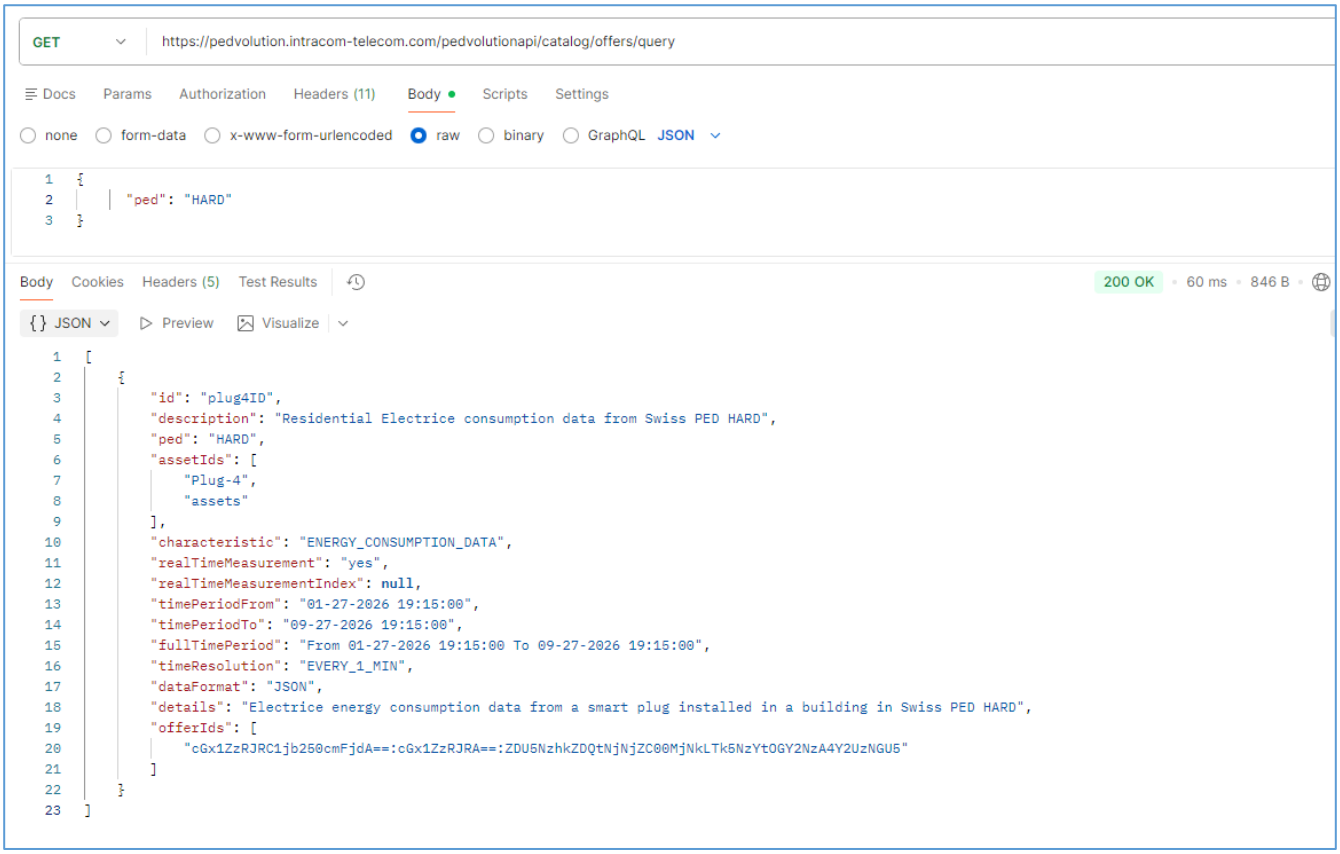


Figure 115: Dataset discovery via the Federated Catalogue using the PED identifier as a search criterion, illustrating a query request and the corresponding metadata response for available datasets.

Response Behavior

- If matching datasets are found, the API returns a list of available data offers (metadata).
- If no datasets match the specified criteria, the API returns an empty array.

The catalogue query endpoint enables efficient and flexible discovery of datasets across the PEDvolution ecosystem, forming the entry point for policy-driven data consumption.

2. Transfer Initiation (Contract Negotiation)

This endpoint enables Solution Providers to initiate the data access process by triggering contract negotiation with the Data Provider.

During this step, the Solution Provider requests access to a specific dataset identified in the Federated Catalogue. The Interoperability Platform then coordinates the negotiation process between the participating parties, ensuring that all access and usage policies defined by the Data Provider are satisfied.

Endpoint: GET https://pedvolution.intracom-telecom.com/pedvolutionapi/transfer

Overview of the Process

The transfer initiation process includes the following actions:

- Validation of the selected data offer
- Verification of access policies (e.g., require-membership)
- Validation of usage policies (e.g., require-dataprocessor)
- Execution of contract negotiation between Data Consumer and Data Provider
- Generation of an authorisation token (JWT) upon successful agreement

Example of transfer initialization

Figure 116, illustrates the transfer initiation process within the PEDvolution Interoperability Platform. In this step, a Solution Provider submits a transfer request by invoking the transfer endpoint and providing the selected dataset offer identifier along with the corresponding asset identifier.

The platform evaluates the request against the contract terms associated with the selected dataset, as well as the Verifiable Credentials (VCs) presented by the Solution Provider. If the credentials satisfy the contract policies, the negotiation is successful and the platform returns an authorisation token, which is required for subsequent secure data retrieval operations. Otherwise, the negotiation fails and access to the dataset is denied.

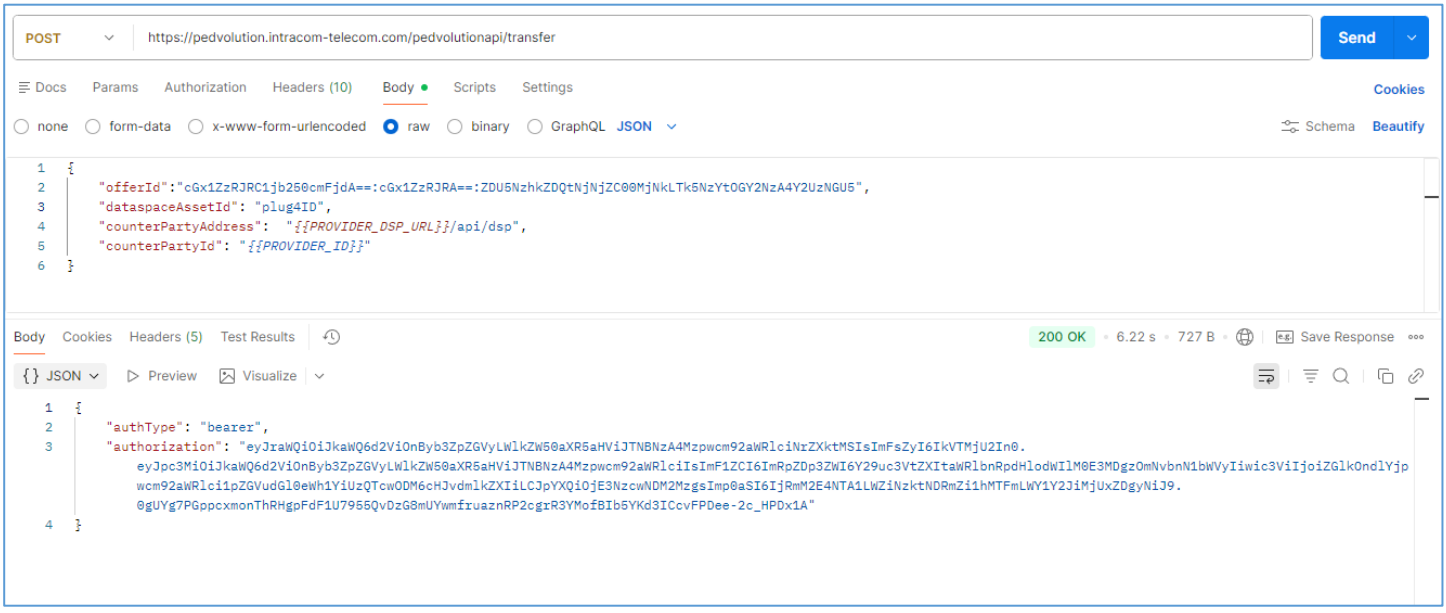


Figure 116: Transfer initiation via the PEDvolution API, illustrating a request containing the dataset offer and asset identifiers and the corresponding response with the issued authorisation token.

In case the negotiation fails during the transfer initiation process, the request is rejected and an error response is returned by the platform. As illustrated in the Figure 117, a 504 Gateway Timeout response may be received, indicating that the negotiation could not be successfully completed, typically due to non-compliance with contract policies or connectivity issues with the provider's connector.

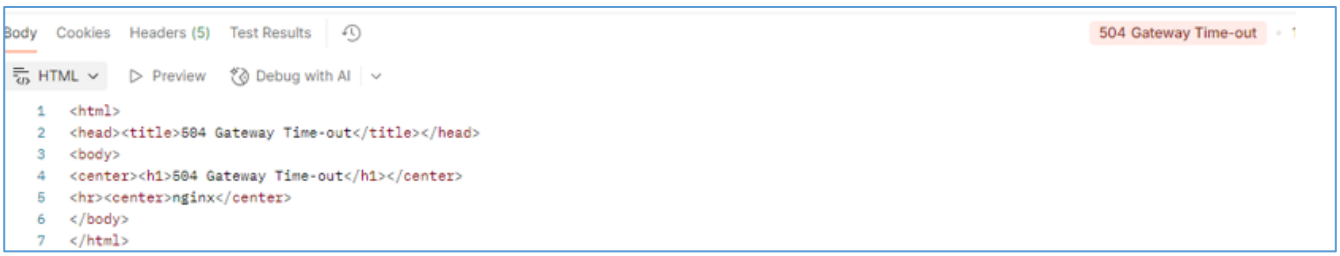


Figure 117: Example of a failed transfer initiation request, showing a 504 Gateway Timeout response returned when the negotiation process cannot be completed.

In the illustrated failed scenario, an asset is registered in the Interoperability Platform with a contract defining the contractPolicyId as "require-sensitive". This policy requires that only Solution Providers with appropriate Verifiable Credentials for handling sensitive data can access the asset.

During the negotiation process, the platform evaluates whether the Verifiable Credentials of the Solution Provider satisfy the data asset contract policies. In this case, the Solution Provider presents credentials aligned with the "require-dataprocessor" policy, which corresponds to DataAccess.level = "processing". This access level allows handling of non-sensitive data. Since the asset requires DataAccess.level = "sensitive", the presented credentials do not satisfy the policy constraint. As a result, the negotiation fails and access to the dataset is denied.

Figure 118, illustrates the contract associated with the dataset asset, highlighting the contractPolicyId set to "require-sensitive", which leads to the policy mismatch and subsequent negotiation failure.



Figure 118: Example of asset contract with policy mismatch, showing contractPolicyId "require-sensitive", which is not satisfied by the Solution Provider's Verifiable Credentials, resulting in negotiation failure.

The "require-sensitive" policy defines a constraint on the DataAccess.level attribute within the policy JSON structure, requiring it to be equal to "sensitive". This access level corresponds to highly confidential datasets that require enhanced security, trust, and compliance capabilities. In contrast, the "require-dataprocessor" policy corresponds to DataAccess.level = "processing", which permits access only to non-sensitive or routine data under standard compliance conditions.

This distinction between "processing" and "sensitive" access levels enables fine-grained, policy-based control over data access. It ensures that sensitive datasets are only shared with participants that

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possess the appropriate level of trust, security capability, and regulatory compliance, while enforcing policy constraints during the contract negotiation phase.

Figure 119, presents the policy definitions used within the PEDvolution Interoperability Platform for enforcing access control during data exchange. It illustrates the "require-sensitive" policy, which is applied in the asset contract, alongside the "require-dataprocessor" policy associated with the Verifiable Credentials of the Solution Providers.



Figure 119: Policy definitions for data access control, showing "require-sensitive" and "require-dataprocessor" policies and their role in contract negotiation.

Description of Body fields

- **PROVIDER_DSP_URL,** the provider's Data Space Protocol (DSP) endpoint where the contract negotiation of data offer and transfer will be executed **value**: http://provider-qna-controlplane:8082.
- **PROVIDER_ID:** did:web:provider-identityhub:7083:provider.
- **offerId,** the same value as the **offerIds** retrieved in **Step 1 – Query the Federated Catalog**.
- **dataspaceAssetId:** the same value as the id retrieved in **Step 1 – Query the Federated Catalog**.

Upon successful execution:

- A contract agreement is established between the parties
- An authorisation token (JWT) is issued

- The Solution Provider is granted permission to access the dataset under the agreed policies

This token is required for the subsequent data retrieval step.

This step ensures that:

- Only authorised and trusted participants can request data,
- All access requests comply with dataspace policies,
- Data usage is governed by contractual agreements,
- Access is granted in a controlled and auditable manner.

The transfer initiation endpoint constitutes the core mechanism for policy-driven data access, ensuring that all data exchanges within the PEDvolution dataspace are governed by secure, contract-based, and trust-enforced procedures.

3. Data retrieval

This endpoint enables Solution Providers to retrieve the dataset from the Data Provider after the successful completion of the contract negotiation process. The data retrieval step represents the final stage of Workflow 2, where authorised access to the dataset is granted and the actual data transfer is performed.

Endpoint: POST **https://pedvolution.intracom-telecom.com/pedvolutionapi/transfer/download**

Overview of the Process

Following the successful execution of the Transfer Initiation step, the Solution Provider receives an authorisation token (JWT). This token must be included in the request to securely download the dataset. The API Server validates the request and coordinates the data transfer from the Data Provider to the Solution Provider.

Figure 120, illustrates the data retrieval process within the PEDvolution Interoperability Platform. In this step, the Solution Provider invokes the transfer/download endpoint, providing the previously issued authorisation token. Upon successful validation, the platform retrieves and returns the requested dataset from the provider. The response contains structured data in JSON format, representing real-time measurements along with their associated metadata.

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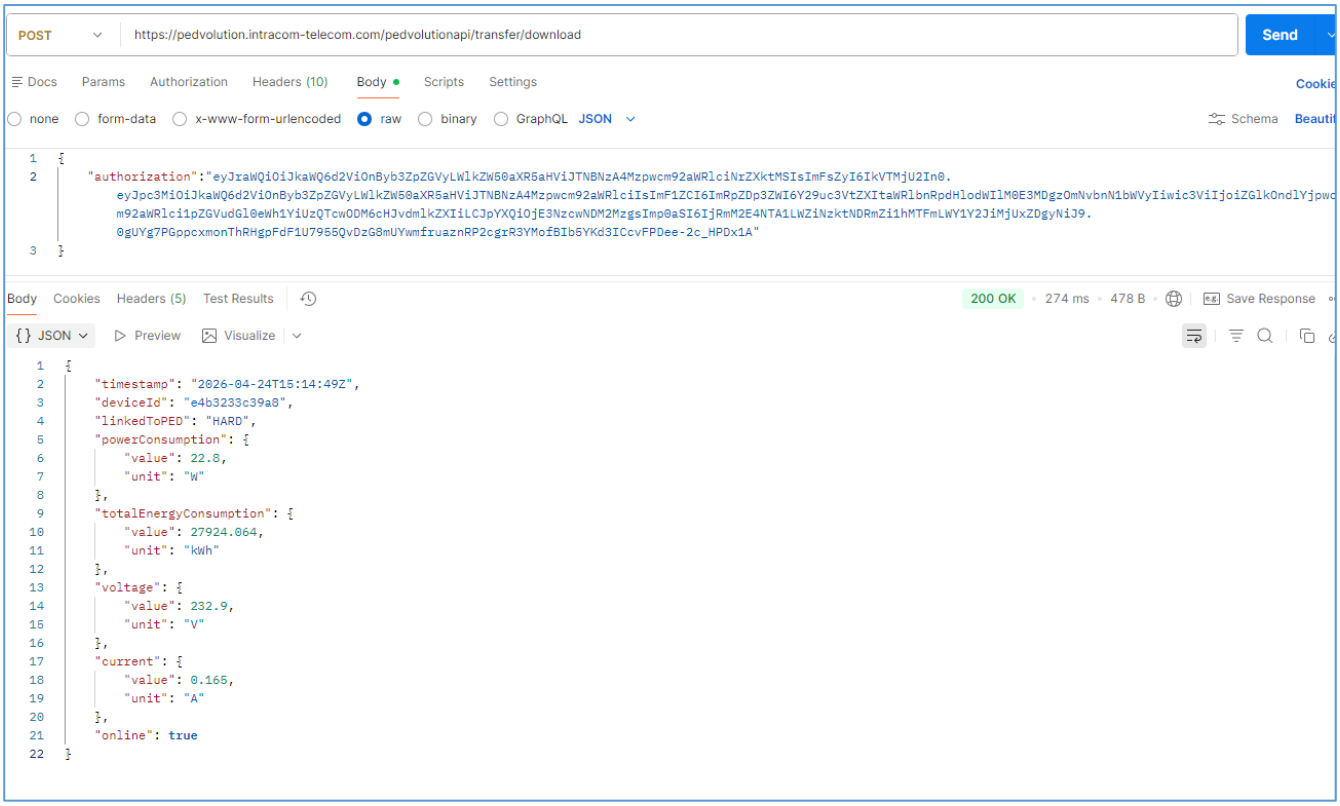


Figure 120: Data retrieval via the PEDvolution API, illustrating a request using an authorisation token and the corresponding response containing structured dataset measurements in JSON format.

Figure 121, illustrates the error handling mechanism during the data retrieval process when an invalid or expired authorisation token is provided. In this case, the platform performs token validation and, upon failure, rejects the request without accessing the dataset. An error response is returned, indicating that the token verification has failed. This mechanism ensures that only authenticated and authorised requests are allowed to access protected data resources.

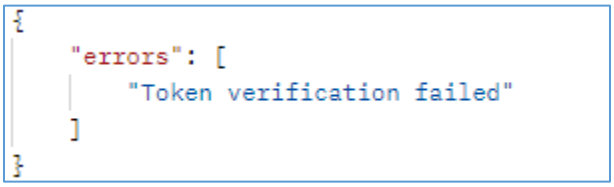


Figure 121: Example of failed data retrieval due to an invalid or expired authorisation token, showing the error response returned by the PEDvolution API.

Security and Policy Enforcement

This step ensures that:

- Only authorised requests with valid tokens can retrieve data.
- All access is compliant with access and usage policies.
- Data exchange is performed via secure HTTPS communication.

- Access is traceable and auditable.

The data retrieval endpoint completes the secure data exchange lifecycle, enabling controlled, policy-compliant, and sovereign access to PED datasets within the PEDvolution dataspace ecosystem.

ANNEX XIV: SECURITY AND PRIVACY REQUIREMENTS OF THE PEDVOLUTION PROJECT

In this Annex, the security and privacy requirements of the PEDvolution project are documented. Table 3 summarises the security requirements, while Table 4 the privacy requirements.

Abbreviations for the tables:

- NF: Non-functional
- FN: Functional
- SC: Security
- PR: Privacy

Table 3: PEDvolution Security Requirements

Requirement ID	Title	Description	Rationale	Priority
NF-SC-01	Secure Communications	All communications between PEDvolution components shall be protected using secure communication protocols and encryption mechanisms.	Protect confidentiality and integrity of exchanged information and prevent interception or tampering.	High
NF-SC-02	Authentication of Users and Systems	Access to PEDvolution services, APIs and data exchange mechanisms shall be restricted to authenticated users, systems and organisations.	Prevent unauthorised access to project resources and data.	High
NF-SC-03	Authorisation and Access Control	Access to data and services shall be granted according to assigned roles, responsibilities and the need-to-know principle.	Ensure users and systems access only the information necessary for their duties.	High
NF-SC-04	Identity and Access Management	The PEDvolution Interoperability Platform shall provide identity and access management capabilities for managing participant identities, permissions and trusted participation in data exchanges.	Enable controlled and trusted access to shared resources within the Data Space.	High
NF-SC-05	Trusted Data Exchange	Data exchanges through the PEDvolution Interoperability	Ensure that only approved entities	High

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		Platform shall occur only between authorised and trusted participants.	participate in data sharing activities.	
NF-SC-06	Policy-Based Data Access	Access to shared data shall be subject to agreed usage policies and access conditions defined by the data provider.	Ensure compliance with contractual, organisational and data governance requirements.	High
NF-SC-07	Network Exposure Control	Critical platform services shall be protected through controlled network exposure and restricted connectivity mechanisms.	Reduce the attack surface and minimise opportunities for unauthorised access.	High
NF-SC-08	Protection of Platform Components	Critical components of the PEDvolution Interoperability Platform shall be protected from direct unauthorised access and deployed using appropriate isolation mechanisms.	Limit the impact of attacks and protect core platform services.	High
NF-SC-09	Vulnerability and Patch Management	PEDvolution components shall be maintained through appropriate vulnerability management and security update processes.	Reduce exposure to known vulnerabilities and cybersecurity risks.	Medium
NF-SC-10	Backup and Recovery	Appropriate backup and recovery mechanisms shall be implemented for systems and data supporting PEDvolution activities.	Support service continuity and recovery from failures or incidents.	Medium
NF-SC-11	Incident and Breach Management	Security incidents and personal data breaches shall be detected, managed and communicated according to defined procedures.	Minimise impact and support compliance with legal and contractual obligations.	High
NF-SC-12	Secure Software Development	Software components developed within PEDvolution shall follow secure development and deployment practices.	Reduce introduction of security vulnerabilities during implementation.	Medium
NF-SC-13	Personnel Security and Awareness	Personnel with access to PEDvolution systems or data	Reduce human-related security risks.	Medium

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		shall be subject to confidentiality obligations and receive appropriate security awareness training.		
NF-SC-14	Data Protection Safeguards	Personal data shall be protected against unauthorised access, disclosure, alteration, loss or destruction through appropriate technical and organisational measures.	Preserve confidentiality, integrity and availability of personal data.	High

Table 4: PEDvolution Privacy Requirements

Requirement ID	Title	Description	Rationale	Priority
NF-PR-01	Lawful Processing of Personal Data	Personal data shall be processed only on a valid legal basis and exclusively for PEDvolution project purposes.	Ensure compliance with GDPR and project commitments.	High
NF-PR-02	Data Minimisation	Only personal data necessary for achieving the relevant PEDvolution objectives shall be collected and processed.	Reduce privacy risks and comply with GDPR principles.	High
NF-PR-03	Purpose Limitation	Personal data shall not be used for purposes incompatible with those communicated to participants.	Ensure transparent and lawful processing.	High
NF-PR-04	Privacy by Design and by Default	Privacy considerations shall be incorporated into the design and operation of PEDvolution solutions from the outset.	Reduce privacy risks and support regulatory compliance.	High
NF-PR-05	Anonymisation and Pseudonymisation	Personal data shall be anonymised whenever feasible and otherwise pseudonymised before disclosure or sharing.	Reduce privacy risks and limit exposure of identifiable information.	High
NF-PR-06	Restriction of Personal Data Access	Access to personal data shall be limited to authorised personnel with a legitimate operational need.	Protect participant privacy and prevent unnecessary exposure.	High

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NF-PR-07	Consent Management	The project shall maintain mechanisms for obtaining, recording and managing participant consent where consent constitutes the legal basis of processing.	Demonstrate lawful processing and participant awareness.	High
NF-PR-08	Personal Data Sharing Controls	Personal data may be shared only with authorised PEDvolution partners or authorised service providers operating under appropriate obligations and safeguards.	Ensure controlled and lawful disclosure of personal data.	High
NF-PR-09	International Data Transfer Compliance	Transfers of personal data outside the EU/EEA shall be performed only under appropriate legal safeguards and applicable data protection requirements.	Maintain GDPR compliance for international transfers.	Medium
NF-PR-10	Data Retention and Disposal	Personal data shall be retained only for the approved retention period and shall thereafter be securely deleted or anonymised unless otherwise required by law.	Limit privacy risks associated with excessive retention.	High
FN-PR-01	Consent Withdrawal Handling	PEDvolution shall support the withdrawal of consent and the subsequent cessation of processing, deletion or anonymisation of personal data where applicable.	Fulfil participant rights and GDPR obligations.	High
FN-PR-02	Support for Data Subject Rights	Mechanisms shall be provided to support the exercise of applicable GDPR rights by participants.	Ensure compliance with data protection legislation.	High

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