Semantic Interoperability for Federated Digital Twins in the Energy Domain

Lessons, Gaps, and a Roadmap from TwinEU, ORION, Hedge-IoT and Eclipse Digital

26 November 2026



Co-funded by the European Union

Project:	101136119	|	www.twineu.net
	101158432	|	https://he-orion.eu/
	101136216	|	https://hedgeiot.eu/
	101158494	|	https://eclipse-digital.eu/

Contributors

Nuran Cihangir Martin (STEDIN)

Beyza Cizmeci (Fraunhofer FIT)

Ferdinando Bosco (Engineering - Ingegneria Informatica)

Juan Galeano Martinez (RWTH Aachen University)

Fengshuo Hao (RWTH Aachen University)

Verzhinia Ivanova (Entra Energy)

Apostolos Kapetanios (European Dynamics)

Antonio Kung (Trialog)

Francesco Messano (Terna)

Antonello Monti (Fraunhofer FIT, RWTH Aachen University)

Esteban Pastor Calatayud (ETRA)

Nuno Pinho da Silva (R&D Nester)

Daniele Porcu (Enel Grids)

Marco Proietto (Enel Grids)

Francesca Soldan (Ricerca sul Sistema Energetico - RSE)

Ilias Zafeiropoulos (Ubitech Energy)

Table of Contents

Executive Summary 5

1 Introduction 6

2 Background and State of the Art 8

2.1 Digital Twin Federation 8

2.2 Semantic Interoperability & Ontologies 10

2.2.1 Data Models and Standards in the Smart Energy Sector 12

2.2.2 Ontology and data model harmonization 13

2.2.3 The Smart Grid Architecture Model and the Data Exchange Reference Architecture 14

2.3 Standardization and semantic data governance 16

3 Lessons from TwinEU, ORION, Hedge-IoT and Eclipse Digital 19

3.1 TwinEU Findings 20

3.1.1 TwinEU Key Achievement: Reference Architecture 22

3.1.2 TwinEU Achievement: Digital Twin & Data Space integration 23

3.1.3 TwinEU pilot results 25

3.2 ORION Findings 31

3.2.1 Key achievements 32

3.2.2 ORION use cases 35

3.3 Hedge-IoT Findings 37

3.3.1 Hedge-IoT Reference Architecture 37

3.3.2 Hedge-IoT Semantic interoperability findings 40

3.4 ECLIPSE DIGITAL Findings 42

3.4.1 Identified gaps 42

3.5 Cross-Project Insights and Gap Analysis 43

4 Vision: Semantic Interoperability for Federated Digital Twins 46

4.1 Semantic interoperability as the core of Federated Digital Twins 46

4.2 Key priorities 47

4.3 Key Principles 48

5 Proposed Roadmap and Stakeholder recommendations 50

6 Conclusion 55

References 56
Acronyms 62
Annex 1: Data models and standards in the smart energy domain 65
Annex 2: Ontology alignment, ontology mapping and application ontologies 68
Annex 2.1 Ontology alignment 68
Annex 2.2 Ontology mapping 68
Annex 2.3 Application ontologies 69
Annex 3: Standards and standardization organizations related to the energy domain .. 71

Executive Summary

The EU-funded project TwinEU aims to enable a federated ecosystem of Digital Twins at European scale, where independently developed platforms can collaborate while preserving their autonomy, data sovereignty and implementation choices. Achieving this vision requires more than common interfaces and trusted Data Space services: exchanged data, models and services must also be consistently understood and reused across organizational, technological and national boundaries.

Experience from TwinEU pilots, complemented by the analysis of ORION, HEDGE-IoT and ECLIPSE DIGITAL, highlights several challenges for semantic interoperability. Existing standards and semantic models provide valuable foundations but remain heterogeneous in adoption and coverage. Further challenges concern data-to-model mapping, cross-domain alignment, persistent identification of entities, semantic description of models and services, validation, and long-term governance of semantic assets.

The main conclusion is that semantic interoperability should become an explicit capability of federated Digital Twin and Data Space architecture. Rather than defining a single common ontology or Digital Twin implementation, the proposed approach is to reuse and extend established standards, introduce controlled and use-case-driven mappings between domain models, develop reusable interoperability profiles, and manage semantic models, mappings and validation rules as governed federation assets. AI-assisted approaches can facilitate mapping and interoperability, if traceability, validation and human oversight are ensured.

TwinEU should therefore move towards a governed semantic ecosystem for federated Digital Twins, shifting from organization-centric to ecosystem-level interoperability and favoring federation over centralization. In the longer term, this approach can support reliable discovery, interpretation and reuse of data, models and services across European energy actors, providing a semantic foundation for Pan-European Digital Twin scenarios.

1 Introduction

Digital Twin (DT) platforms are increasingly being adopted in the energy sector, emerging as valuable tools for system operators and market participants to support decision-making and coordinate their operations. Despite this growing adoption, DT platforms are often developed in isolation, resulting in limited interoperability across organizational and technological boundaries. At the same time, it is essential that each stakeholder retains the flexibility to make implementation choices that best fit its specific requirements while remaining capable of exchanging data and services with the broader ecosystem.

The challenge is further amplified by the growing interaction between multiple domains (energy, buildings, mobility, and smart city applications), each relying on different semantic models and standards. Existing frameworks based on IEC CIM, BIM/IFC, SAREF, and other domain-specific ontologies provide valuable foundations, but their coexistence often results in fragmented semantic representations and interoperability barriers. Without appropriate alignment and reuse mechanisms, Digital Twin initiatives risk developing isolated and application-specific ontologies that are difficult to reuse, extend, or integrate within a broader ecosystem.

In this context, the EU-funded TwinEU project aims to establish a federated ecosystem of Digital Twin solutions at European scale. To achieve this vision, the project seeks to develop the technological foundations and interoperability mechanisms required to enable seamless collaboration among heterogeneous DT platforms. A key objective is the creation of a European data exchange core, based on Data Space Connectors, which facilitate the integration of data from multiple sources and allow different applications to access the same data assets without requiring data duplication.

Within this federated environment, data and information models represent key interoperability assets, defining how physical and logical entities, attributes, relationships, identifiers and constraints are represented and exchanged across Digital Twins. The availability of common interfaces and trusted Data Space services is therefore a necessary, but not sufficient, condition for federation: exchanged data must also be structured, validated and semantically described in a way that enables consistent interpretation and reuse by different participants and applications.

Achieving meaningful interoperability across diverse platforms requires a shared understanding of the information being exchanged. Semantic interoperability therefore becomes a fundamental requirement, ensuring that data is interpreted consistently by all participating systems. In this regard, ontologies and shared data models provide a powerful mechanism for representing domain knowledge and establishing a common semantic framework for data exchange.

However, the development and implementation of the TwinEU pilot projects have revealed several limitations in existing ontologies, standards, and semantic technologies. These findings are complemented by the analysis of other European research and innovation projects, including ORION, HEDGE-IoT, and ECLIPSE DIGITAL, which provide

additional perspectives on semantic interoperability across different Digital Twin architectures, Data Space environments, and energy-sector use cases. The combined analysis provides a broader evidence base for identifying recurring interoperability challenges and distinguishing project-specific limitations from more general gaps requiring cross-project and standardization efforts. Rather than necessarily requiring a single comprehensive TwinEU ontology, addressing these limitations may require a federated semantic approach based on the reuse and extension of established domain models, governed mappings between heterogeneous representations, and the definition of shared semantic elements where a common understanding is required.

Such an effort would result in a harmonized semantic framework tailored to the needs of Digital Twins in the energy domain.

Therefore, the objective of this white paper is to identify the key semantic interoperability challenges encountered in TwinEU, analyse the limitations of current semantic approaches, and outline priority actions and future directions towards a governed semantic framework for federated energy Digital Twins.

2 Background and State of the Art

2.1 Digital Twin Federation

The federation of Digital Twins through a Data Space implementation as defined in TwinEU project enables autonomous Digital Twins to collaborate across organizational and domain boundaries while preserving data sovereignty, interoperability, and governance. Rather than relying on centralized integration, each Digital Twin exposes and consumes information through trusted Data Space services, allowing participants such as Transmission System Operators (TSOs), Distribution System Operators (DSOs), Market Operators (MOs), aggregators, energy communities, and service providers to exchange data according to agreed policies, usage constraints, and interoperability standards.

Digital Twin federation in TwinEU goes beyond the interconnection of hardware and software systems. Its objective is to enable independently developed Digital Twins to collaborate while preserving their autonomy, ownership and implementation choices. Digital Twins leverage the Data Space's shared trust and governance mechanisms to discover, exchange, and consume the data, models, and services needed to support hardware infrastructure. In this context, the Data Space acts as the operational backbone of the federation by providing discovery services, metadata management, policy enforcement, secure exchange and support for semantic interoperability. The federation therefore enables the creation of a pan-European ecosystem of Digital Twins without requiring centralized Digital Twin implementation.

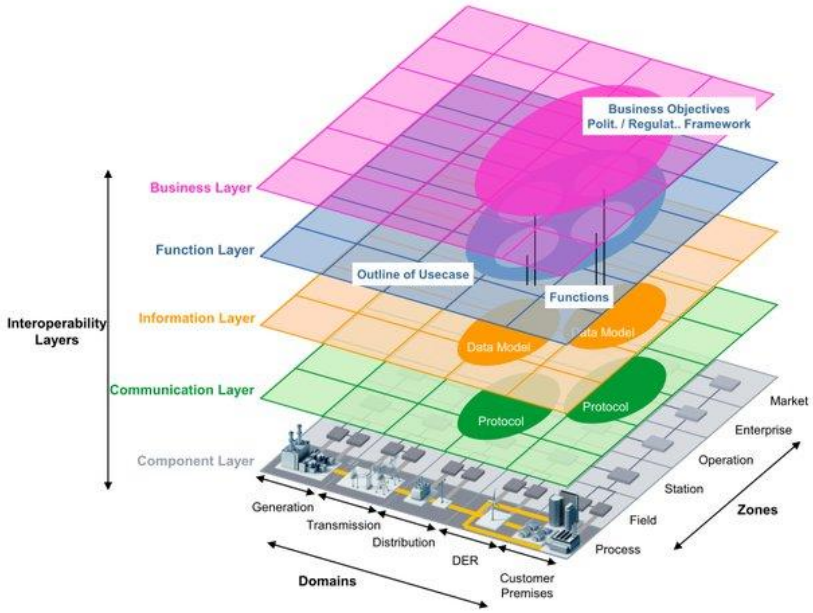

Figure 1 - Smart Grid Architecture Model (SGAM) [1]

The implementation methodology is based on modelling the federation using the Smart Grid Architecture Model (SGAM) (Figure 1), which provides a structured approach for describing the technical architecture required for interoperable Digital Twin

collaboration. The methodology focuses on the technical layers of SGAM, enabling the systematic specification of the components, communication mechanisms, semantic models, and data exchanges that constitute the federated ecosystem.

The Component Layer identifies Digital Twins, Data Space connectors, data providers, consumers, edge devices, cloud services, orchestration platforms, and supporting software components participating in each use case. It also captures the physical and logical connectivity among these components, establishing the deployment topology of the federated environment.

The Communication Layer specifies how Digital Twins exchange information through standardized communication protocols and Data Space interfaces. Besides traditional industrial communication protocols (e.g., MQTT, TCP/IP, HTTPS, SFTP, OPC UA), this layer introduces trusted Data Space communication mechanisms, including connector-to-connector interactions, secure data transfer, identity management, policy negotiation, and contract-based data exchange. These mechanisms ensure that every interaction complies with interoperability and governance requirements while maintaining secure and auditable data sharing.

The Information Layer defines the semantic interoperability required for federation and is organized into three complementary views:

- **Business Context View**, describing the operational interactions among participating Digital Twins by identifying the information assets exchanged, such as measurements, forecasts, flexibility requests, optimization results, control commands, asset descriptions, and operational events.
- **Canonical Data Model View**, specifying the common semantic models, ontologies, and data standards that enable heterogeneous Digital Twins to interpret exchanged information consistently, regardless of their internal implementation.
- **Standards and Information Mapping View**, linking exchanged information objects to the corresponding interoperability standards, semantic models, APIs, and Data Space assets, thereby ensuring consistent interpretation, discovery, and reuse across all participants.

By modelling every federation use case across these layers, a complete technical specification of the Digital Twin federation is established. This specification not only identifies the participating Digital Twins and infrastructure components but also defines the communication interfaces, Data Space services, semantic standards, governance policies, and information flows required to support trusted collaboration.

The resulting architecture enables the federation of heterogeneous Digital Twins through a common Data Space infrastructure where data remains under the control of its owner while becoming securely discoverable and reusable by authorized participants. Consequently, the federation evolves from a collection of isolated Digital Twins into an interoperable ecosystem capable of supporting cross-domain analytics, distributed optimization, coordinated decision-making, and real-time operational collaboration without sacrificing autonomy, scalability, or data sovereignty.

2.2 Semantic Interoperability & Ontologies

The TwinEU project aims to design a pan-European Digital Twin ecosystem by federating local Digital Twins. In this context, interoperability is a fundamental requirement to ensure the seamless integration and interaction of the different platforms developed within the project. More broadly, in the smart energy domain, interoperability is required to: (i) integrate distributed data sources within a single operator, (ii) ensure continuity across asset lifecycle phases, (iii) enable information exchange among different utilities, and (iv) support the integration of multi-energy systems.

According to the European Interoperability Framework (EIF), interoperability can be analysed across four complementary layers: legal, organisational, semantic, and technical [2]. EIF influenced standards on interoperability such as ISO/IEC 19941-1 or the ISO/IEC 21823 family of standards have made some subtle changes by considering interoperability through five complementary facets: policy, behavioural, semantic, syntactic and transport. Among these layers of facets, semantic interoperability plays a central role, as it ensures that both the meaning and the structure of exchanged data are consistently understood across systems, typically through the adoption of shared standards and common data models.

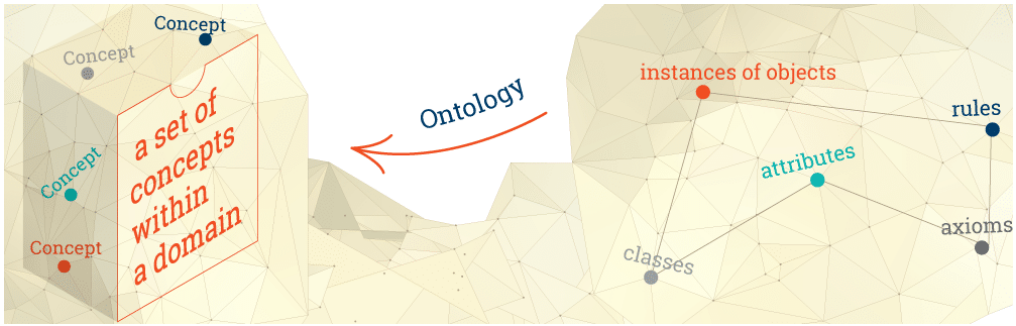

Figure 2 - Components of an ontology [3]

In this context, ontologies can provide a formal specification of a shared conceptualization and enable a common understanding of data across heterogeneous systems. An ontology is defined as a formal representation of knowledge, including a set of concepts within a domain and the relationships among them [3]. It is composed of individuals (instances), classes, attributes, relations, as well as restrictions, rules, and axioms (Figure 2). This structure enables not only the sharing and reuse of knowledge but also the derivation of new knowledge through inference. Classes represent the focus of most ontologies, as they formalize the concepts of a domain. For example, the class of "energy generation" represents all types of generation units. Solar or wind generation units are subclasses of this class.

The definition of an ontology is carried out using specific languages, such as the Web Ontology Language (OWL), which is described as a "semantic web computational logic-based language" [4]. It allows the definition of the entities of a model, together with their relationships and attributes, also considering their hierarchical organization and relying on semantic RDF (Resource Description Framework) triples (subject–predicate–object)

[5]. Within a triple, the subject and the object are represented as nodes in a graph, while the predicate is a directed edge connecting the two nodes. An example of a subject–predicate–object triple is ("DER_unit", "connectedTo", "Grid_Node"). Another triple can specify the subclass relationship of a class: ("DER_unit", "rdfs:subClassOf", "Plant").

When the model introduced by an ontology is applied to real-world entities, this results in the definition of a knowledge graph [6]. Referring again to the triple ("DER_unit", "connectedTo", "Grid_Node"), an example of an instance in the knowledge graph could be: "PV_plant_12", "connectedTo", "MV_node_45", where both the subject and the object refer to specific real-world elements.

Among their main benefits, ontologies enable automated reasoning by embedding semantic relationships within the data model, support intuitive navigation across concepts, and can be incrementally extended as new data becomes available [3]. This flexibility enables incremental evolution without affecting existing systems. Furthermore, ontologies can represent structured, semi-structured, and unstructured data, thereby supporting heterogeneous data integration, cross-database querying, and effective knowledge management.

However, despite their strengths, ontologies present some limitations [3]. OWL 2[1] [4], which is the most widely adopted language for defining ontologies, offers powerful class modelling constructs but has more limited support for expressing complex property-level metadata, an issue partially addressed by RDF-Star[2] [7]. Additionally, OWL focuses on inference rather than constraint validation, which can make the integration of externally sourced data challenging when such data does not conform to expected structures. In this context, SHACL[3] provides a complementary approach, enabling flexible validation of RDF data, including data already stored in a triple store, and offering a more adaptable mechanism for enforcing data quality constraints [8].

To better understand their scope and applicability, ontologies can be classified according to their level of abstraction and domain coverage. Upper ontologies capture general, domain-independent concepts (e.g., SUMO[4], DOLCE[5]), while core ontologies describe more specific but still widely applicable notions (e.g., OASIS[6], OWL-Time[7]).

[1] The OWL 2 Web Ontology Language is an ontology language for the Semantic Web with formally defined meaning. OWL 2 ontologies provide classes, properties, individuals, and data values and are stored as Semantic Web documents. OWL 2 ontologies can be used along with information written in RDF, and OWL 2 ontologies themselves are primarily exchanged as RDF documents.
[2] RDF-star is an extension of RDF with a convenient way to make statements about other statements.
[3] SHACL (Shapes Constraint Language) is a W3C standard used to validate RDF knowledge graphs against a set of explicit conditions.
[4] The SUMO ontology (Suggested Upper Merged Ontology) is an upper ontology intended as a foundation ontology for a variety of computer information processing systems [84].
[5] DOLCE (Descriptive Ontology for Linguistic and Cognitive Engineering) is a foundational (top-level) ontology designed to capture the basic, commonsense categories of reality as they are reflected in natural language and human cognition [85].
[6] The OASIS ontology (Ontology for Agents, Systems, and Integration of Services) offers a formal and shared framework for modelling agents, interactions, processes, procedures and events [86].
[7] OWL-Time is an ontology of temporal concepts, for describing the temporal properties of resources in the world or described in Web pages [87].

Domain ontologies focus on concepts within a particular field, such as SEAS (Smart Energy Aware Systems) ontology to describe energy systems and their interactions [9] and SSN (Semantic Sensor Network) ontology to describe observations, in terms of the procedures executed and sensors used [10]. Finally, application ontologies are derived from these layers, extending and combining them to address specific use cases.

In practice, new ontologies are rarely developed from scratch but are instead built by reusing and integrating existing ontologies, or by specializing domain ontologies on top of upper-level ones. This approach promotes knowledge reuse, consistency, and alignment with established models. In this context, the Alliance for AI, IoT and Edge Continuum Innovation (AIOTI) has published a *Manifesto for Reusable Ontologies* [11], which provides a set of principles for the design, governance and lifecycle management of ontologies, promoting reuse-by-design, collaborative development, versioning, and alignment with FAIR (Findable, Accessible, Interoperable, Reusable) and interoperability requirements to support complex, cross-domain ICT systems.

Currently, several sectors are actively developing ontologies to provide semantic solutions to interoperability issues related to knowledge and collected data. In the energy sector as well, ontologies have been used to support information exchange across multiple domains and form the foundation of artificial intelligence and Digital Twin solutions. While these models provide a structured foundation, no single ontology can capture the full complexity of energy systems, as also highlighted by the IEC System Committee Smart Energy in its *Guidance and plan to develop smart energy ontologies* [12]. This makes it essential to evaluate and reuse existing semantic models for specific applications, avoiding redundancy and ensuring alignment with established standards. However, harmonizing heterogeneous ontologies remains a key challenge for effective data integration, as current models address different subdomains and levels of detail, making the definition of a unified Smart Energy Ontology difficult in practice.

2.2.1 Data Models and Standards in the Smart Energy Sector

In the energy domain, numerous ontologies are available, each characterized by a specific focus and developed for different application contexts. This diversity makes it challenging for users to identify the ontology that best fits their use case. In this regard, the LOV4IoT-Energy Ontology Catalog [13] represents a useful tool for promoting the reuse of existing ontologies by providing an overview of various projects related to the smart energy sector. Another useful reference is the IEC SyC Smart Energy document [12], which aims to establish a landscape giving an overview of existing ontology and guiding energy ontology stakeholders to compare and select them according to their usage. Moreover, it establishes best practices and sets guidelines to build an effective ontology, avoiding inadequate ontology design.

However, semantic interoperability in the energy domain cannot be addressed through ontologies alone. In practice, smart energy systems rely on a broader and heterogeneous ecosystem of standardized information models, semantic models, ontologies, vocabularies, and interoperability specifications. These resources differ in their level of formalization and technological implementation but provide complementary

representations of energy-domain concepts. In this broader perspective, Figure 3 shows an overview of the standards used in the smart grid domain.

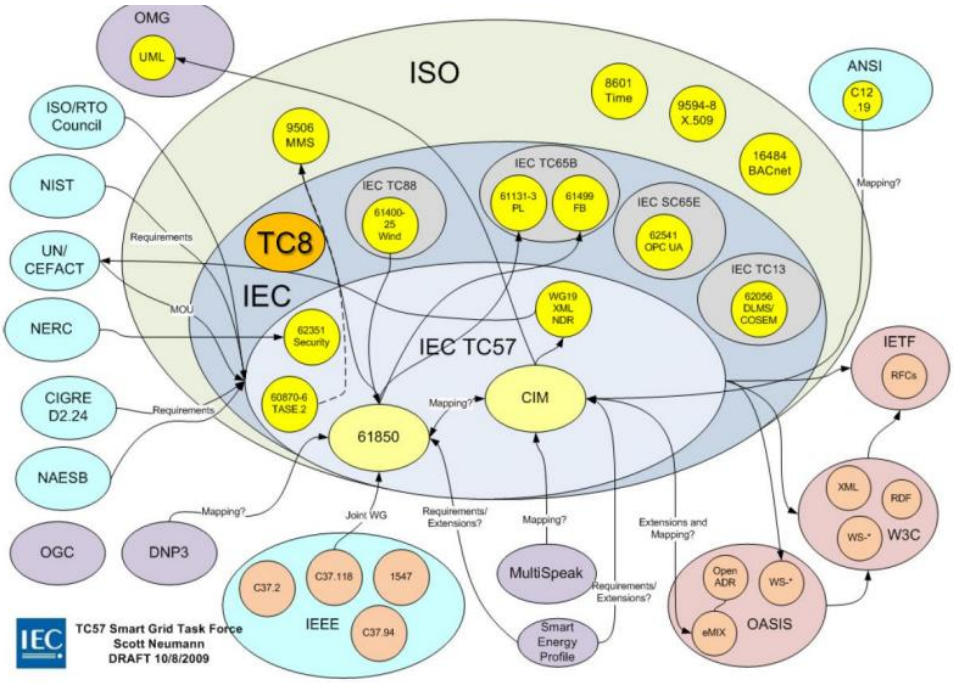

Figure 3 - Overview of standards in the smart grid domain and their dependencies [14]

Accordingly, “Annex 1: Data models and standards in the smart energy domain”, provides examples of relevant resources from this broader landscape. The appendix does not intend to classify all these resources as ontologies but complements the ontology-focused discussion above by illustrating the heterogeneous models and standards with which an ontology-based interoperability framework needs to interact.

Data model perspective adopted in TwinEU

Within this white paper, a data model is understood as the structured representation of the entities, attributes, relationships, identifiers and constraints required to describe a Digital Twin use case. An information model provides a domain-level and implementation-independent representation of this structure, while an ontology adds explicit, machine-interpretable semantics and formal relationships. Exchange formats such as IFC, RDF/XML, JSON, CSV or GeoJSON serialize only part of this information and should therefore not be considered equivalent to the underlying semantic model.

2.2.2 Ontology and data model harmonization

Achieving semantic interoperability across heterogeneous systems requires the harmonization of ontologies and data models that have been developed independently and often target different application domains. Several approaches have been proposed in the literature, ranging from the alignment of existing ontologies to the creation of shared semantic models that serve as a common reference for data exchange. Two fundamental harmonization processes can be distinguished: ontology alignment and ontology mapping. Ontology alignment establishes correspondences between

heterogeneous semantic models, while ontology mapping connects source data to shared semantic concepts. Complementarily, application ontologies can reuse and extend established models to address project-specific requirements and use cases. These approaches support a federated semantic ecosystem in which domain models such as IEC CIM, IFC and SAREF remain autonomous but can be connected through explicit mappings and controlled extensions. Further methodological details and examples are provided in "Annex 2: Ontology alignment, ontology mapping and application ontologies".

2.2.3 The Smart Grid Architecture Model and the Data Exchange Reference Architecture

As described, semantic models play an important role in addressing interoperability from an information perspective. A relevant example is the Smart Grid Architecture Model (SGAM) framework (Figure 1), developed under the initiative of the European Commission to promote standardization and interoperability in the smart grid domain [1]. SGAM is a three-dimensional model structured along three dimensions: interoperability layers (Business, Function, Information, Communication, Component), zones (Process, Field, Station, Operation, Enterprise, Market), and domains (Generation, Transmission, Distribution, DER, and Customer Premise).

The SGAM framework supports the design of smart grid use cases and facilitates their alignment with relevant standards, enabling interoperability across all architectural layers. Relationships can be established both within a single layer and across multiple layers. For example, business processes defined in the Business layer are realized through functions in the Function layer, which are subsequently implemented by physical or logical assets represented in the Component layer. This layered approach provides a systematic link between business objectives, operational functions, information exchanges, communication mechanisms, and physical infrastructures.

Building upon the SGAM framework, the BRIDGE Data Management Working Group developed a European reference architecture for energy data exchange [15]. As illustrated in Figure 4, the architecture distinguishes between an electricity-sector-specific layer and a cross-sector layer for facilitating interoperability across different domains. Within the electricity-specific layer, the IEC Common Information Model (CIM) is identified as one of the key information models supporting semantic interoperability. The architecture also introduces the concept of CIM+ as a possible extension of CIM capable of representing information beyond the traditional electricity domain and enabling interoperability with sectors not currently covered by existing standards.

The evolution of this architecture led to the definition of the Data Exchange Reference Architecture (DERA) 2.0, which represents an intermediate step towards the realization of cross-sector data exchange [16]. Compared to its predecessor, DERA 2.0 adopts a more domain-independent perspective by introducing generic architectural building blocks applicable across multiple energy sectors rather than focusing only on the electricity domain.

Subsequent developments in the European data-sharing landscape, particularly the emergence of the data space paradigm, motivated a further evolution of the architecture [17]. The latest release, DERA 3.1, incorporates concepts promoted by major European initiatives and industrial associations, including Gaia-X, the International Data Spaces Association (IDSA), and the Data Spaces Business Alliance (DSBA). As shown in Figure 5, DERA 3.1 distinguishes between local data platforms and federated data space infrastructures, interconnected through Data Space Connectors.

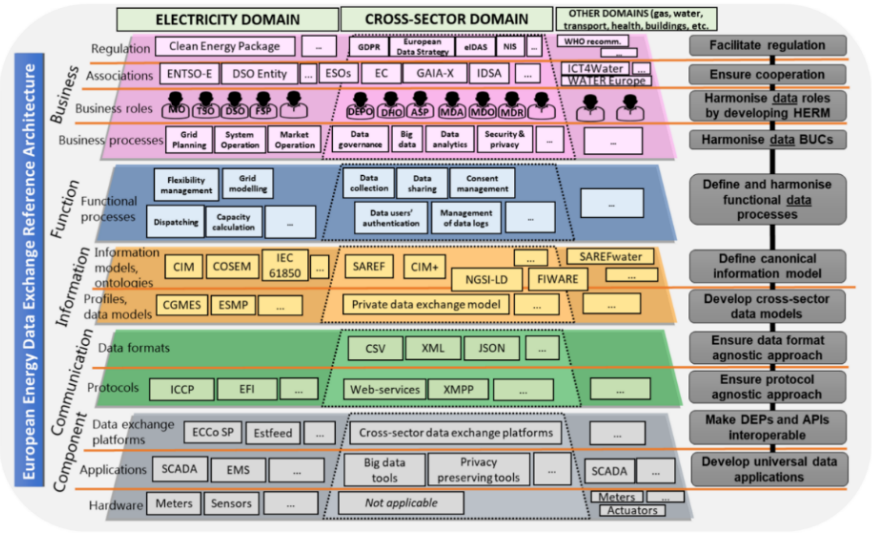

Figure 4 - European reference architecture for data exchange in the energy sector [15]

Data Space Connectors facilitate the integration of data originating from multiple sources and allow different applications to access the same data assets without requiring data duplication. To ensure interoperability, connectors rely on standardized communication mechanisms and agreed semantic descriptions of exchanged information.

Within DERA 3.1, data harmonization is identified as a key function on the local platform side. Its objective is to ensure that data formats and semantics are consistent with agreed information models before data are shared. At the federated data space level, this functionality is complemented by the Vocabulary Provider, which acts as a governance mechanism for semantic interoperability. On one hand, it publishes and manages the vocabularies, ontologies, and data models adopted within the ecosystem; on the other hand, it enables the verification of semantic compliance of exchanged data against these shared vocabularies.

Finally, the BRIDGE Data Management Working Group recommends addressing existing interoperability gaps through stronger semantic governance, clearer terminology management, and collaborative mapping efforts between data models. Among the available standards, IEC CIM and IEC 61850 are explicitly identified as key enablers of semantic interoperability. In particular, CIM is recognized as a natural candidate reference model within the DERA framework due to its widespread adoption in the energy sector and its capability to support consistent information exchange across organizational and technological boundaries [18].

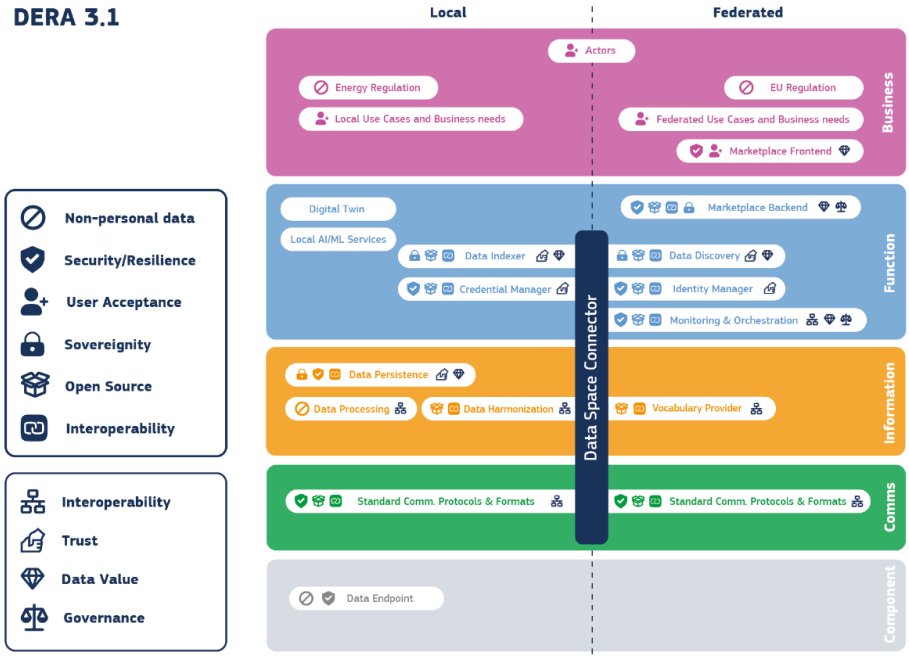

Figure 5 - DERA 3.1 layered architecture [17]

2.3 Standardization and semantic data governance

Semantic domain standardization has the aim of formally defining and maintaining a semantic domain with an appropriate extent of formality and rigour. Another goal is to maximize the audience for such work in contrast to private semantic domain. It is necessary to ensure the participation of the largest panel of stakeholder and maximizing the level of consensus for this content, in order to prevent an uncontrolled proliferation of standardized semantic domains [19]. The main standards and documents related to the energy domain, with the related standardization organizations, groups committees, are summarized in “Annex 3: Standards and standardization organizations related to the energy domain”.

A central element is related to the governance of semantic domains [19]. While data governance generally addresses the management, quality, ownership, and exchange of data, semantic data governance focuses specifically on the governance of information models, vocabularies, ontologies, taxonomies, interoperability profiles, and other semantic assets that enable a common understanding of exchanged data across organizations and domains.

According to the ENTSO-E position paper on the “Common Energy Data Space” [20], data exchange governance should be considered across all levels of interoperability and can be mapped onto the Smart Grid Architecture Model (SGAM) interoperability layers (Figure 6), as introduced in Chapter 2.2.3 “The Smart Grid Architecture Model and the Data Exchange Reference Architecture”.

Business layer	Function layer	Information and Communication layer	Component layer
1. Data governance business case	4. Data ownership governance	7. Data vocabulary governance	8. Data platforms
2. Orchestrated data governance	5. Data access governance		9. Interfaces
3. Rules and norms	6. Data security governance		10. Repositories

Figure 6 - Data governance elements clustered per SGAM interoperability layers [20]

Within the context of this position paper, orchestrated data governance plays a central role and is referred as a coordinated governance approach through which the different stakeholders of a Data Space jointly define, align and evolve common rules, responsibilities and governance mechanisms for data sharing and interoperability. As highlighted in [20], effective governance requires a dedicated steering structure involving projects, initiatives, stakeholders, and Member States. Existing bodies such as the Data for Energy Working Group [21], the European Data Innovation Board [22], the Data Spaces Support Centre [23], and the joint ENTSO-E and EU DSO Entity working groups [24] represent potential governance mechanisms to support coordination and decision-making in energy data spaces.

Rules and norms related to data formats, communication protocols, cybersecurity, standardised APIs, and information standards are also key enablers of data governance within data spaces. Furthermore, data vocabulary governance addresses the semantic modelling of roles, information exchanges, and processes through shared reference models. In the European context, this activity should be aligned with data interoperability implementing acts and supported by governance structures capable of coordinating the development, maintenance, and adoption of common reference models across stakeholders. The BRIDGE Data Management Working Group further highlights the importance of governance mechanisms for vocabularies and semantic assets to reduce ambiguities, avoid conflicting terminologies, and foster the adoption of standardized information models [17]. In this context, initiatives such as FIWARE and IDSA promote the concept of a Vocabulary Hub or Vocabulary Provider, providing centralized registries where semantic assets can be discovered, published, maintained, and reused across projects and domains. These vocabularies may include established semantic resources, such as IEC standards, as well as domain-specific data models developed for specific pilots or applications.

The governance challenge becomes even more significant when considering semantic data governance. Governance activities typically include semantic asset authoring, review, publication, validation, version management, deprecation, and long-term maintenance. In addition to governing individual semantic assets, governance frameworks should address the creation, validation, maintenance, and evolution of

mappings between information models, ensuring that semantic interoperability can be sustained across heterogeneous domains and standards.

In this context, int:net and AIOTI [25] highlight several semantic data governance gaps. A first issue concerns the lack of information models addressing transversal and cross-cutting topics such as privacy, resilience, artificial intelligence, digital sovereignty, and trusted data. A second challenge is the limited reuse of existing information models, which are often developed independently by different organizations. Additional issues include insufficient coordination among information models and weaknesses within Standards Developing Organizations (SDOs) in supporting model governance, reuse, maintenance, tool interoperability, licensing, and semantic model translation.

To address these challenges, int:net and AIOTI [25] proposed three complementary governance recommendations. First, standardization committees should actively coordinate and govern information models considered relevant within their domains. Second, standardization committees should also establish cross-domain coordination mechanisms to register information models and interoperability profiles, document dependencies among them, and provide consensus, conflict-resolution, and assurance processes for their evolution. Third, SDOs should adapt their processes, tooling environments, and governance practices to manage information models throughout their entire lifecycle, from creation and publication to maintenance and evolution.

Several initiatives have already recognised the importance of semantic governance. Examples include IEC SRD 63417, the ISO/IEC 21823 series, and collaborative activities conducted within AIOTI, JRC, BRIDGE, int:net, and IEC Smart Energy initiatives. Building upon these efforts, a new thematic group, TG4 on Semantic Coordination and Governance, has been proposed within IEC SyC Smart Energy WG3 to establish governance processes for semantic assets, leverage existing standards and initiatives, and facilitate collaboration among stakeholders involved in semantic modelling activities [26]. The rationale for this work is particularly evident in the context of Digital Twins, where heterogeneous data definitions, information models, tools, and methodologies are developed and maintained by different technical committees with limited coordination and reuse. Consequently, interoperability increasingly depends not only on the availability of standards, but also on governance mechanisms capable of coordinating semantic assets across domains, organizations, and lifecycle phases. This coordination should combine shared semantic registries with explicit ownership and lifecycle processes for publishing, validating, versioning and deprecating semantic assets, while maintaining governed mappings and dependencies across models developed by different domains and organizations.

3 Lessons from TwinEU, ORION, Hedge-IoT and Eclipse Digital

This section aims to illustrate the main semantic and interoperability gaps in the energy domain, building on the main results of TwinEU, ORION, HEDGE-IoT and ECLIPSE DIGITAL.

Although the selected projects differ in scope and technical implementation, they all address interoperability challenges emerging from the digitalisation of the energy sector, including the integration and exchange of heterogeneous data, models and services. TwinEU, HEDGE-IoT and ECLIPSE DIGITAL rely on Data Space principles for distributed and governed data sharing, whereas ORION adopts shared data-management and interoperability services. Together, they therefore provide complementary examples for analysing current approaches, achievements and remaining gaps in energy-sector interoperability. An overview and comparison of the four projects is presented in Table 1.

Table 1 – Overview of the selected projects

Dimension	**TwinEU** [27]	**ORION** [28]	**Hedge-IoT** [29]	**ECLIPSE-DIGITAL** [30]
Project scope	Pan-European Digital Twin of the electricity system	Integration of edge digital technologies and DT services	IoT/edge to cloud interoperability	Common European Reference Framework for energy consumer applications
Geographical/pilot coverage	Pilots across Europe	European and international use cases	6 European pilots	European use cases
Main use cases	Grid operation and monitoring, forecasting, coordinated planning, flexibility, grid resilience	Port decarbonisation, renewable integration, fault detection and predictive maintenance	Grid resilience and monitoring, flexibility, edge intelligence, AI-based energy services	Demand response, consumer flexibility, energy efficiency, grid alerts and consumer applications
Architectural approach	Federated Digital Twins + Data Space	Modular/distributed toolbox with shared data management and interoperability services	Data Space-based framework with cloud-edge orchestration and dedicated semantic layer	Data Space-based Common European Reference Framework

Dimension	TwinEU [27]	ORION [28]	Hedge-IoT [29]	ECLIPSE-DIGITAL [30]
Interoperability focus	Data exchange, semantic interoperability and DT federation	Data/model semantic interoperability and service integration	Data, semantic, computational and functional interoperability	Data, semantic, service and cross-domain interoperability

3.1 TwinEU Findings

The pilots in TwinEU use a wide range of data sources, formats, communication protocols, and information models. This diversity reflects the different requirements of the use cases and the different stakeholders involved. The following provides a consolidated overview of the data sources and formats identified in the project.

The identified information was categorised using the OneNet catalogue [31] as a basis. Some categories were extended (*OneNet (extended scope)*) to cover additional activities and data relevant to digital twins and the project-specific use cases. New categories were also introduced where the identified data could not be adequately represented by the existing classification. The categories and their descriptions are provided in Table 2, while Table 3 shows the number of identified data exchanges per category. Since some data items can support more than one activity, they may appear in multiple categories.

Table 2 - OneNet Extended Data Categories

Name	Source	Description
Measurements & Monitoring	OneNet	Exchange of measurement data, sensor readings, and monitoring information
Forecasts	OneNet	Exchange of forecasts and predictive data
Constraint/Limit Data	New	Exchange of data specifying operational or technical limits and constraints
Grid models (Asset/Network Topology Data)	OneNet (extended scope)	Exchange of data related to grid structure, network topology, or asset configurations, including visualization and enrichment of network data
Simulation results	OneNet	Exchange of simulation results, for example, power flow results
Reports & invoices (Analysis/Result Data)	OneNet (extended scope)	Exchange of analytical reports, invoices, or settlement documents related to energy and flexibility services
Resource (pre-) qualification	OneNet	Activities related to the (pre-) qualification of resources, including qualification of product's/ service's technical parameters

Name	Source	Description
Resource control (Control/Command Data)	OneNet (extended scope)	Sending operational commands or control signals to assets and flexibility resources
System service activation	OneNet	Instructions or requests to activate system services
(Flexibility) Market participation	OneNet	Exchange of data for market interactions
Status/Alert Data	New	Exchange of real-time or periodic status updates, alerts, alarms, health status, fault notifications, and maintenance alerts
Other	New	Reserved for data exchanges not clearly fitting into the defined categories

Table 3 - Number of information exchange per Category

Category Name	Count
Simulation results	9
Grid models (Asset/Network Topology Data)	8
Constraint/Limit Data	12
Resource control (Control/Command Data)	10
Forecasts	29
(Flexibility) Market participation	41
Measurements & Monitoring	38
Status/Alert Data	12
Reports & invoices (Analysis/Result Data)	8
System service activation	3
Resource (pre-) qualification	4
Other	20

The pilots use a variety of data formats and standards. Where formats were specified, these included JSON and XML, for example, for Day-Ahead and Intraday market data, as well as CIM RDF/XML for grid models compliant with CGMES profiles.

The use of the SGAM Information Layers and a project-wide questionnaire also identified a broad range of communication protocols and domain-specific models. These include IEEE C37.118 for PMU data, Modbus, EN 60870-5-102/104, and IEC 62056 (DLMS/COSEM). Other examples include IEC 61970 (CGMES), IEC 61968-9, and IEC 62541, as well as specific models developed for TSOs, DSOs, Market Operators, and Aggregators/DER Operators.

The questionnaire further identified renewable generation data for wind and photovoltaic assets accessed through HTTPS APIs in JSON format, and network and simulation models based on CIM and IIDM. IIDM is used in the PowSyBl framework and in simulation environments such as Dynawo and OpenModelica. CIM is used as input for the open-source simulation tool DPSim.

This diversity is not only a matter of different file formats or communication protocols. The pilots also use different data models, terminology, identifiers, attributes, and definitions for similar entities and information. For example, two systems may represent the same type of asset using different names or structures, even when both use JSON. Similarly, different formats can represent semantically equivalent information.

This heterogeneity creates a key challenge for semantic interoperability. Converting data between formats is not sufficient when the meaning, structure, or terminology differs between systems. This therefore requires mechanisms such as semantic models, ontologies, mappings, and semantic annotations to establish relationships between heterogeneous data sources and enable their consistent interpretation across pilots and digital-twin applications.

Building on this heterogeneous landscape, the following sections examine the TwinEU approach to interoperability from architecture to implementation. The TwinEU Reference Architecture is first introduced as the framework supporting Digital Twin federation and Data Space-based exchange, followed by selected pilot results illustrating practical data-modelling solutions, interoperability achievements, and remaining semantic gaps.

3.1.1 TwinEU Key Achievement: Reference Architecture

The TwinEU Reference Architecture (RA) design is based on the following four pillars (Figure 7):

1. **Digital Twin Federation:** RA enables secure, decentralized collaboration among energy stakeholders (TSOs, DSOs, Market Operators, Aggregators) by orchestrating interoperability between their Digital Twin systems.
2. **Data Space integration:** RA implements the core principles of European Data Spaces, ensuring secure, sovereign, and policy-driven data exchange between energy stakeholders.
3. **Model Sharing and Reusability:** TwinEU RA facilitates the reuse and exchange of Digital Twin models across domains and applications through standardized interfaces.
4. **Semantic Interoperability**: RA ensures semantic alignment of exchanged data by adopting common vocabularies, ontologies, and data models.

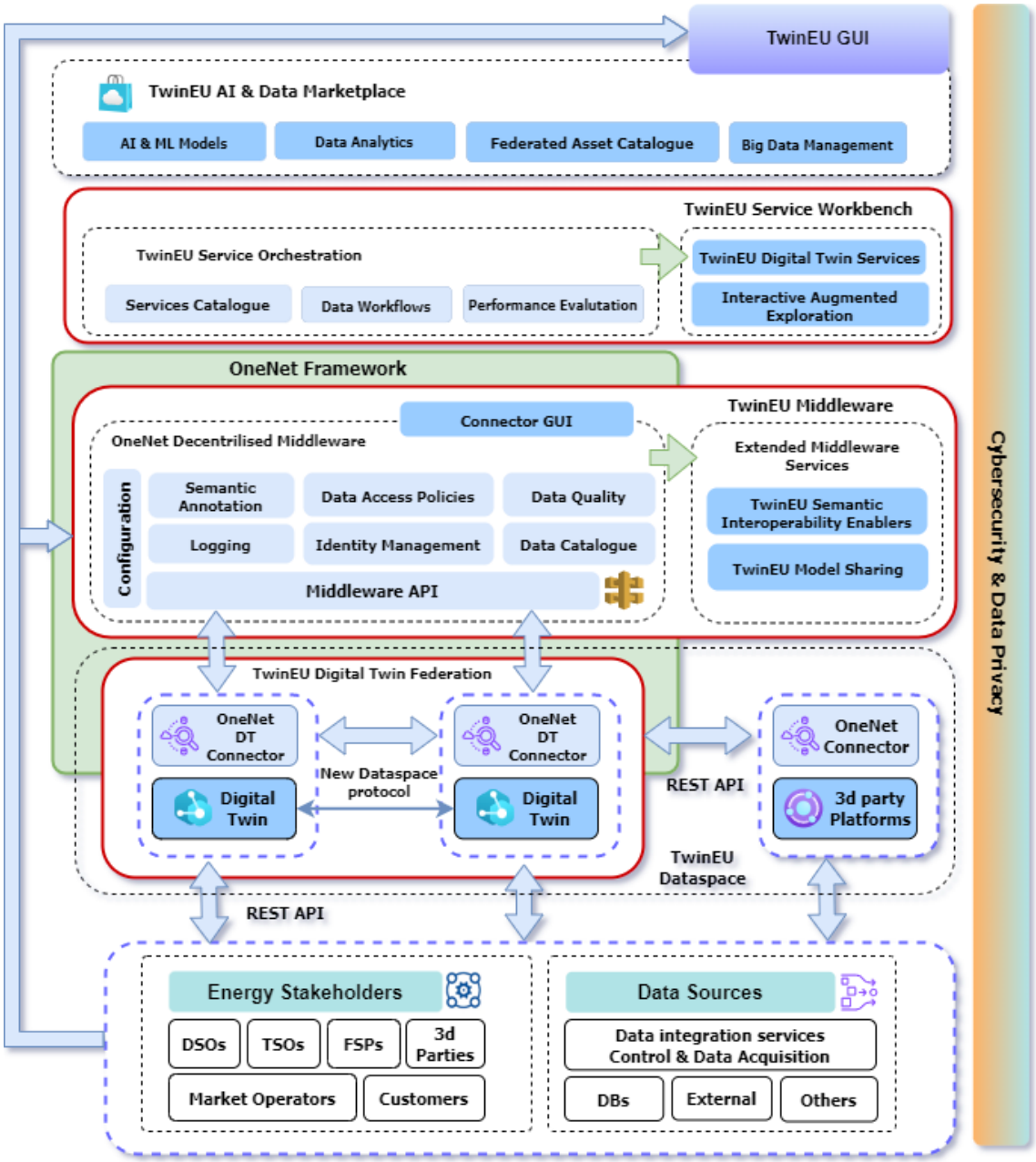

Figure 7 - TwinEU Reference Architecture

3.1.2 TwinEU Achievement: Digital Twin & Data Space integration

The Digital twin is a technology that requires intensive data exchange between both homogeneous and heterogeneous data sources. Additionally, the TwinEU federated digital twin concept requires the constant data exchange (consumption and provision) between TwinEU members aligned with necessary dataspace contract negotiation to construct the required universal and federated Digital Twin. Hence, a concept of a standard technological enabler that provides distributed data exchange and integration is required. This role is perfectly performed by the Data Space concept, which is a concept of distributed data integration creating interconnected ecosystems. The data space concept contains various structural, administrative and functional components that all operate together to coordinate or process the data exchange between the data

space participants, as described above in this deliverable. The core functional component of the IDS data space is the connector that facilitates peer-to-peer data exchange between Digital Twin, data, and service owners. Data Space Connectors in TwinEU serve every Digital Twin owner, enabling the exchange of Digital Twin models or the data analytics that emerge from these models, among the Digital Twin owners. In that way Data Space connectors facilitate the federated Digital Twin concept that is introduced in TwinEU. Additionally, the Data Space connectors enable the exchange of the huge amount of data that is generated, shared and processed in the TwinEU Digital Twin ecosystem with high heterogeneity and complex usage and access policies. More specifically the Data Space concept offers its functionality and attributes to serve the following scenarios:

- **Digital Twin Data Handling:** Focuses on facilitating information exchange and interaction among diverse stakeholders, each managing either a different version of the same digital twin or entirely separate digital twins.
- **Digital Twin Analytics:** Includes functions that provide data analytics services within the data space.
- **Digital Twin Manipulation:** Encompasses functionalities that allow users to interact directly with the digital twin. Through simulation and visualization, users can gain real-time insights, modify the digital twin, observe the effects of those changes, and consequently influence the corresponding physical assets.

The integration of the Digital Twin concept within the Data Space standard in the TwinEU RA includes the following processes:

1. The registry, which is responsible for the registration and the discovery of digital twin components based on feature information and metadata. The Data Space is very user-friendly and flexible regarding the registration of a new component, updating a registered component, and removing the registered component of the digital twin. Additionally, there is the capability of constructing a Catalog that facilitates the discovery of the registered component or Digital Twin based on its metadata.
2. The federation attribute is a functional requirement for the TwinEU also. The Data Space concept supports federated architecture since it is based on distributed Data Space Connectors. In that way Digital Twins construct a federated system where individual Digital Twins collaborate or contribute to shared virtual models, maintaining data privacy and security, ensuring autonomy for each digital twin and respecting the sovereignty and control of data from different stakeholders.
3. The translation process involves facilitating the syntactic and semantic transformation of data inside a digital twin data space across different domains. The Data Space concept is semantic agnostic and supports a wide variety of data formats and units.
4. The brokering function plays a critical role in ensuring seamless digital twin operations by identifying and authenticating digital twins, facilitating the transmission and reception of information, and handling data filtering, real-time

delivery, and reliable data transfer. The Data Space offers these components that can deliver the brokering operation.

5. Finally, synchronizing multiple interactions between digital twins and physical entities is essential for preserving consistency and coherence within the digital twin ecosystem. Additionally, Digital Twins should synchronize and update following real-world assets and devices. In the same way Data spaces should follow and record these changes of attributes or metadata.

3.1.3 TwinEU pilot results

This paragraph describes results from TwinEU pilots, together with identified gaps and recommendations related to semantic modelling and interoperability.

3.1.3.1 Slovenian pilot

Within the Slovenian pilot, a CGMES-compliant equivalent distribution model, including aggregated DERs and load representations, was developed and automatically integrated into the Slovenian transmission system model for dynamic security assessment studies. The approach used to extend transmission network model with distribution equivalent is based on incremental updates and difference models, as defined in standard IEC 61970-552. Interoperability between CGMES 3.0 and DIgSILENT PowerFactory [32] was successfully validated, enabling automated data importing through EQ and DY profiles. The work demonstrated the feasibility of developing standardized dynamic distribution equivalents and integrating them into transmission-level analyses, while highlighting current limitations of CGMES in representing inverter-based photovoltaic (PV) dynamics. The resulting methodology, illustrated in Figure 8, improves interoperability, reduces manual model engineering effort, and supports scalable digital twin applications for real-time power system operation.

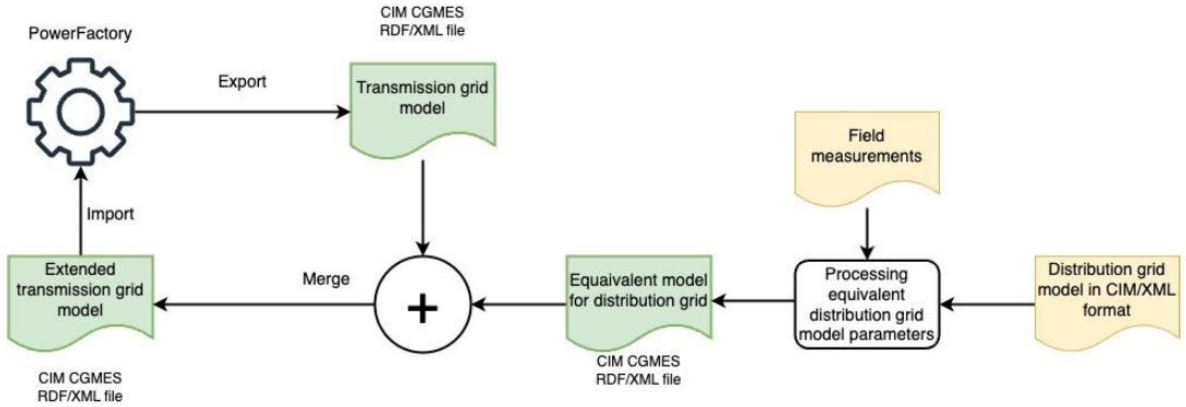

Figure 8 – The process of automatic extending transmission network model with distribution equivalent

3.1.3.1.1 Identified gaps

The pilot exploited the CGMES Dynamics package to represent the dynamic behaviour of rotating machines, such as synchronous and asynchronous generators, as well as the load dynamics. While the CGMES EQ profile provides a static representation of power

system equipment and network topology, dynamic characteristics are captured separately in the CGMES DY profile.

For photovoltaic generation, the CGMES PowerElectronics package supports the static modelling of PV systems through the PhotovoltaicUnit class, representing the generation unit, and the PowerElectronicsConnection class, representing its connection to the electrical network through the inverter interface. However, inverter dynamic behaviour must be modelled through the CGMES Dynamics package, which currently lacks native support for inverter-based dynamic models specific to PV generation. Consequently, PV units were represented in the EQ profile, whereas detailed inverter dynamics were implemented directly within the PowerFactory environment.

Although the generic DynamicsFunctionBlock class could, in principle, be used to associate dynamic behaviour with PV units, such an approach would require non-standard CIM extensions. This would reduce interoperability and limit the automated model exchange between tools. As a result, the current CGMES framework does not yet provide a fully standardized mechanism for the exchange of detailed inverter-based PV dynamic models, limiting its applicability for advanced dynamic studies involving converter-interfaced generation.

3.1.3.2 German pilot

The German pilot investigated the integration of small-scale distributed flexibility resources (e.g., PV systems, batteries, electric vehicles, and heat pumps) into future redispatch processes through improved coordination among TSOs, DSOs, and aggregators. To support interoperable data exchange, the pilot evaluated the TwinEU Connector within the TwinEU Data Space, exploiting semantic metadata and harmonized vocabularies to enable a common understanding of exchanged information. In addition, a prototype [33] was developed to map wind turbine data from the German Marktstammdatenregister (MaStR)[8] to IEC CIM concepts using the open-source tools LinkML [34] and linkml-map [35]. Extending the mapping to other asset types such as PV or biomass is identified as future work. This work demonstrated how external energy datasets can be semantically mapped to CIM to support interoperability and digital twin applications. However, the current outputs are provided in CSV format [36] and do not yet constitute CIM-compliant RDF/XML exchanges, highlighting the need for future work on automated generation of standard CIM representations.

3.1.3.2.1 Identified gaps

A major limitation identified is that semantic mappings are still largely defined manually. Data providers are often responsible for specifying metadata, schemas, and semantic descriptions, resulting in significant implementation effort, limited scalability, and an increased risk of inconsistencies across systems. Furthermore, current solutions provide only limited support for the automated mapping of data to ontologies and semantic models.

[8] MaStR is the official German registry of energy assets and contains records for approximately 40,000 wind turbines, together with a large number of other generation units [88].

The pilot also highlighted substantial heterogeneity in the data models, terminologies, and information structures adopted by TSOs, DSOs, aggregators, and other stakeholders. While IEC CIM provides a strong base for interoperability, broader adoption of common semantic standards is required to reduce fragmentation and facilitate cross-organizational integration. Consequently, future work suggestions include developing automated ontology-alignment mechanisms and promoting common semantic governance practices to improve interoperability and reduce data model fragmentation.

3.1.3.3 Italian pilot

Within the Italian pilot, Building Information Modelling (BIM) methodology was adopted to support the design validation of transmission and distribution substations and related infrastructure, described using the data model Industry Foundation Classes (IFC)[9]. To improve the quality, consistency, and interoperability of project deliverables, the pilot developed an automated validation framework based on three complementary layers: a Data Dictionary, a Rules Engine, and a Validation Tool (Figure 9). The Data Dictionary provides a common definition of asset classes and attributes, based on OpenBIM principles and the buildingSMART Data Dictionary (bSDD)[10]. The Rules Engine formalizes technical and regulatory requirements as reusable machine-readable rules, which can be expressed using interoperable standards such as Industry Delivery Specification (IDS)[11]. The Validation Tool automatically checks BIM models against these rules, which can cover different aspects, such as property check, model completeness and relationships between elements, in order to identify non-conformities and supporting iterative feedback workflows. Overall, the pilot demonstrates that combining standardized open models, machine-readable requirements, and automated validation can improve data quality, promote interoperability, and provide a scalable foundation for future BIM-based Digital Twins in the energy sector.

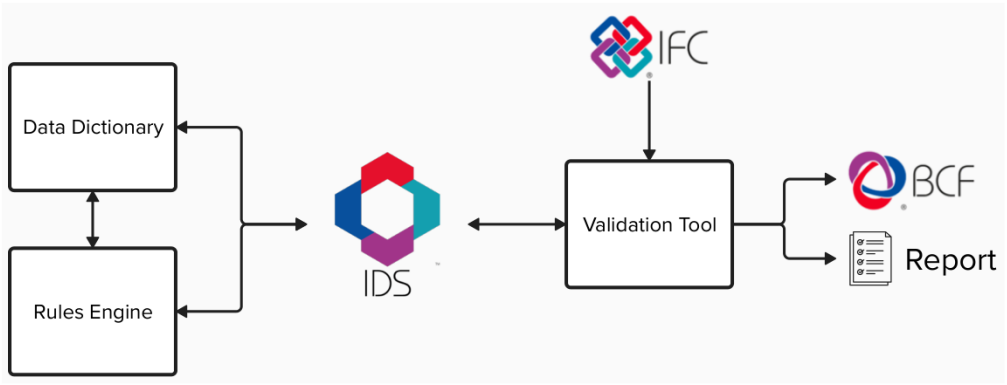

Figure 9- Building blocks of the Validation Tool

[9] IFC are a set of standardized, digital descriptions of the built asset industry, published as ISO 16739 [89].
[10] bSDD is a collection of interconnected data dictionaries with definitions of terms to describe the built environment [90].
[11] IDS is a buildingSMART standard for defining information requirements in computer interpretable form. It allows for automatic compliance checking of IFC models, which increases quality control and fidelity of data [91].

From information requirements to reusable data assets

The Italian pilot demonstrated that semantic interoperability cannot be achieved by adopting an open exchange format alone. Interoperability requires a continuous and traceable chain connecting use-case information requirements, the project data dictionary, IFC entities and property sets, machine-readable validation rules and the data assets published through the TwinEU Data Space. In this chain, the data model acts as the common reference against which information is authored, validated, exchanged and reused.

The pilot therefore highlighted the need to maintain explicit links between each information requirement, its corresponding IFC representation, the applicable validation rule and the semantic description used for discovery and reuse. This traceability is essential to ensure that a formally valid file also conveys information with the expected meaning, quality and applicability.

A relevant outcome of the Italian pilot is the definition and testing of a reusable asset data model for HV/MV substations. The model connects asset classifications, properties and project information requirements with their IFC-based representation and the corresponding automated validation rules. This approach allows the information structure to be reused across different projects and progressively extended to address additional asset types and lifecycle requirements.

The pilot also highlighted that the value of a BIM model does not derive only from its graphical representation, but increasingly from the consistency, accessibility and reusability of the structured asset data it contains. The data model should therefore be considered an autonomous and governed project result, which can support validation, database ingestion, information retrieval and integration with other Digital Twin components.

Beyond model validation, the Italian pilot also demonstrated the integration of BIM-derived data assets within the TwinEU federated Digital Twin ecosystem through the TwinEU Data Space infrastructure. Standardized representations of asset information were published and exchanged through the TwinEU Connector, enabling BIM-related information to become discoverable and reusable by other participants within the federation. In particular, the Data Space acted as an entry point for discovering real-time data to be integrated into external applications such as TwinEU XR Framework.

This approach demonstrated how Data Space technologies can support the controlled sharing of engineering and asset information while preserving data sovereignty and enabling interoperability across organizational boundaries. The experience confirmed that Data Spaces can act as a practical interoperability layer between engineering data sources and federated Digital Twin environments.

Different levels of data model conformity

The TwinEU experience confirmed that syntactic, informational and semantic conformity should be assessed separately. Syntactic conformity verifies whether a dataset

complies with the expected exchange format and schema. Informational conformity assesses whether the required classes, properties, relationships and values are present and correctly structured. Semantic conformity verifies whether the meaning of the exchanged information is consistently understood across systems and can be linked to governed vocabularies and reference models. A dataset may therefore be technically valid while still lacking mandatory information or using concepts that cannot be consistently interpreted outside the originating system. Automated validation should combine schema validation, information requirement checking and semantic consistency controls.

3.1.3.3.1 Identified gaps

The analysis identified two main gaps limiting the adoption of BIM in the energy sector. First, a modelling gap exists because IFC does not adequately represent electrical components, requiring custom extensions that reduce interoperability across utilities and systems. Current initiatives, such as the collaboration between CEI and IBIMI [37]have started to address this limitation by extending the IFC electrical domain, but organizational inertia and the necessary investments in training, platforms, and data governance slow progress.

A prerequisite for addressing this interoperability gap is the consistent identification of assets across domain models. The same physical or logical asset may be represented differently in BIM, GIS, CIM, operational systems, technical documents and Data Space catalogues. Cross-domain interoperability therefore requires persistent identifiers and governed cross-reference mechanisms that allow these different representations to be linked without forcing all participating systems to adopt the same internal identifier.

Second, an interoperability gap exists between BIM, GIS (Geographical Information System), and operational models such as IEC CIM, which limits the creation of a coherent asset lifecycle view from design to operation. In this context, the EN 17632 series provide a relevant reference for applying Semantic Web and Linked Data principles in the built environment. Rather than replacing existing domain-specific information models, it supports an additional interoperability layer for linking heterogeneous datasets and making information more findable, accessible, interoperable and reusable. This gap can be addressed through semantic technologies, particularly by representing IFC models as RDF knowledge graphs using IfcOWL [38] and linking them to CIM and GIS data. Such ontology-based integration enables semantic interoperability, lifecycle data management, reasoning, SPARQL querying, and data quality validation through SHACL. Overall, while current BIM solutions mainly support Physical Digital Twins, achieving a true Functional Digital Twin requires richer semantic models and tighter integration between physical, electrical, geospatial, and operational domains.

3.1.3.4 Iberian pilot

The Iberian pilot demonstrated that the TwinEU Data Space can provide the operational backbone for federating independently developed Digital Twins across transmission, distribution, market and service-provider environments. The pilot covered

heterogeneous applications including probabilistic cross-border capacity assessment, flexibility prequalification, hosting-capacity calculation, maintenance planning, local flexibility markets and TSO–DSO information exchange. These applications rely on different network models, time resolutions, simulation tools and data sources, ranging from SCADA and smart-meter measurements to grid models, forecasts, asset-availability information and simulation results.

In the probabilistic cross-border capacity use case, reduced transmission models, planned outages, operational forecasts, uncertainty information and transfer capacity datasets were exchanged between independently operated environments through the TwinEU connector infrastructure, covering dataset publication, creation of the data service, contract negotiation, transfer initiation and retrieval by the consumer. All planned exchanges in the validation exercise were successfully completed. The experience confirms that Data Space connectors can support recurrent, sovereign and auditable data exchange between organisations and provide the technical basis for coordinated Digital Twin workflows.

On the distribution level, hosting-capacity results calculated by the local Digital Twin were aggregated by substation and transmitted through the Data Space to a pan-European hosting-capacity map. This shows how locally calculated results can become reusable federation assets without transferring the complete distribution-network model or exposing detailed operational data.

Sharing full grid models is sensitive and not a viable possibility in the pilot. However, several workflows can operate sharing final results such as forecasts, hosting-capacity values or aggregated flexibility volumes. These reduced representations must include sufficient semantic context to avoid misinterpretation.

3.1.3.4.1 Identified gaps

Current interfaces demonstrate technical connectivity and sovereign exchange, but semantic descriptions, mappings and validation rules are not yet consistently managed as first-class Data Space assets. This limits automated federation and creates a risk that every new Digital Twin pair must repeat schema interpretation and transformation work. Additionally, grid assets, substations, market participants, flexibility resources and model nodes may be referenced differently in operational systems, simulation tools and Data Space catalogues. Without governed identifiers and cross-reference mechanisms, it is difficult to establish that two exchanged representations refer to the same physical or logical entity.

Finally, end-to-end semantic conformity is not yet systematically verified. Conformance testing should distinguish syntactic validity, completeness of required information and semantic consistency, and it should be integrated into Data Space publication and consumption workflows.

The Iberian pilot has validated the Data Space as a necessary enabler of federated Digital Twins, requiring integrated conformance testing with ontological validation for semantic interoperability.

3.2 ORION Findings

ORION (Novel Digital Components for International Renewable Energy Value Chains, Horizon Europe, Grant Agreement No. 101158432) runs from September 2024 to August 2027 and is coordinated by SINTEF [28]. The project develops a modular toolbox of digital components and validates it in use cases in Norway and Cape Verde, Iberia, Slovenia, Brazil and Canada [39] , covering port energy systems, hybrid wind and solar parks, wave energy, large-scale wind integration and distributed energy resources. Compared with TwinEU, ORION puts less emphasis on cross-organisational Data Space exchange and more on integrating heterogeneous data and models within a shared toolbox. Its findings are therefore complementary on data-to-model mapping, cross-representation linking and model reuse.

The ORION project addresses interoperability through the development of a modular toolbox that connects heterogeneous energy data sources, analytical and simulation services, Digital Twin applications, and user-facing interfaces. Rather than requiring all data, models, and computational processes to be migrated into a single monolithic environment, the ORION architecture supports both centralised and distributed deployment and relies on common data-management mechanisms and defined interfaces to coordinate independently developed services (Figure 10).

A central interoperability challenge identified in ORION is the structural and semantic heterogeneity of energy-related data and models. Data originate from different use cases and technical domains and may use different file structures, naming conventions, schemas, terminology, spatial representations, and modelling approaches. Consequently, technical connectivity alone does not ensure that information produced by one component can be correctly interpreted and reused by another.

To address this challenge, ORION develops a dedicated Data and Models Interoperability Service. The service transforms heterogeneous tabular datasets into semantically annotated and machine-readable representations and combines ontology-based semantic annotation, knowledge graph generation, time-series data management, and knowledge-graph-enhanced question answering.

The current approach links source-data structures to formal semantic concepts. It identifies the overall topic of a dataset, the semantic type represented by individual columns, and the properties connecting the corresponding concepts. Confirmed mappings are represented through RDF triples and used to construct a knowledge graph representing datasets, assets, measurements, locations, and their semantic relationships.

ORION therefore treats semantic interoperability as an intermediate layer between heterogeneous source data and higher-level Digital Twin applications. Source information can remain in representations that are suitable for the corresponding application, while semantic relationships, identifiers, and mappings provide a mechanism for interpretation and reuse across services.

At toolbox level, this semantic layer is complemented by shared data management, analytical and simulation services, integration APIs, and the Graphical Digital Twin. The current ORION implementation should nevertheless be distinguished from the target architecture: several services still operate in local partner environments, and the Graphical Digital Twin remains separately deployed. Its initial integration with the ORION Platform is planned primarily through GeoJSON-based exchange of assets, locations, and processed results.

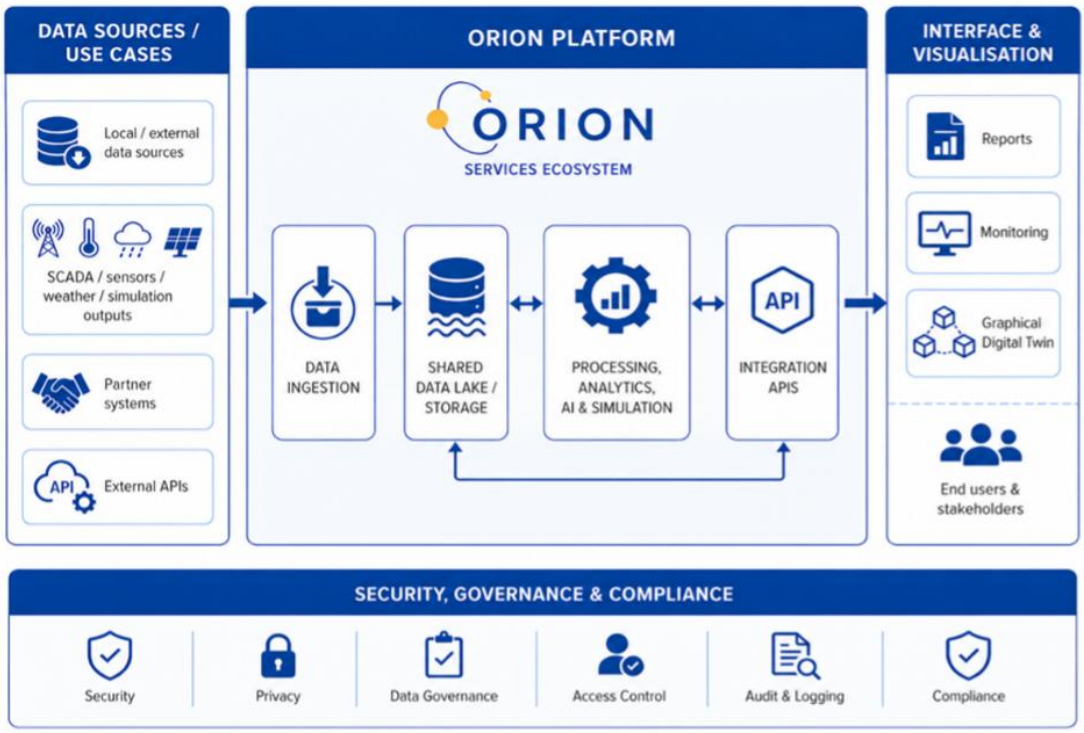

Figure 10 - ORION platform architecture

3.2.1 Key achievements

Ontology-guided semantic annotation and knowledge graph construction

A major achievement in ORION is the implementation of a semi-automatic semantic annotation workflow for heterogeneous energy datasets. The implemented process includes Topic Annotation, Column-Type Annotation, and Column-Property Annotation. Candidate mappings are generated automatically but remain subject to user validation before knowledge graph construction, allowing automation to reduce manual effort without automatically accepting uncertain semantic correspondences.

After validation, semantic information is represented through RDF triples. Neo4j is used to manage semantic entities and relationships, while associated time-series measurements are stored separately in MySQL and connected to the graph through shared identifiers. This separation avoids storing large volumes of numerical time-series values directly in the knowledge graph while preserving the semantic links required to discover and retrieve them.

Linking established domain standards instead of replacing them

ORION investigates interoperability between electrical-system representations based on CIM and physical asset representations based on BIM/IFC. The approach does not attempt to transform the complete CIM model into IFC or vice versa. Instead, semantic links are created between corresponding concepts so that electrical, operational, and physical asset information can be jointly discovered and accessed.

The current mapping remains preliminary and covers selected electrical equipment categories, mainly at class level, with selected property-level correspondences. Full geometric IFC processing and complete bidirectional CIM-IFC conversion are not part of the current implementation. This experience nevertheless demonstrates the practical value of connecting established domain standards rather than introducing another monolithic project-specific information model.

Separation of semantic and operational data representations

ORION separates general file-based data management from semantic information management. Raw and processed files can be managed within the shared data environment, while semantic entities and relationships are maintained in the knowledge graph and linked to the corresponding source and time-series information through identifiers. This provides a scalable pattern in which semantic interoperability does not require all operational information to be physically converted into RDF.

Multi-representation Digital Twin visualisation

The Graphical Digital Twin provides a common user-facing environment for assets, geographic information, operational data, and analytical results. GeoJSON is prioritised for the first connection to the ORION Platform because it provides a lightweight representation of locations and asset features, while IFC remains relevant for more detailed asset and infrastructure modelling.

A key lesson is that common visualisation is not equivalent to semantic interoperability. Displaying an electrical asset, a GeoJSON feature, an IFC object, and an operational time series within the same Digital Twin does not automatically establish that these representations describe the same real-world object. Persistent identifiers and explicit semantic relationships are still required.

Modular and distributed model integration

ORION also demonstrates an architectural approach in which analytical, simulation, prediction, optimisation, and interoperability services can remain independently deployable. The target integration architecture uses shared data management and standardised service interfaces rather than requiring each service to directly depend on the internal implementation of other services.

Model sharing and reusability

The ORION experience indicates that modular implementation facilitates model reuse, but does not guarantee it. Models developed for individual pilots frequently rely on use-

case-specific input structures, assumptions, terminology, spatial resolutions, and temporal characteristics.

For a model to be transferred from one Digital Twin or use case to another, its interface needs to be described independently from its internal implementation. In practice, interoperable model reuse therefore requires machine-readable descriptions of the expected inputs and outputs together with their semantic meaning, units, identifiers, temporal characteristics, spatial context, and relevant assumptions.

This finding extends semantic interoperability beyond datasets. Future Digital Twin ecosystems should consider semantic descriptions of computational models and service interfaces as first-class interoperability assets.

Semantic interoperability findings

The implementation experience in ORION shows that semantic interoperability can be achieved incrementally rather than through the immediate harmonisation of all underlying information models.

CIM, IFC, GeoJSON, time-series databases, simulation models, and use-case-specific schemas describe different aspects of an energy system and have different technical purposes. A practical interoperability strategy is therefore to retain these specialised representations while introducing explicit mappings, shared identifiers, and semantic metadata where cross-domain information needs to be exchanged.

ORION consequently suggests that controlled partial mappings are often more practical than complete ontology harmonisation. Mapping the concepts and properties that are relevant for a specific cross-domain workflow can already provide substantial interoperability benefits while reducing implementation and maintenance complexity.

The project also confirms the importance of reusing established standards. CIM can provide the semantic basis for electrical assets and grid-related information, IFC for detailed physical asset representations, and GeoJSON for lightweight geospatial exchange. Semantic technologies can then provide the links between these representations instead of replacing them with a single new model.

Limitations and remaining gaps

Several limitations remain in the current ORION implementation. The semantic annotation workflow currently focuses mainly on CSV and Excel source data, and meaningful column headers remain important for successful annotation. Additional metadata can improve the mapping process, but complete automatic interpretation of arbitrary data sources is not yet available.

The CIM-IFC mapping covers only selected equipment classes and remains preliminary. IFC import, complete geometry processing, and bidirectional CIM-IFC conversion have not yet been implemented.

The Data and Models Interoperability Service has been implemented and tested locally, but its complete deployment on the ORION Server and operational connection with the Graphical Digital Twin remain part of the next integration phase.

More generally, the current ORION platform still represents an intermediate integration stage. The shared infrastructure and data-management environment are available, while a common execution and orchestration workflow across all analytical, simulation, and interoperability services is still being developed.

These gaps highlight the need for future work on scalable semantic mappings, common identifiers, machine-readable model interfaces, richer metadata, additional format support, and end-to-end validation of semantic relationships across operational ORION use cases.

3.2.2 ORION use cases

3.2.2.1 Norway

The Norwegian use case focuses on the Ålesund port and demonstrates the integration of heterogeneous datasets required for energy-system planning and decision support. The analysed information includes electricity demand, market information, renewable energy resources, infrastructure-development assumptions, and other data required for the assessment of port electrification and renewable-energy integration. ORION deliverable 3.3 reports that the initial study uses hourly data for the year 2024.

From a semantic-interoperability perspective, this use case illustrates that decision-support models depend on information originating from heterogeneous sources that use different structures and terminology. Reuse of such data across models therefore requires explicit descriptions of quantities, units, locations, time resolution, energy sources, and the entities to which the measurements refer.

3.2.2.2 Cape Verde

The Cape Verde use case extends the port-oriented decision-support developments to Mindelo. D3.3 reports that current activities build on the work performed for Ålesund and focus primarily on integrating data specific to the Mindelo use case.

The comparison between the two port applications provides a relevant interoperability lesson: even when the underlying analytical methodology is similar, transferring it to another location requires adaptation to locally available datasets, data structures, naming conventions, and contextual information. Semantic descriptions of the model interface and input data can help separate the reusable analytical logic from use-case-specific data preparation.

3.2.2.3 Iberia

The Iberian use case provides one of the most developed demonstrations of the interaction between operational data, technical models, analytical services, and the Graphical Digital Twin. The reference site is the Villacastín photovoltaic power plant, including the Villacastín and Cruz de Hierro sections. Current technical development includes plant-specific electrical modelling, SCADA-data processing, preliminary fault

scenario generation, fault-diagnosis algorithms, and user-oriented access to technical information.

The use case is also the basis of the first Graphical Digital Twin demonstration in D3.3. It combines asset locations, photovoltaic-system information, time-series information, graphical representations, and three-dimensional objects in an interactive environment.

From an interoperability perspective, this use case demonstrates the importance of linking different representations of the same physical system. Electrical models, SCADA measurements, spatial objects, Digital Twin assets, technical documentation, and analytical results require consistent asset identifiers and semantic relationships if they are to be interpreted jointly rather than merely displayed within the same interface.

3.2.2.4 Slovenia

The Slovenian use case focuses on structural health monitoring of the SIGMA Energy Wave Energy Converter. Accelerometer measurements are used to monitor structural behaviour of the tension-leg platform and power-take-off components, while numerical COMSOL models support analysis and scaling of the methodology. D3.3 specifies that the structural-health-monitoring development is explicitly connected to the Slovenian use case.

This use case broadens the interoperability challenge beyond conventional electrical-network datasets. Sensor measurements, structural components, numerical models, derived modal information, and Digital Twin visualisation need to be connected despite originating from different engineering domains and modelling environments.

It therefore demonstrates the relevance of semantic interoperability for integrating physical asset descriptions, sensor observations, simulation models, and derived condition-monitoring information within a common Digital Twin context.

3.2.2.5 Brazil

The Brazilian use case demonstrates distributed Digital Twin and co-simulation concepts for renewable-rich power systems. The framework combines real-time simulation, hardware-in-the-loop capabilities, renewable-generation models, and Graphical Digital Twin visualisation while allowing participating organisations to retain control over their detailed internal models.

A particularly relevant interoperability aspect is that model federation does not necessarily require the exchange of the complete internal model. Independent simulation environments can remain under the control of their owners while exchanging the information required for coordinated simulation and analysis.

For semantic interoperability, this implies that well-defined model interfaces and a shared understanding of exchanged variables, identifiers, parameters, and simulation context can be more important than forcing all participants to adopt an identical internal modelling representation.

3.3 Hedge-IoT Findings

Digitalizing the European energy system means connecting behind-the-meter assets, distribution grids and transmission operations that were designed independently. The resulting heterogeneity affects devices, protocols, data models and governance rules. Connectivity alone does not resolve it, because the same term can carry different meanings in different systems. This is why semantic interoperability is treated as a prerequisite for cross-platform integration and not as an optional add-on.

HEDGE-IoT (Horizon Europe, Grant Agreement No. 101136216) addresses this problem through an interoperable IoT-enabled edge-to-cloud framework [40]. The framework is validated in six national pilots (Finnish, Greek, Italian, Dutch, Portuguese and Slovenian). The project combines four pillars: a technology facilitator, interoperability, standardization and an ecosystem enabler.

3.3.1 Hedge-IoT Reference Architecture

Hedge-IoT RA [41] was implemented based on a convergence-driven design method that integrates four input streams: stakeholder requirements, landscape analysis, technical implementation feedback and pilot validation. The requirements baseline comprises 14 Business Use Cases, 39 System Use Cases and three Transversal Use Cases (TUCs). The TUCs cover data interoperability through the HEDGE-IoT Dataspace, computational interoperability through cloud-edge orchestration, and functional interoperability through the App Store. Methodologically, the architecture description follows ISO/IEC/IEEE 42010:2022 to link concerns to viewpoints. It is presented through the 4+1 view model (logical, development, process, physical and scenarios). It is mapped to the Smart Grid Architecture Model (SGAM) and to the BRIDGE Data Exchange Reference Architecture (DERA), and it follows IDSA, Gaia-X, SAREF and IEC CIM principles (Figure 11). The stated design principles are modularity, interoperability, data sovereignty, decentralization and regulatory awareness.

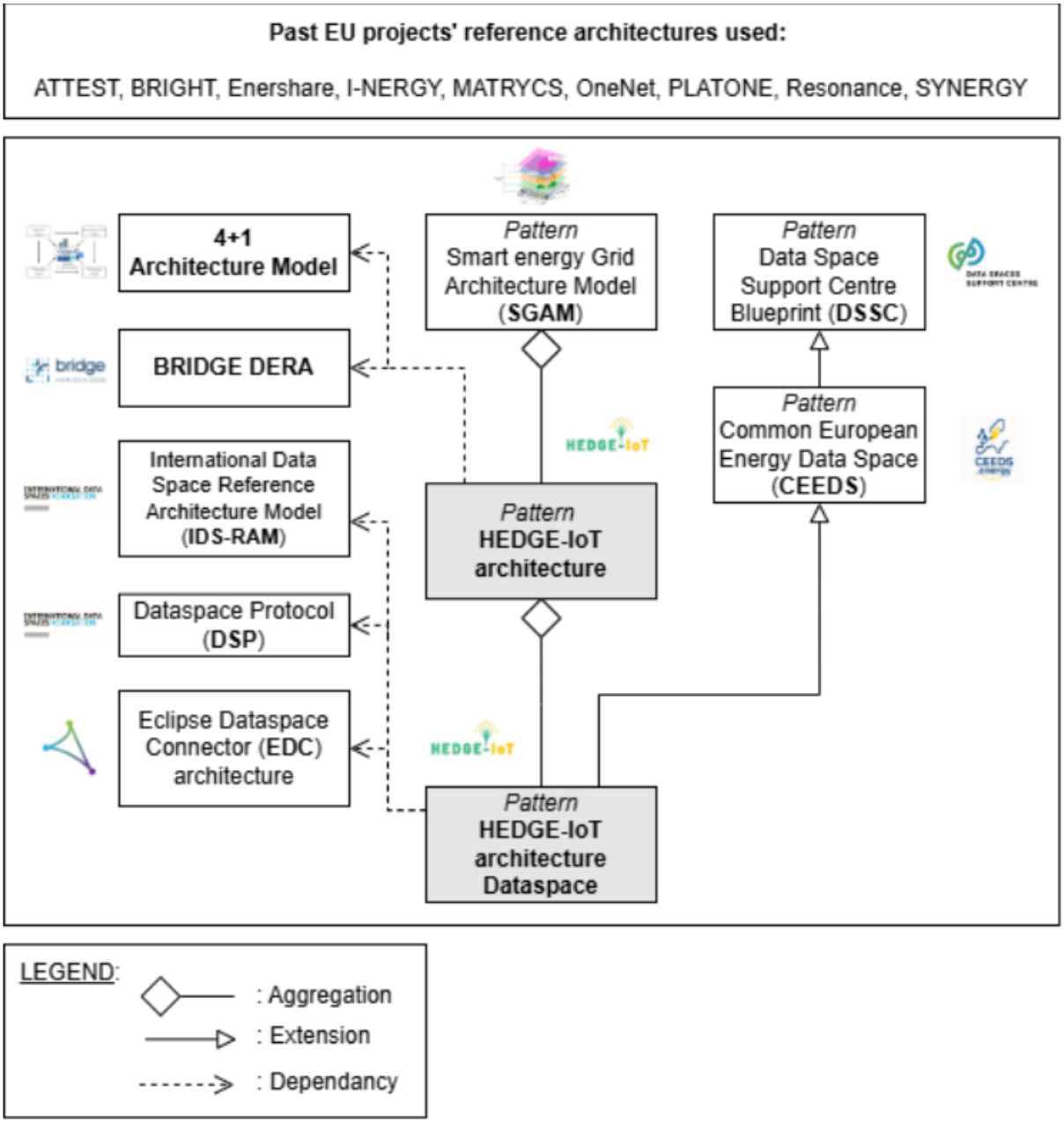

Figure 11 - Hedge-IoT Reference Architecture Pattern

The final architecture is organized into four layers (Figure 12):

1. **Physical Layer.** Pilot infrastructures, IoT devices, edge nodes, local platforms (SCADA, EMS, BEMS), digital twins and data sources. It is also where control outputs return to the field. A generic IoT-edge node model defines a mandatory baseline: data acquisition, standardized data exposure with semantic annotations, secure communication, interoperability integration, basic local processing and remote management. Pilot-specific configurations are layered on top of this baseline.

2. **Dataspace Layer.** The operational core, with three groupings. The first is the dataspace core, with Eclipse Dataspace Components (EDC) connectors, a federated catalogue, identity management, policies and contract negotiation, based on the

Dataspace Protocol. The second is the App Store with the Open Service Catalogue, for publishing and reusing services. The third is the Orchestrator, for workload placement across edge, fog and cloud. The dataspace layer can be considered the common link between data space architectures between different dataspaces and eventually will lead to interoperable dataspaces with different technological enablers.

3. **Semantic Interoperability Layer.** A dedicated layer that harmonizes models, vocabularies and service descriptions so that data and services remain portable across pilots.

4. **Application Layer.** Identity-aware access, dashboards and analytics, federated learning, fog/cloud services and adapters to proprietary operational platforms.

Read end to end, data originates in the Physical Layer. It becomes discoverable and governable in the Dataspace Layer, is semantically aligned and validated in the Semantic Layer, and is consumed in the Application Layer. A reverse path carries optimised set-points and deployed services back towards the edge.

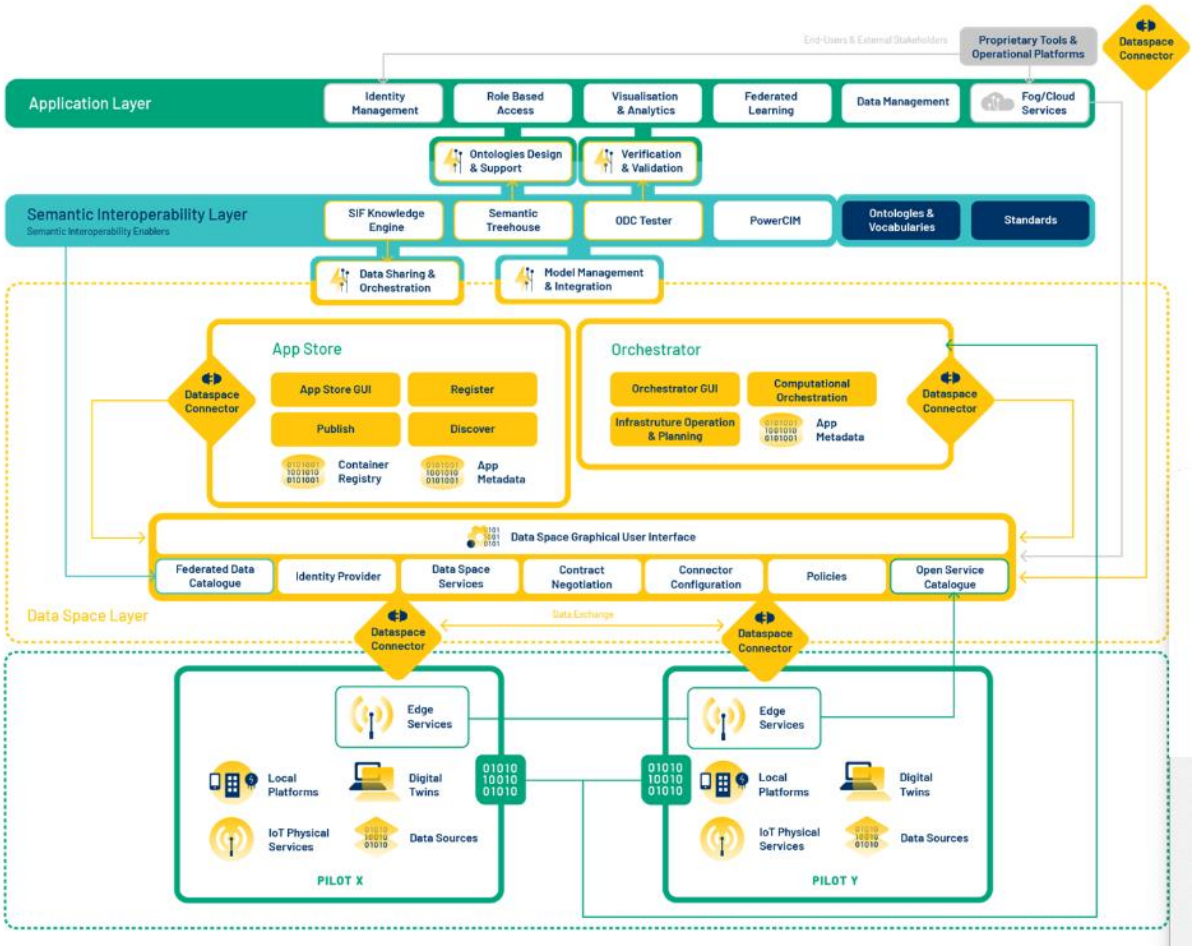

Figure 12 - Hedge-IoT Reference Architecture

Hedge-IoT RA introduces interoperability profiles for four selected interoperability points: the dataspace connector interface, the computational orchestrator interface,

the App Store interface and the DSO–aggregator flexibility market interface. Each profile follows the five-facet model of ISO/IEC 21823-1 and ISO/IEC 19941 (transport, syntactic, semantic, behavioral and policy). Two findings can be reported which can be considered for the generic semantic interoperability aspect:

- The semantic facet of the dataspace connector is not enforced by EDC itself. It depends on the data models adopted by participants, which is the architectural justification for a separate semantic layer. HEDGE-IoT uses SAREF where possible.
- The flexibility-market interface is not standardized across pilots. Semantic choices range from SAREF and IEC CIM 62325-2 to market-specific models.

3.3.2 Hedge-IoT Semantic interoperability findings

3.3.2.1 Architectural position & rationale

Hedge-IoT elevates semantics to a dedicated layer. This reflects lessons from related projects such as OneNet and Resonance, which showed that cross-platform integration needs shared semantic mediation. The layer includes the SIF Knowledge Engine, Semantic Treehouse, the ODC Tester, PowerCIM, ontologies and vocabularies, and verification and model-management functions. Its aim is that the same analytics or service logic can move between pilot contexts without losing meaning. In the SGAM and DERA mappings, the semantic layer corresponds to the Information layer. It uses SAREF and its energy extensions (SAREF4ENER, SAREF4GRID), IEC CIM, NGSI-LD, DCAT and RDF/OWL. The architecture model specifies also how semantics propagate through the dataspace. Data enters through EDC connectors under contract- and policy-based governance. It is then enriched against shared ontologies and vocabularies, informed by standards such as ETSI SAREF and IEC CIM. The Knowledge Engine transforms it into federated knowledge by reasoning and matchmaking. The ODC Tester checks semantic and behavioral compliance, and the federated catalogue exposes semantically annotated assets for reuse by the App Store and applications.

3.3.2.2 Semantic enablers

Semantic Treehouse (STH). An open-source vocabulary hub that helps data-sharing communities define, agree on and improve shared data models. It makes semantic specifications findable and supports their adoption by data owners and consumers. In HEDGE-IoT it is used to improve interoperability between pilots. Notably, the Italian pilot used it to map an existing JSON-based data structure to SAREF, which extended the semantics of deployed interfaces without changing their implementation.

Knowledge Engine / Semantic Interoperability Framework (SIF). An open-source distributed middleware that exchanges data based on its meaning. Releases during the project improved robustness in distributed settings, performance with large data volumes, developer documentation and configuration. They also added a multi-level reasoning algorithm that can be adjusted to the desired semantic interoperability level, and a feature for including domain knowledge in reasoning. Future work focuses on robustness and performance in operational settings.

PowerCIM. A platform for managing IEC CIM-based grid models. In the Slovenian pilot it acts as a central integration layer for GIS, smart metering, dynamic thermal rating (DTR) and environmental data. Static models are transferred from the GIS by IEC 61970-552 CIM/XML files, and telemetry is semantically linked to measurement points defined in the static model. DTR is computed locally on edge devices, which links semantic modelling to edge intelligence.

Ontology-Driven Constraint Tester (ODC-Tester). Led by TRIALOG, it extends semantic compliance testing towards behavioral testing, defined via ISO/IEC 21823-5 as interoperability "so that the actual result achieves the expected outcome". A review of 25 publications led to BPMN being selected as the formalism. It was preferred to Petri nets and OWL-based approaches for combining expressiveness, scalability and mapability to RDF, SHACL and SPARQL. The prototype architecture has an ontology input and a system input. A Behavioral State Manager builds the executable flow graph, and a time-management component and a Flow Runner execute and validate transitions. A compliance report is the output. Since real appliance data covered only some JRC Code of Conduct scenarios (Miele and Beko), a simulated dataset was built for the remaining one. D4.2 states that this architecture "will be validated in the project", so it remains a proof of concept.

3.3.2.3 Semantic findings

The deliverables support the following findings.

1. **Semantics must be an explicit layer.** Dataspace connectors give governed exchange but do not guarantee shared meaning, so a dedicated semantic layer is needed.
2. **Convergence on SAREF and CIM, with pragmatic bridging.** SAREF dominates in the demand-side and community pilots, and CIM in grid-operator pilots. The SAREF–CIM bridge and the PowerCIM and Knowledge Engine tools are positioned to connect the two perspectives.
3. **Semantic retrofitting is feasible.** The Italian mapping showed that semantic annotation can be added to existing JSON interfaces without re-implementing them.
4. **Semantic maturity varies across pilots.** Interoperability levels 3 to 5 are reported, and D2.4 stresses that its baseline is not evidence of uniform maturity.
5. **Plug-and-play interoperability cannot yet be assumed.** Local adapters and pilot-specific transformations remain necessary, and semantic alignment depends on the quality and stability of pilot data models.
6. **Open issues remain.** The flexibility-market interfaces are heterogeneous. The App Store is at alpha stage, with a DSP-aligned beta planned. Ontology lifecycle governance and scalability beyond the pilots have not been demonstrated.

3.4 ECLIPSE DIGITAL Findings

ECLIPSE DIGITAL demonstrates that semantic interoperability should not be treated as a standalone technical layer but as an architectural capability spanning data exchange, Digital Twins, energy services, flexibility markets and user-facing applications [42]. The project developed the Common European Reference Framework (CERF) as an interoperability framework capable of connecting heterogeneous stakeholders including Distribution System Operators (DSOs), aggregators, flexibility service providers, energy communities, consumer applications and future Energy Data Spaces through a common set of interfaces, data models and interoperability profiles.

The project adopted SGAM, DERA and Data Space concepts to organise interoperability across business, functional, information, communication and component layers. This confirms that semantic interoperability cannot be achieved solely through common ontologies or APIs. Shared semantics must be linked to governance mechanisms, discovery services, identity management, consent management and policy enforcement. Data Spaces therefore provide an important operational foundation, but semantic models remain necessary to ensure that exchanged information is interpreted consistently by all parties.

Throughout the project, IEC CIM, ESMP, IEC 61850, DLMS/COSEM, SAREF and OpenADR emerged as recurring reference models capable of supporting different interoperability needs, from power-system operation to smart-metering and demand response. The challenge is therefore not the absence of standards but the lack of systematic alignment, mapping and governance across them. ECLIPSE DIGITAL confirms that future interoperability efforts should prioritise reuse and harmonisation of existing semantic assets rather than the creation of new project-specific information models.

The project recognises that data catalogues, connectors and interoperability profiles require machine-readable descriptions of datasets, services, ownership, access conditions, provenance and quality. The work on data catalogues, DCAT-compliant metadata, semantic modelling frameworks and interoperability profiles demonstrates that semantic interoperability increasingly extends beyond data payloads and must also encompass the description of datasets, APIs, services and Digital Twin components themselves.

3.4.1 Identified gaps

While standards such as IEC CIM, SAREF, OpenADR, DLMS/COSEM and IEC 61850 provide strong foundations for specific domains, no accepted interoperability framework currently exists to consistently link consumer applications, flexibility services, smart-meter infrastructures, operational grid systems and Data Space assets. Significant effort is still required to define and maintain mappings across these models.

The project promotes SHACL-based validation and semantic interoperability profiles, but the adoption of automated semantic compliance testing remains limited. Future ecosystems require systematic validation mechanisms capable of verifying not only

syntactic correctness but also semantic consistency, policy compliance and interoperability readiness.

ECLIPSE DIGITAL shows that the main challenge is no longer achieving technical connectivity, but enabling semantic understanding, governance and reuse of data, services and digital twin assets across organizational and domain boundaries. This is highly aligned with the overarching message emerging from TwinEU and ORION that semantic interoperability is the critical enabler for federated Digital Twins in the energy domain.

3.5 Cross-Project Insights and Gap Analysis

The following table summarizes the results and gaps obtained in TwinEU, ORION, Hedge-IoT and ECLIPSE DIGITAL initiatives.

Table 4 - Results and gaps from TwinEU and related projects

Project / pilot	Semantic models / standards	Scope	Key semantic interoperability results	Semantic interoperability gap
TwinEU - Slovenian	IEC CIM/CGMES	Dynamic transmission/distribution grid models with aggregated DERs and loads	Automated TSO–DSO exchange and integration of dynamic distribution equivalents	Limited standard representation of inverter-based PV dynamics in CGMES
TwinEU - German	IEC CIM	Generation assets and associated metadata	Semantic mapping of external energy data to CIM using LinkML	Lack of automated ontology mapping and harmonized semantic governance across stakeholders
TwinEU - Italian	IFC	HV/MV substations	Reusable IFC-based asset model linked to information requirements and validation rules	Limited electrical representation in IFC and weak BIM–GIS–CIM alignment
TwinEU - Iberian	Heterogeneous domain- and use-case-specific data models	Grid planning, flexibility, forecasts and market coordination	Federated Data Space exchange without sharing complete	Semantic descriptions, mappings, identifiers and validation are not consistently

Project / pilot	Semantic models / standards	Scope	Key semantic interoperability results	Semantic interoperability gap
			internal grid models	governed across exchanges
ORION	IEC CIM, IFC, GeoJSON and use-case specific schemas	Energy assets, measurements and computational models	Semi-automatic semantic annotation, KG construction and partial CIM–IFC linking	Partial mappings, cross-representation identification and machine-readable model descriptions remain challenging
Hedge-IoT	SAREF, IEC CIM	IoT/edge, grid, flexibility and services	Explicit semantic interoperability capability with semantic mediation, retrofitting and conformance testing	Data Space connectivity does not ensure shared semantics; heterogeneous models still require adapters and mappings
ECLIPSE DIGITAL	IEC CIM, ESMP, IEC 61850, DLMS/COSEM, SAREF and OpenADR	Grid, metering, flexibility, services and DT assets	CERF (Common European Reference Framework) combines interfaces, models and interoperability profiles across the architecture	Existing standards require systematic alignment and mappings; automated semantic compliance remains limited

Despite differences in scope and implementation, the analysed projects and pilots reveal a recurring set of semantic interoperability challenges. These can be organised into eight main areas:

1. **Semantic model adoption, coverage and extension**: existing standards and semantic models, including IEC CIM/CGMES, IFC, SAREF, IEC 61850, DLMS/COSEM and OpenADR, provide complementary foundations for different domains and applications. However, their adoption remains heterogeneous, while emerging requirements are not always fully covered by existing models, sometimes requiring domain- or application-specific extensions.

2. **Semantic interoperability within Data Space architecture**: Data Space connectivity and common exchange mechanisms are necessary but not sufficient to achieve semantic interoperability. Connectors can support secure and governed data exchange, but do not by themselves ensure that exchanged information is interpreted consistently.
3. **Data-to-model mapping**: Heterogeneous source data, including legacy and application-specific structures, need to be related to shared semantic models without necessarily requiring changes to existing interfaces. Current data-to-model mappings remain heterogeneous and often require substantial manual effort.
4. **Cross-domain semantic alignment**: Digital Twin ecosystems combine information from energy, buildings, ICT, metering, geospatial, flexibility and market domains, whose models represent complementary perspectives and cannot always be directly reconciled.
5. **Persistent identification and entity linking**: the same physical or logical entity may have different representations and identifiers across CIM, IFC, GIS, operational platforms, simulation environments and Data Space catalogues.
6. **Semantic description of models and services**: Semantic interoperability increasingly extends beyond data payloads. Datasets, computational models, APIs, services and Digital Twin components also require machine-readable descriptions to support discovery, interpretation and reuse.
7. **Semantic validation and conformance testing**: Validation should complement syntactic and schema checks with mechanisms for assessing information completeness and semantic consistency against agreed models, mappings and interoperability profiles.
8. **Semantic governance and lifecycle management**: The analysed projects indicate that no single semantic model can adequately cover all physical, electrical, operational, geospatial, market and Digital Twin perspectives. A federated approach based on reusable domain models is therefore more appropriate than a monolithic semantic model. The main governance challenge is to manage the resulting semantic ecosystem over time, including ontologies, vocabularies, mappings, interoperability profiles and validation rules.

These gaps show that the transition from project-specific interoperability solutions to federated Digital Twin ecosystems requires more than individual semantic technologies. It requires a common approach combining reusable domain models, governed mappings, persistent identification, machine-readable descriptions of data, models and services, semantic validation, and lifecycle governance. These evidence-based requirements provide the foundation for the vision, priorities and roadmap presented in the following sections.

4 Vision: Semantic Interoperability for Federated Digital Twins

The transition to a digitally enabled European energy system requires more than isolated digital technologies. AI, digital twins, data spaces, cloud and edge computing, and real-time analytics can improve the efficiency, resilience and sustainability of electricity networks, but their value depends on semantic and structural interoperability across organizational, technological and geographical boundaries. The common vision for the "*Semantic Interoperability for Federated Digital Twins"* identifies this challenge and highlights two key ecosystem building blocks: federated digital twins and federated data spaces. It argues that these should be connected through a common ecosystem architecture and shared semantic layers. This effort aligns closely with EU digital and energy policies and the TwinEU project, which aims to develop a Pan-European digital twin by federating local digital twins and enabling interoperability and data/model exchange across the electricity system. Semantic interoperability is therefore not merely a technical concern but a fundamental enabler of a European energy ecosystem, allowing TSOs, DSOs, market participants, technology providers and researchers to collaborate while retaining control of their systems and data.

4.1 Semantic interoperability as the core of Federated Digital Twins

Technical interoperability alone is insufficient for a federated digital-twin ecosystem. Two systems may successfully exchange messages through APIs while still interpreting the information differently. For example, the same term may have different meanings in different organizations, measurements may use different units or time references, or an asset represented in one digital twin may have no direct semantic equivalent in another.

It is therefore important to establish shared semantic layers within an ecosystem and between ecosystems. This is one of the most significant aspects of federation because semantic interoperability determines whether exchanged information can actually be understood and reused.

For TwinEU RA [43], this requirement becomes especially important because the target is not one monolithic digital twin. Instead, the project is creating a federation of digital twins representing different parts of the European electricity system. The current TwinEU concept includes local twins belonging to different TSOs, DSOs and other electricity-system actors, with the ambition of federating them through a common platform. In 2026, TwinEU also defined pan-European scenarios in areas such as grid hosting capacity, market coupling, forecasting, flexibility and frequency support, system security and power-line monitoring. These cases illustrate why semantics matter. A forecasting model, for example, is only reusable across borders if the meaning of its inputs and outputs is understood consistently. Similarly, a grid-security model requires common interpretations of assets, topology, operational states, constraints and events. Semantic interoperability therefore becomes an enabling layer between physical infrastructure and higher-level AI and decision-support functions.

TwinEU proposes that existing standards should be extended rather than replaced. At the architecture level it refers to existing digital-twin and data-space standards, while at the interoperability level it proposes extending existing interoperability standards and harmonized standards. This approach is consistent with EU policy. The European Commission identifies interoperability specifications, semantics and data models as important supporting components of Common European Data Spaces. The Data Act also explicitly recognizes interoperability as necessary for enabling data flows within and between data spaces and for facilitating portability and switching between data-processing services. Thus, semantic interoperability should be understood as a shared European capability, not simply a feature of individual software components.

Within the TwinEU context, semantic interoperability is not considered as an objective in itself but as enabler for the implementation of Pan-European scenarios. While pilot deployments could operate with locally tailored data models and interfaces, cross-border Digital Twin collaboration requires a shared understanding of assets, measurements, models, services and operational events. The Pan-European Scenarios defined within TwinEU demonstrate that semantic interoperability requirements are crucial when information, models and decision-support capabilities need to be reused across organizational and national boundaries. In this case, semantic interoperability should be designed starting from ecosystem-level use cases and federation requirements rather than from individual system implementations.

Minimum common semantic core

Experiences from TwinEU and related projects suggest that full harmonization of all domain models is neither necessary nor immediately feasible. A more pragmatic approach is to define a minimum common semantic core containing the concepts required for the discovery, identification, linking, validation and reuse of Digital Twin data assets.

This common core should include, at minimum, persistent asset identifiers, asset type and classification, lifecycle stage, spatial location, temporal validity, property and measurement definitions, units of measure, data provenance, version, validation status, access conditions and links to related documents, models and services.

Domain-specific models such as CIM, IFC, GeoJSON and IEC 61850 can remain autonomous, provided that they expose the metadata required by the federation and implement governed mappings toward the common semantic core. This approach preserves domain specialisation while avoiding the creation of a new monolithic model.

Among the elements of this common core, persistent asset identification is particularly important, as it enables different domain-specific representations of the same asset to be connected throughout its lifecycle.

4.2 Key priorities

Five priorities emerge from the combined analysis, especially evident from TwinEU implementation [44]:

1. **Establish a common semantic foundation**

A common semantic core needs to be established covering the concepts that must be understood consistently across the European electricity ecosystem, while allowing domain-specific extensions.

2. **Develop reusable interoperability profiles**

Instead of defining interfaces separately for every use case, reusable profiles should specify the relevant data structures, semantic mappings, APIs, security requirements and interaction patterns.

3. **Integrate digital twins with the European energy data space** [45]

Digital twins and data spaces should be treated as complementary rather than independent infrastructures. This would allow digital-twin models and data-sharing mechanisms to operate within a common European trust and governance environment.

4. **Introduce AI-assisted but governed interoperability**

AI can support semantic matching, schema transformation and model adaptation, but automated interoperability should be accompanied by validation, provenance, traceability and human oversight.

5. **Create long-term governance and versioning mechanisms**

Interoperability profiles, semantic models and architecture specifications need lifecycle management. Governance should continue beyond the end of an individual research project so that the resulting ecosystem remains maintainable and extensible.

4.3 Key Principles

The future evolution of semantic interoperability for federated Digital Twins should be guided by a set of ecosystem-oriented principles.

First: Ecosystem-Driven Interoperability. Semantic interoperability should be approached from an ecosystem perspective rather than from the perspective of individual organizations or Digital Twin platforms. While Digital Twins remain independently governed and implemented, they should be able to participate in common operational scenarios through shared interoperability mechanisms. This shift is particularly important for Pan-European Scenarios, where information, models and services originating from different stakeholders need to be consistently understood and reused across organizational and national boundaries.

Second: Federation over Centralisation. Federation should be preferred over centralization. The objective is not to converge towards a single European Digital Twin or a common implementation, but to enable autonomous Digital Twins to collaborate across organizational, sectorial and national boundaries while preserving sovereignty, ownership and implementation freedom. For example, TSOs, DSOs, energy communities and market operators should remain free to adopt their own technologies and data models while still being able to participate in common operational scenarios.

In this context, Data Spaces provide the trust, governance and exchange mechanisms required to support federation at scale.

Third: Reuse and Extend Existing Standards. Existing standards and semantic assets should be reused and extended whenever possible. Rather than developing new monolithic ontologies, future interoperability frameworks should build upon established standards and domain models, complementing them with reusable interoperability profiles and governed mappings where necessary. Examples include the reuse and harmonization of standards such as IEC CIM, IEC 61850, IFC and SAREF, which already provide valuable semantic foundations for different domains. This approach enables domain specialization while maintaining ecosystem-wide interoperability.

Fourth: Governance as a Long-Term Capability. Interoperability should be supported by long-term governance mechanisms capable of managing semantic assets, mappings, interoperability profiles and architectural artefacts throughout their lifecycle. Governance should address versioning, validation, change management and stakeholder coordination, ensuring that interoperability remains sustainable as Digital Twin ecosystems evolve over time. As semantic models, standards and use cases continuously evolve, governance becomes essential to guarantee backward compatibility, controlled evolution and trust across participating ecosystems.

5 Proposed Roadmap and Stakeholder recommendations

Based on the gaps identified in "Cross-Project Insights and Gap Analysis", this section proposes a roadmap, structured into short-, mid-, and long-term actions, together with stakeholder recommendations. Short-term actions focus on establishing a baseline and inventory of existing resources and requirements; mid-term actions address the development and validation of reusable interoperability solutions; and long-term actions focus on their operationalisation and governance across Digital Twin ecosystems. The proposed roadmap and related stakeholder recommendations are summarised in Table 5.

The three horizons are indicative. The short term covers the remaining lifetime of the analysed projects (until 2027), the mid term the period 2028 to 2030, and the long term the period beyond 2030. For each identified gap, Table 5 also names the projects and pilots whose findings provide the evidence.

Table 5 – Roadmap actions and stakeholder recommendations per identified gap

Identified gap	Short-term actions	Mid-term actions	Long-term actions	Stakeholder recommendations
Semantic model adoption, coverage and extension *Evidence: TwinEU Slovenian and Italian pilots, HEDGE-IoT, ECLIPSE DIGITAL*	Assess the adoption, coverage and limitations of existing semantic models across projects and identify the concepts and metadata that require a common representation across Digital Twin ecosystems	Define a minimum common semantic core, while developing open, well-documented semantic resources, reusable reference models, and implementation guidelines	Develop and maintain supporting tools, reference implementations and governed extensions and align reusable semantic assets and interoperability specifications with relevant European and international standardisation activities	**For research projects**: adopt existing data models and ontologies in the development of innovation technology pilots, and report project-specific extensions back to the responsible standardisation committees **For industry:** participate in semantic model design and validation using operational scenarios and use cases to ensure that the ontologies are supported by real use cases **For standardisation bodies:** provide guidance on the governance of semantic models in federated digital twin in energy (e.g. ongoing proposal in IEC Syc Smart energy)

Identified gap	Short-term actions	Mid-term actions	Long-term actions	Stakeholder recommendations
Semantic interoperability within Data Space architecture *Evidence: TwinEU Iberian pilot, HEDGE-IoT, ECLIPSE DIGITAL*	Identify the semantic assets required for Data Space exchanges, including vocabularies, mappings, profiles and validation rules	Integrate semantic discovery mechanisms, such as vocabulary hubs and machine-readable semantic specifications, into Data Space workflows	Manage semantic models, mappings, validation rules and interoperability profiles as governed, discoverable and reusable first-class federation assets within Data Space ecosystems	**For industry**; promote open architectures and standardized interfaces for collaboration of different digital twins developed by different organisations **For research projects**: demonstrate how semantic assets can be published, discovered and reused through Data Space infrastructures **For standardisation bodies:** provide architecture patterns that include semantic interoperability capabilities in dataspace architecture (e.g., ISO/IEC 30152)
Data-to-model mapping *Evidence: TwinEU German pilot, ORION, HEDGE-IoT*	Create an inventory of existing data schemas, semantic models and mappings, and identify recurring mapping requirements from projects	Define reusable mapping patterns and develop semi-automatic approaches for mapping heterogeneous source data to established semantic models	Create governed mapping pipelines, supported where appropriate by AI/Generative AI, with human validation, provenance and traceability	**For research projects**: develop and openly document reusable mapping patterns, including provenance, confidence and validation mechanisms for semi-automated and AI-assisted mappings **For industry:** document the schemas and data dictionaries of existing data exports, provide anonymised or synthetic sample data in standardised formats, and reuse published mappings instead of building bilateral conversions **For standardisation bodies:** promote machine-readable specifications and reusable mapping patterns between established standards where recurrent interoperability requirements are identified (e.g. with contribution to ETSI 303760)

Identified gap	Short-term actions	Mid-term actions	Long-term actions	Stakeholder recommendations
Cross-domain semantic alignment *Evidence: TwinEU Italian pilot, ORION, HEDGE-IoT, ECLIPSE DIGITAL*	Collect existing cross-domain mappings and identify the concepts and relationships required by priority interoperability use cases, such as CIM–IFC and CIM–SAREF	Develop and validate controlled, use-case-driven partial mappings between domain models rather than pursuing complete model harmonisation	Establish governed and reusable cross-domain alignment services and mapping repositories, supported where appropriate by AI-assisted alignment	**For industry:** participate in cross-vendor and cross-domain interoperability demonstrations using realistic situations to demonstrate interoperability across independently developed heterogenous digital twins **For standardization bodies**: support reusable, governed cross-domain mapping specifications between established domain models, prioritising use-case-driven partial mappings where complete harmonisation is unnecessary **For research projects:** publish cross-domain mappings (e.g. CIM–IFC, BIM–GIS–CIM) together with their declared coverage, mapping method and validation status, so that partial mappings are reused and extended instead of re-created
Persistent identification and entity linking *Evidence: TwinEU Italian and Iberian pilots, ORION*	Analyse identifier schemes used across pilots and identify entities represented across multiple systems or domain models	Define persistent identification and cross-reference mechanisms for linking equivalent representations across CIM, IFC, GIS, operational systems and Data Space catalogues	Establish governed cross-ecosystem entity-linking mechanisms supporting persistent identification across organisations, systems and lifecycle stages	**For industry:** adopt persistent identifiers and maintain explicit cross-references between representations of the same assets across Digital Twin environments **For standardization bodies**: support interoperable identification and cross-reference mechanisms enabling consistent entity linking across domain models and lifecycle stages **For research projects:** test identifier and cross-reference mechanisms on entities represented in several systems, and report where identifiers were agreed bilaterally instead (as in the TwinEU German pilot, where the customer-to-node mapping was pre-provisioned)

Identified gap	Short-term actions	Mid-term actions	Long-term actions	Stakeholder recommendations
Semantic description of models and services *Evidence: ORION, TwinEU Iberian pilot, ECLIPSE DIGITAL*	Define minimum metadata requirements for datasets, models and services, including inputs/outputs, units, semantic meaning, spatial/temporal scope, provenance and applicability	Define and validate reusable machine-readable profiles for datasets, computational models, APIs and Digital Twin services	Establish federated catalogues enabling semantic discovery, interpretation and reuse of data, models and services across Digital Twin ecosystems	**For research projects and industry**: publish machine-readable descriptions of datasets, computational models, APIs and Digital Twin services using reusable semantic profiles to support their discovery and reuse **For standardisation bodies**: promote interoperable metadata and service-description profiles covering semantic meaning, inputs/outputs, units, provenance, temporal and spatial scope, applicability and access conditions
Semantic validation and conformance testing *Evidence: TwinEU Italian and Iberian pilots, HEDGE-IoT, ECLIPSE DIGITAL*	Collect existing validation rules, interoperability profiles and conformance mechanisms and identify project-specific validation requirements	Define and validate reusable interoperability profiles, together with a common conformance framework distinguishing syntactic, informational and semantic conformity	Integrate automated semantic conformance testing into publication and consumption workflows and develop interoperable certification/conformance mechanisms	**For industry:** validate semantic models, interoperability profiles and conformance mechanisms against realistic cross-vendor and cross-domain data exchanges and operational scenarios **For standardisation bodies:** support machine-readable conformance specifications and testable interoperability profiles distinguishing syntactic, informational and semantic conformity **For research projects:** report validation results separately for syntactic, informational and semantic conformity, and declare whether each result rests on real, anonymised or synthetic data

Identified gap	Short-term actions	Mid-term actions	Long-term actions	Stakeholder recommendations
Semantic governance and lifecycle management *Evidence: TwinEU German pilot, HEDGE-IoT*	Identify semantic assets requiring governance and assign ownership and maintenance responsibilities	Define common procedures for publication, versioning, change management, validation and deprecation of ontologies, mappings, profiles and validation rules	Establish cross-ecosystem governance mechanisms for the coordinated lifecycle management of semantic assets across organisations and domains	**For research projects**: define ownership, maintenance and versioning responsibilities for semantic assets from the beginning of project activities and ensure their transfer beyond project lifetime **For industry**: participate in long-term governance mechanisms to ensure that semantic assets evolve according to operational requirements **For standardisation bodies**: provide processes and guidance supporting versioning, compatibility and controlled evolution of standardised semantic assets and interoperability specifications

6 Conclusion

The white paper brings together the experiences and lessons learned from four European projects: TwinEU, ORION, Hedge-IoT and ECLIPSE DIGITAL. Although these initiatives differ in scope, architecture and implementation maturity, they address a common challenge: enabling heterogeneous data, models and services to be consistently understood, exchanged and reused across increasingly interconnected energy systems and Digital Twin ecosystems.

The analysis shows that technical connectivity alone is not sufficient to achieve interoperability. The investigated projects provide complementary approaches and evidence, ranging from Data Space-based federation and semantic annotation to cross-domain mappings, interoperability profiles and conformance mechanisms. Their combined analysis highlights eight recurring challenges: semantic model adoption, coverage and extension; semantic interoperability within Data Space architectures; data-to-model mapping; cross-domain semantic alignment; persistent identification and entity linking; semantic description of models and services; semantic validation and conformance testing; and semantic governance and lifecycle management.

A common lesson emerging from these challenges is that interoperability should not rely on a single monolithic information model. Instead, existing domain standards and semantic assets should remain specialised and evolve through governed extensions, mappings, persistent identifiers and reusable interoperability profiles. A minimum common semantic core can provide the shared foundation required to discover, link, validate and reuse data, models and services, while Data Spaces can provide the trusted infrastructure needed to federate them across organisational boundaries.

Building on these findings, the white paper proposes a roadmap that translates the identified gaps into short-, mid- and long-term actions, complemented by recommendations for research projects, industry and standardisation bodies. The roadmap progresses from assessing existing semantic resources and interoperability requirements, through the development and validation of reusable solutions, towards their operationalisation and long-term governance across Digital Twin ecosystems.

Achieving this vision would bring concrete benefits to energy stakeholders. More consistent semantic interoperability can reduce the effort required to integrate heterogeneous systems, facilitate the reuse and transfer of data, models and services across applications and organisations, and support more effective cross-domain and cross-border collaboration. Ultimately, moving from project-specific interoperability solutions towards reusable and governed ecosystem-level capabilities can reduce duplication and integration costs while providing a scalable foundation for federated Digital Twins in the European energy system.

References

[1] International Electrotechnical Commission, "IEC SRD 63200 – SGAM basics," [Online]. Available: https://syc-se.iec.ch/deliveries/sgam-basics/.

[2] European Commission, "European Interoperability Framework (EIF) Toolbox - Levels of Interoperability," [Online]. Available: https://interoperable-europe.ec.europa.eu/collection/iopeu-monitoring/solution/european-interoperability-framework-eif-toolbox/levels-interoperability.

[3] Ontotext, "What are ontologies?," [Online]. Available: https://www.ontotext.com/knowledgehub/fundamentals/what-are-ontologies/ .

[4] "OWL 2 Web Ontology Language - Document Overview (Second Edition)," W3C, 11 December 2012. [Online]. Available: https://www.w3.org/TR/owl2-overview/.

[5] Ontotext, "What is RDF?," [Online]. Available: https://www.ontotext.com/knowledgehub/fundamentals/what-is-rdf/.

[6] Ontotext, "What is a knowledge graph?," [Online]. Available: https://www.ontotext.com/knowledgehub/fundamentals/what-is-a-knowledge-graph/.

[7] W3C Community Group - Draft Report, "RDF-star and SPARQL-star," 11 May 2026. [Online]. Available: https://w3c-cg.github.io/rdf-star/cg-spec/editors_draft.html.

[8] W3C, "Shapes Constraint Language (SHACL)," 20 July 2017. [Online]. Available: https://www.w3.org/TR/shacl/.

[9] Mines Saint-Étienne, "SEAS Ontology," [Online]. Available: https://ci.mines-stetienne.fr/seas/index.html.

[10] W3C, "Semantic Sensor Network Ontology," 19 October 2017. [Online]. Available: https://www.w3.org/TR/vocab-ssn/.

[11] AIOTI, "Manifesto for Reusable Ontologies," [Online]. Available: https://ontologymanifesto.org/.

[12] SyC Smart Energy, "IEC Systems Reference Deliverable 63417 - Guidance and plan to develop smart energy ontologies," 2025.

[13] LOV4IoT, "LOV4IoT-Energy Ontology Catalog," [Online]. Available: https://lov4iot.appspot.com/?p=lov4iot-energy.

[14] S. Olsen, "IEC-standardisering for det digitale kraftsystemet," 2018. [Online]. Available: https://www.nek.no/wp-content/uploads/2018/03/10-Statnett-Svein-Harald-Olsen.pdf.

[15] BRIDGE Data Management Working Group, "European energy data exchange reference architecture," 2021. [Online]. Available:

https://energy.ec.europa.eu/system/files/2021-06/bridge_wg_data_management_eu_reference_architcture_report_2020-2021_0.pdf.

[16] BRIDGE, Data Management Working Group, "European (energy) data exchange reference architecture 2.0," 2022. [Online]. Available: https://www.cde.ual.es/wp-content/uploads/2023/03/european-energy-data-exchange-reference-architecture-MJ0323056ENN-1.pdf.

[17] BRIDGE Data Management Working Group, "European (energy) data exchange reference architecture 3.1," 2024.

[18] BRIDGE Data Management Working Group, "Data Exchange Reference Architecture (DERA) - Updated report 2025," 2025.

[19] IEC SMB / SG 12, "Semantic interoperability: What is it? Why is it important? And what needs to be done in standardization?," 2023.

[20] ENTSO-E Information and Communication Technology Committee (ICTC), "Common Energy Data Space," 2024.

[21] European Commission, "Key actions for digitalising energy," [Online]. Available: https://energy.ec.europa.eu/topics/eus-energy-system/digitalisation-energy-system/key-actions-digitalising-energy_en.

[22] European Commission, "Register of Commission Expert Groups and Other Similar Entities - European Data Innovation Board," [Online]. Available: https://ec.europa.eu/transparency/expert-groups-register/screen/expert-groups/consult?lang=en&groupID=3903.

[23] Data Spaces Support Centre, "Scaling trusted data sharing across Europe," [Online]. Available: https://dssc.eu/.

[24] ENTSO-E, "TSO/DSO Cooperation," [Online]. Available: https://www.entsoe.eu/publications/tso-dso/.

[25] int:net and AIOTI, "Information Models Coordination and Governance: Standardisation Recommendations," 2024.

[26] E. Lambert, "AIOTI - Semantic Modelling of Digital Twins - Session 8," 25 March 2026. [Online]. Available: https://aioti.eu/wp-content/uploads/0.-AIOTI_SemanticModellingofDigitalTwin_Session8_ELambert-v1.pdf.

[27] TwinEU project website, [Online]. Available: https://twineu.net/.

[28] ORION project website, [Online]. Available: https://he-orion.eu/.

[29] Hedge-IoT project website, [Online]. Available: https://hedgeiot.eu/.

[30] ECLIPSE-DIGITAL project website, [Online]. Available: https://eclipse-digital.eu/.

[31] GitHub - European Dynamics RnD, "OneNet Catalogue," [Online]. Available: https://github.com/european-dynamics-rnd/OneNet.

[32] DIgSILENT - Power System Solutions, "PowerFactory," [Online]. Available: https://www.digsilent.de/en/powerfactory.html.

[33] GitHub - FlorianK13, "Mapping Marktstammdatenregister data to the Common Information Model (CIM) from IEC," [Online]. Available: https://github.com/FlorianK13/mastr-cim.

[34] LinkML, "Bring structure to your data," [Online]. Available: https://linkml.io/.

[35] LinkML - Map, [Online]. Available: https://linkml.io/linkml-map/.

[36] TwinEU Zenodo, "German Power Plant Registry "Marktstammdatenregister" expressed using CIM terms [Wind, Biomass, Hydro]," [Online]. Available: https://zenodo.org/records/20698190.

[37] Comitato Elettrotecnico Italiano (CEI), "Building Information Model (BIM)," [Online]. Available: https://mycomitato.ceinorme.it/comitati/sm/bim/building-information-model-bim.

[38] buildingSMART, "ifcOWL," [Online]. Available: https://technical.buildingsmart.org/standards/ifc/ifc-formats/ifcowl/.

[39] ORION project, "Use Cases," [Online]. Available: https://he-orion.eu/use-cases/.

[40] Hedge-IoT, "Holistic Approach towards Empowerment of the DiGitalization of the Energy Ecosystem through adoption of IoT solutions," [Online]. Available: https://hedgeiot.eu/.

[41] Hedge-IoT, "D 2.4 - HEDGE-IoT Reference Architecture (Final Release)," [Online]. Available: https://hedgeiot.eu/wp-content/uploads/2026/06/D2.4-HEDGE-IoT-Reference-Architecture-Final-Release.pdf.

[42] ECLIPSE DIGITAL, "Energy consumption reduction based on open-source reference framework," [Online]. Available: https://eclipse-digital.eu/.

[43] TwinEU, "D3.1 - TwinEU Open Reference Architecture," [Online]. Available: https://twineu.net/wp-content/uploads/2025/07/TwinEU_D3.1_v1.0.pdf.

[44] TwinEU, "D4.1 - Integration and deployment of TwinEU platform," [Online]. Available: https://twineu.net/wp-content/uploads/2025/07/TwinEU_D4.1_v1.0.pdf.

[45] TwinEU, "D4.2 - TwinEU Open Data Space v1," [Online]. Available: https://twineu.net/wp-content/uploads/2025/09/TwinEU_D4.2_v1.0.pdf.

[46] International Electrotechnical Commission, "IEC 61970-301 - Energy management system application program interface (EMS-API) - Part 301: Common information model (CIM) base," 2020.

[47] IEC 61968, "Application integration at electric utilities - System interfaces for distribution management - Part 11: Common Information Model (CIM)," 2013.

[48] IEC 62325 , "Framework for energy market communications - Part 301: Common information model (CIM) extensions for markets," 2018.

[49] IEC 61970-600-1, "Energy management system application program interface (EMS-API) - Part 600-1: Common Grid Model Exchange Standard (CGMES) - Structure and rules," 2021. [Online].

[50] International Electrotechnical Commission, "IEC 61850 Series - Communication networks and systems for power utility automation," 11 March 2025. [Online]. Available: https://webstore.iec.ch/en/publication/6028.

[51] IEC TC57, "IEC Technical Specification 62361-102," 2018.

[52] ETSI, "SAREf for Energy Flexibility," [Online]. Available: https://saref.etsi.org/saref4ener/v1.2.1/.

[53] ETSI, "SAREF: the Smart Applications REFerence ontology," [Online]. Available: https://saref.etsi.org/core/v3.2.1/.

[54] n5Geh, "SARGON - ontology for smart energy domain," 2025. [Online]. Available: https://sargon-n5geh.netlify.app/.

[55] Azure GitHub, "Digital Twins Definition Language (DTDL) ontology for Energy Grid," [Online]. Available: https://github.com/Azure/opendigitaltwins-energygrid.

[56] International Electrotechnical Commission, "Common Data Dictionary - CDD," [Online]. Available: https://tc3.iec.ch/tc-activity/common-data-dictionary-cdd/.

[57] Technical Committee CEN/TC 294, "EN 13757-1:2021 - Communication systems for meters - Part 1: Data exchange," 2021.

[58] International Electrotechnical Commission, "IEC Technical Specification 62056-6-9," 2016.

[59] NRECA, "MultiSpeak," [Online]. Available: https://www.multispeak.org/.

[60] International Electrotechnical Commission, "IEC Technical Specification 61968-14," [Online]. Available: https://webstore.iec.ch/en/publication/22645.

[61] ISO 16739-1, "Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries - Part 1: Data schema," 2014.

[62] "QUDT," [Online]. Available: https://www.qudt.org/.

[63] Open Geospatial Consortium, "GeoSPARQL," [Online]. Available: https://www.ogc.org/publications/standard/geosparql/.

[64] W3C, "Time Ontology in OWL," [Online]. Available: https://www.w3.org/TR/owl-time/.

[65] IEC TC57, "IEC 62357-1 – Power systems management and associated information exchange – Part 1: Reference architecture," 2015.

[66] H.J. Kim et al., "A Comprehensive Review of Practical Issues for Interoperability Using the Common Information Model in Smart Grids," *Energies,* vol. 13, no. 1435, 2020.

[67] AIOTI, "Data to Ontology Mapping Tools," 2025.

[68] PLATOON project, [Online]. Available: https://platoon-project.eu/.

[69] European Commission, "Big Data for OPen innovation Energy Marketplace (BD4OPEM project)," [Online]. Available: https://cordis.europa.eu/project/id/872525/it.

[70] InterConnect project, [Online]. Available: https://interconnectproject.eu/.

[71] "Deliverable D2.3 - Common Data Models for Energy," PLATOON project, 2022.

[72] International Organization for Standardization, "ISO/IEC JTC 1/SC 41 - Internet of things and digital twin," [Online]. Available: https://www.iso.org/committee/6483279.html.

[73] European Telecommunications Standards Institute (ETSI), [Online]. Available: https://www.etsi.org/.

[74] CEN-CENELEC, "CEN and CENELEC," [Online]. Available: https://www.cencenelec.eu/european-standardization/cen-and-cenelec/.

[75] CIM Users Group, [Online]. Available: https://cimug.org/.

[76] 61850 Users Group, [Online]. Available: https://61850ug.org/.

[77] buildingSMART International, [Online]. Available: https://www.buildingsmart.org/.

[78] ENTSO-E, [Online]. Available: https://www.entsoe.eu/.

[79] DLMS User Association, "The smart link between consumption and supply," [Online]. Available: https://www.dlms.com/.

[80] openADR Alliance, [Online]. Available: https://www.openadr.org/.

[81] Plattform Industrie 4.0, "Industrie 4.0," [Online]. Available: http://plattform-i40.de/IP/Navigation/EN/Industrie40/WhatIsIndustrie40/what-is-industrie40.html.

[82] European Commission - interoperable Europe, "CAMSS Assessment of Asset Administration Shell (AAS) - EIF Scenario," [Online]. Available: https://interoperable-europe.ec.europa.eu/collection/common-assessment-method-standards-and-specifications-camss/solution/camss-assessment-asset-administration-shell-aas-eif-scenario.

[83] Alliance for AI, IoT and Edge Continuum Innovation (AIOTI), [Online]. Available: https://aioti.eu/.

[84] Ontology Portal, "Suggested Upper Merged Ontology (SUMO)," [Online]. Available: https://www.ontologyportal.org/.

[85] ISTC-CNR Laboratory for Applied Ontology, "DOLCE : Descriptive Ontology for Linguistic and Cognitive Engineering," [Online]. Available: https://www.loa.istc.cnr.it/dolce/overview.html.

[86] W3C, "Ontology for agents, systems, and integration of services community group," [Online]. Available: https://www.w3.org/community/oasis/.

[87] W3C, "Time Ontology in OWL," 15 November 2022. [Online]. Available: https://www.w3.org/TR/owl-time/.

[88] Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen, "German Power Plant Registry "Marktstammdatenregister"," April 2024. [Online]. Available: https://www.marktstammdatenregister.de/MaStR. [Accessed July 2026].

[89] buildingSMART International, "Industry Foundation Classes (IFC)," [Online]. Available: https://www.buildingsmart.org/standards/bsi-standards/industry-foundation-classes/. [Accessed July 2026].

[90] buildingSMART, "buildingSMART Data Dictionary (bSDD)," [Online]. Available: https://www.buildingsmart.org/users/services/buildingsmart-data-dictionary/. [Accessed July 2026].

[91] buildingSMART, "Industry Delivery Specification (IDS)," [Online]. Available: https://www.buildingsmart.org/standards/bsi-standards/information-delivery-specification-ids/. [Accessed July 2026].

Acronyms

Acronym	Description
61850UG	61850 User Group
AAS	Asset Administration Shell
ADMS	Advanced Distribution Management System
AIOTI	Alliance for AI, IoT and Edge Continuum Innovation
BIM	Building Information Modelling
BD4OPEM	Big Data for Open Innovation Energy Marketplace
buildingSMART Data Dictionary	bSDD
CDD	Common Data Dictionary
CEN	Comité Européen de Normalisation
CENELEC	Comité Européen de Normalisation Électrotechnique
CGMES	Common Grid Model Exchange Standard
CIM	Common Information Model
CIMUG	CIM User Group
CVS	Comma-Separated Values
DER	Distributed Energy Resource
DERA	Data Exchange Reference Architecture
DLMS/COSEM	Device Language Message Specification / Companion Specification for Energy Metering
DOLCE	Descriptive Ontology for Linguistic and Cognitive Engineering
DR	Demand Response
DSBA	Data Spaces Business Alliance
DSO	Distribution System Operator
DT	Digital Twin
DTDL	Digital Twins Definition Language
EIF	European Interoperability Framework
EMS	Energy Management Systems
ENTSO-E	European Network of Transmission System Operators for Electricity
ETSI	European Telecommunications Standards Institute

Acronym	Description
FAIR	Findable, Accessible, Interoperable, Reusable
GIS	Geographical Information System
GOOSE	Generic Object-Oriented Substation Events
ICT	Information and Communication Technologies
IDO	Industrial Data Ontology
IDS	Industry Delivery Specification
IDSA	International Data Spaces Association
IEC	International Electrotechnical Commission
IFC	Industry Foundation Classes
IGM	Individual Grid Model
ISO	International Organization for Standardization
JSON	JavaScript Object Notation
LinkML	Linked Data Modeling Language
MaStR	Marktstammdatenregister
MMS	Manufacturing Message Specification
OASIS	Ontology for Agents, Systems, and Integration of Services
OpenADR	Open Automated Demand Response
OWL	Web Ontology Language
PLATOON	Digital PLAtform and analytic TOOls for eNergy
PV	Photovoltaic
QUDT	Quantities, Units, Dimensions and Types
RA	Reference Architecture
RDF	Resource Description Framework
SAREF	Smart Applications REFerence ontology
SARGON	Smart Energy Domain Ontology
SCADA	Supervisory Control and Data Acquisition
SEAS	Smart Energy Aware Systems
SEDMOON	Semantic Data Models Of Energy
SGAM	Smart Grid Architecture Model
SHACL	Shapes Constraint Language

Acronym	Description
SOSA	Sensor, Observation, Sample, and Actuator
SSN	Semantic Sensor Network
SUMO	Suggested Upper Merged Ontology
SV	Sampled Values
TSO	Transmission System Operator
UCA	Utility Communication Architecture
W3C	World Wide Web Consortium
XML	Extensible Markup Language

Annex 1: Data models and standards in the smart energy domain

Some examples of relevant data models in the smart energy domain are here summarised:

- **IEC Common Information Model (CIM)** – IEC CIM is one of the core standards for smart grids and can be considered as the reference information model for representing electrical network assets, operational data, and business processes within utilities. The CIM family comprises IEC 61970 [46], focused on the description of electrical components and energy management system applications; IEC 61968 [47], addressing information exchange between utility enterprise applications; and IEC 62325 [48], covering market communication and electricity market processes. Built upon IEC CIM, CGMES [49] (Common Grid Model Exchange Specification) is a technical specification developed to facilitate data exchange among Transmission System Operators (TSOs). In particular, within ENTSO-E (European Network of Transmission System Operators for Electricity), all TSOs are required to adapt their operational systems to support the exchange of Individual Grid Models (IGMs) for different network scenarios in compliance with the CGMES v3.0 standard.
- **IEC 61850 (Communication networks and systems for power utility automation)** – IEC 61850 is an international standard for the design of communication systems in substations and power system automation [50]. It defines an object-oriented information model and communication services supporting protection, control, monitoring, and measurement functions. The abstract data models specified by IEC 61850 can be mapped to different communication protocols, including Manufacturing Message Specification (MMS), Generic Object-Oriented Substation Events (GOOSE), and Sampled Values (SV), enabling interoperable and real-time information exchange in power system applications. As shown in the integration architecture represented in Figure 13, the harmonization between IEC CIM and IEC 61850 is crucial for ensuring semantic interoperability in power system automation environments, since these standards address overlapping domains but were developed independently. In this context, the IEC TC57 WG19 working group, entitled “Interoperability within TC57 in the long term”, was established to coordinate harmonization activities between IEC CIM and IEC 61850, with the objective of defining practical mechanisms for integrating the respective information models and systems. The outcomes of this work are documented in the technical specification IEC TS 62361-102 [51].
- **SAREF4ENER (SAREF for Energy Flexibility)** – SAREF4ENER [52] is an extension of the European Telecommunications Standards Institute (ETSI) Smart

Applications REFerence ontology (SAREF) [53] dedicated to the energy domain. While the core SAREF ontology provides a shared semantic model for IoT devices and services, SAREF4ENER focuses on modelling energy management concepts, energy flexibility, and demand-response interactions. It supports the representation of protocol-independent messages exchanged among energy management systems, devices, and customer energy managers to optimize energy consumption and production in smart homes and smart grid environments.

- **SARGON (SmArt eneRGy dOmain oNtology)** – SARGON [54] extends SAREF to provide a richer semantic representation of the smart energy domain, with particular emphasis on building automation and power system management. The ontology supports use cases such as medium-voltage distribution network automation, building energy optimization, residential and commercial energy management, and district-level energy coordination.
- **Microsoft Digital Twins Definition Language (DTDL) ontology for Energy Grid** – Developed and maintained by Microsoft, the DTDL ontology is based on IEC CIM concepts and is intended to accelerate the development of digital twin solutions for the energy sector [55]. It provides semantic models for assets, equipment, and grid components to support applications such as asset monitoring, fault analysis, predictive maintenance, impact assessment, and simulation. The ontology is publicly available in JSON format [55].
- **IEC 61360 – Common Data Dictionary (CDD)** – IEC 61360 provides a standardized repository of concepts, properties, and definitions for the electrotechnical domain [56]. It establishes a shared vocabulary and machine-readable semantic definitions derived from international standards and industrial references. The model is structured around the four concepts of components, materials, features, and geometries.
- **DLMS/COSEM (Device Language Message Specification / Companion Specification for Energy Metering)** – DLMS/COSEM is the internationally adopted data model and communication framework for Advanced Metering Infrastructure (AMI) and smart metering systems [57]. It supports interoperability across energy metering, load control, distributed energy resources, electromobility, and flexibility services. The related specification IEC TS 62056-6-9 [58] is particularly relevant as it promotes interoperability between DLMS/COSEM and IEC CIM information models.
- **MultiSpeak** – MultiSpeak is an industry-driven specification developed to facilitate interoperability among utility software applications, particularly in distribution system operations [59]. It defines a set of standardized interfaces based on common utility business processes and operational use cases.

Interoperability with IEC CIM is supported through IEC 61968-14 [60], which specifies mappings between CIM and MultiSpeak using XML-based exchange mechanisms.

- **Industry Foundation Classes (IFC)** – IFC is an open, vendor-neutral information model developed by buildingSMART International and standardized as ISO 16739 [61]. It provides a comprehensive semantic representation of built assets, including physical components, properties, relationships, processes, and stakeholders. Its layered architecture supports interoperability throughout the entire asset lifecycle, making IFC the de facto standard for information exchange in Building Information Modelling (BIM) environments.

In addition to domain-specific information models, several cross-domain ontologies are commonly adopted to enhance semantic interoperability. QUDT (Quantities, Units, Dimensions and Types) provides a standardized representation of quantities and units of measurement, ensuring consistency in data exchange [62]. GeoSPARQL enables the representation and querying of geospatial information on the Semantic Web [63], while OWL-Time offers a formal ontology for modelling temporal concepts and relationships [64]. Together, these models complement domain ontologies by providing reusable semantic foundations for measurements, spatial information, and temporal reasoning.

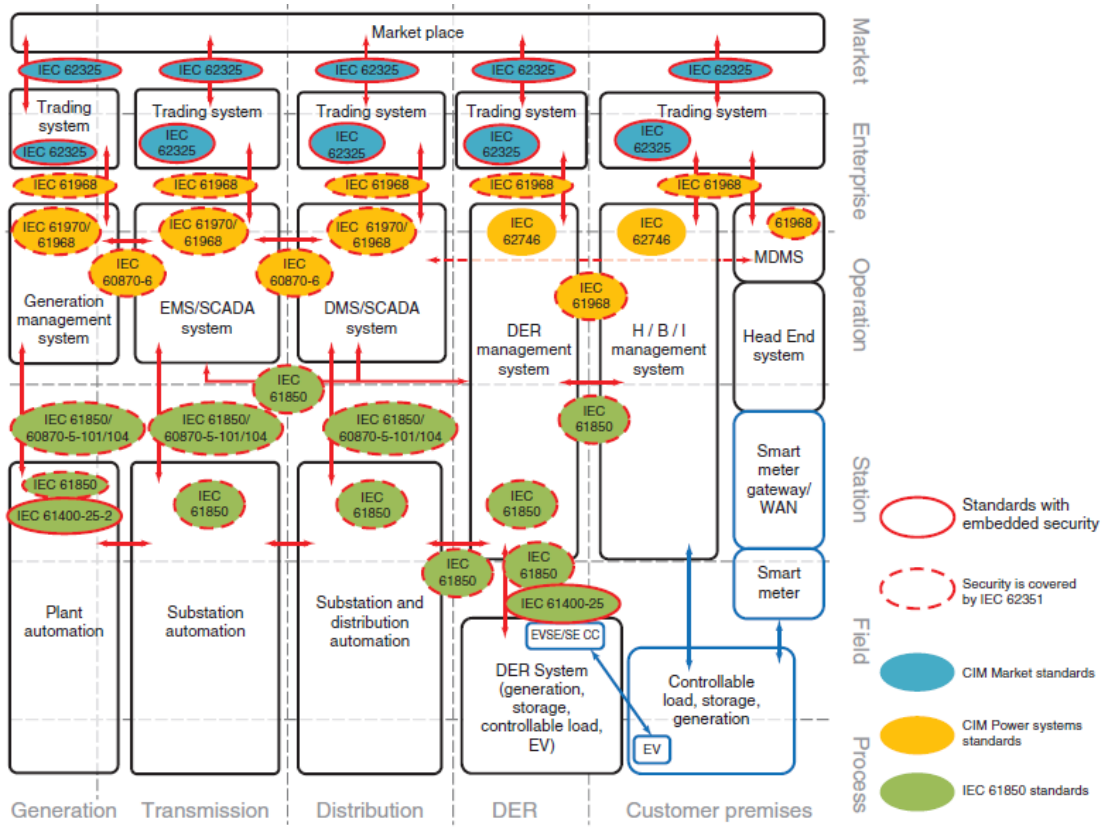

Figure 13 - Integration architecture between IEC CIM and other IEC standards [65]

Annex 2: Ontology alignment, ontology mapping and application ontologies

Annex 2.1 Ontology alignment

Ontology alignment focuses on identifying semantic correspondences between two or more ontologies that describe the same or partially overlapping domains. The objective is to establish relationships between equivalent or related concepts while preserving the autonomy of the original ontologies. Methodologies for harmonizing heterogeneous data models can be grouped into two main categories: ontological approaches and unified modelling [66]. Ontological approaches identify semantically equivalent elements across models, either through manual mapping (simple but error-prone and not scalable) or through automated ontology matching, which uses semantic analysis tools and, increasingly, AI-based methods to reduce human effort. In recent years, approaches integrating generative AI models have also shown promise in further reducing manual intervention. Unified modelling, instead, creates a single integrated data model by extending or combining existing ones, or by using meta-models to resolve inconsistencies. As an alternative, direct links between instances (e.g., via owl:sameAs) can be used to align equivalent entities across knowledge graphs.

One example concerns the ontological alignment between the IEC CIM model and Industry Foundation Classes (IFC). The BIM methodology and the IFC standard are used in the construction sector for asset management, but they are not specifically designed to describe electrical components. On the other hand, IEC CIM includes only a limited number of specific classes useful for the planning, maintenance, and management of network assets—from their installation through to their decommissioning. In fact, the two models were developed for distinct purposes: IFC is typically used for infrastructure design but not for operational tasks, whereas IEC CIM is used during the operational phase but generally not for the design phase. Consequently, combining the two models represents an optimal solution for ensuring comprehensive asset management throughout their entire life cycle.

Another use case involves the alignment of IEC CIM with SOSA (Sensor, Observation, Sample, and Actuator)—a more general ontology designed for representing sensors, actuators, samplers, observations, and measurement activities. Aligning a domain-specific ontology like IEC CIM with a cross-domain ontology like SOSA is a strategic step toward fostering semantic interoperability between the energy sector and other application domains. Such integration facilitates the convergence of different models and promotes a more uniform, interoperable, and reusable approach to knowledge management.

Annex 2.2 Ontology mapping

While ontology alignment establishes correspondences between semantic models, ontology mapping focuses on linking data sources to a shared ontology. In this context,

a source-specific schema or data format is related to concepts defined within a reference ontology, enabling heterogeneous datasets to be represented using a common semantic framework.

The AIOTI whitepaper "*Data to ontology mapping tools*" [67] shows the benefits of this approach when multiple organizations need to exchange information (Figure 14). Without a shared ontology, each data model must potentially be mapped to every other model, resulting in up to n(n−1) pairwise mappings. Such an approach becomes increasingly difficult to maintain as the number of participants grows. In contrast, when a shared ontology is adopted, each data provider only needs to implement a single mapping between its local schema and the common semantic model. The total number of required mappings is therefore reduced to n, significantly simplifying integration, maintenance, and interoperability efforts.

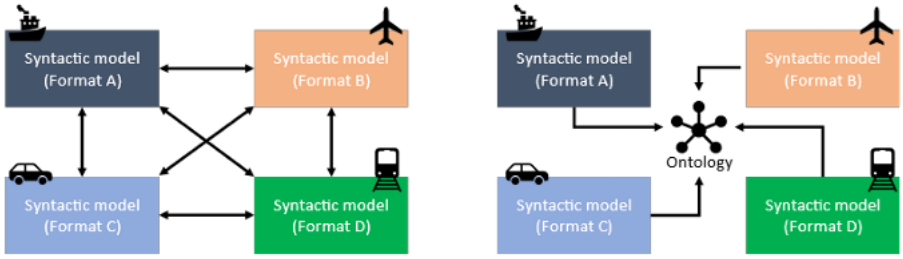

Figure 14 – Situation without a shared semantic model compared to the situation with a shared semantic model [67]

Annex 2.3 Application ontologies

Beyond alignment and mapping, many research and innovation projects have developed application ontologies by integrating and extending existing semantic resources to address project-specific requirements and use cases. Rather than creating new ontologies from scratch, these initiatives generally follow a reuse-oriented approach that combines established domain ontologies and introduces extensions only where necessary.

Several European projects have adopted this strategy. For example, the PLATOON (Digital PLAtform and analytic TOOls for eNergy) project [68] developed the open-source SEDMOON (Semantic Data Models Of Energy) ontology, which combines concepts from standard ontologies such as SAREF, SEAS, and OntoWind, extending them to support the requirements of project pilots. Similarly, the BD4OPEM (Big Data for Open Innovation Energy Marketplace) project [69] integrated semantic models including IEC CIM, SAREF, SAREF4ENER, and OCPP to address the needs of its marketplace-oriented use cases. The InterConnect project [70] followed a comparable approach by extending SAREF to better represent flexibility services and smart energy applications.

Within PLATOON, the development of a common semantic data model was realized through a structured ontology-engineering process consisting of four phases [71].

First, use cases documented according to IEC 62559 are analysed to determine the scope of the semantic model. Competency questions are then defined to capture the

information needs that the ontology should support, enabling the identification of key concepts and relationships.

Second, existing ontologies are evaluated for reuse. Whenever possible, concepts are adopted directly from established ontologies. When partial coverage is available, existing models are extended to preserve compatibility with standards. The creation of new ontological modules is considered only when no suitable semantic resources exist.

Third, the selected modules are integrated into a harmonized semantic data model and validated against pilot-specific scenarios and example datasets.

Finally, the resulting ontology is reviewed with stakeholders and domain experts, refined through iterative feedback, and formalized to provide an interoperable and reusable semantic framework capable of supporting the project's data integration and interoperability requirements.

Annex 3: Standards and standardization organizations related to the energy domain

Table 6 - Main standards and documents related to the energy domain

Document / Standard	Committee / group /organization	Main purpose
IEC 60870-5-101/104	IEC TC 57 WG03	SCADA communication with S/S and RTUs
IEC 61970-301	IEC TC57 WG13, in cooperation with CIMUG	Core IEC Common Information Model (CIM)
IEC 61968-11	IEC TC57 WG14, in cooperation with CIMUG	CIM extensions for distribution networks
IEC 62325-301	IEC TC57 WG16, in cooperation with CIMUG	CIM for energy market communications
IEC 61970-600-1, 61970-600-2 (CGMES)	IEC TC57 WG13, in cooperation with ENTSO-E	Common Grid Model Exchange Standard (CGMES) for pan-European network model exchange
IEC 61850	IEC TC57 WG10, in cooperation with 61850ug	Communication networks and systems for power utility automation
IEC TS 62361-102	IEC TC57 WG19	Harmonization activity between IEC CIM and IEC 61850
IEC 62056-5-3	IEC TC13 WG14, in cooperation with DLMS User Association	Specification of the DLMS/COSEM Application Layer
IEC 62056-6-9	IEC TC13 WG16	Mapping between IEC CIM message profiles and DLMS/COSEM models and protocols
IEC SRD 63417	IEC SyC Smart Energy	Guidance and plan to develop smart energy ontologies
ETSI TS 103 264	ETSI TC SmartM2M	Reference ontology and semantic framework for Smart Applications (basis for SAREF)
ETSI TS 103 410-1	ETSI TC SmartM2M	SAREF extension for the energy domain
IEC 61360-7	IEC TC3 SC 3D	Data dictionary of cross-domain concepts within the

Document / Standard	Committee / group /organization	Main purpose
		IEC Common Data Dictionary (IEC CDD)
IEC 62746-10-1	IEC PC 118 (Smart Grid User Interface), in cooperation with the OpenADR Alliance	Open Automated Demand Response (OpenADR) model and services for automated demand response and flexibility management
ISO 16739-1	ISO TC59 SC13, in cooperation with buildingSMART	Industry Foundation Classes (IFC) data schema
ISO 12006-3	ISO TC59 SC 13, in cooperation with buildingSMART	Framework for object-oriented information and data dictionaries
ISO 23386	ISO TC59 SC 13, in cooperation with buildingSMART	Methodology for defining and governing properties
ISO 23387	ISO TC59 SC 13, in cooperation with buildingSMART	Data templates for construction objects and assets
ISO/IEC 21823-1	ISO/IEC JTC1 SC 41	Framework for interoperability of IoT systems
ISO/IEC 21823-3	ISO/IEC JTC1 SC 41	Semantic interoperability
ISO/IEC 21823-5	ISO/IEC JTC1 SC 41	Behavioural and policy interoperability
ISO/IEC 30151 (under development)	ISO/IEC JTC1 SC 41	Digital Twin - Extraction and transactions of data products
ISO/IEC 30152 (under development)	ISO/IEC JTC1 SC 41	IoT and digital twins – Guidance on the connection to data spaces
ISO/IEC 30153 (under development)	ISO/IEC JTC1 SC 41	Digital twin – Process and guidance for digital twin model construction
ISO/IEC 30141	ISO/IEC JTC1 SC 41	Standardized IoT Reference Architecture using a common vocabulary, reusable designs and industry best practices
ISO/IEC 40141 (under development)	ISO/IEC JTC1 SC 41	Guidance on the use of the IoT reference architecture
ISO/IEC 30188	ISO/IEC JTC1 SC 41	Digital twin reference architecture

Document / Standard	Committee / group /organization	Main purpose
ISO/IEC 40188 (under development)	ISO/IEC JTC1 SC 41	Guidance on the use of the digital twin reference architecture
ISO/IEC 30173	ISO/IEC JTC1 SC 41	Concepts and terminology of Digital Twin
ISO/IEC 30186	ISO/IEC JTC1 SC 41	Digital twin - Maturity model and guidance for a maturity assessment

In order to support the AI Act and the Data Act, the European Commission has published standardisation requests, with four of them directly related to semantic data, listed in Table 7.

- The request from the European Commission as regards high-risk AI systems included ten standards, including one on governance and quality of datasets used in AI systems.
- The request from the European Commission as regards a European trusted data framework included seven standards, including two on semantic models and one on governance.

Table 7 – Harmonized standards related to data and semantic data

Document / Standard	Committee / group /organization	Main purpose
ETSI EN 304 199	ETSI TC Data	Guidelines for Data Catalogue Framework
ETSI EN 303 760	ETSI TC Data	Implementation framework for semantic assets
EN 18352	CEN-CENELEC JTC25	Quality framework for internal data governance for participants in data spaces
EN 18284	CEN-CENELEC JTC21	Artificial Intelligence -- Quality and governance of datasets in AI

The main standardization bodies present in the table are the following:

- **International Electrotechnical Commission (IEC)** is the leading global organization for the preparation and publication of international standards in electrical, electronic, and related technologies. Within the scope of this analysis, IEC develops several key standards and information models for the energy sector, including the Common Information Model (CIM), IEC 61850, DLMS/COSEM, OpenADR, and the IEC Common Data Dictionary (CDD).
- **International Organization for Standardization (ISO)** is an independent, non-governmental international organization that brings together experts from around the world to develop consensus-based international standards. Within the context of this work, ISO standards related to Building Information Modeling (BIM) and digital twins are particularly relevant, as they provide semantic models and data structures that can support interoperability between the built environment and smart energy systems. Moreover, **the ISO/IEC Joint Technical Committee 1 (JTC 1)**, particularly **SC 41** on Internet of Things and Digital Twin [72], plays an increasingly important role in the development of standards for cross-domain interoperability, digital twins, ontology reuse, semantic technologies, and IoT reference architectures.
- **European Telecommunications Standards Institute (ETSI)** [73] is an independent, non-profit organization that develops and maintains globally applicable standards for Information and Communication Technologies (ICT), including mobile networks, broadcasting, and internet technologies. ETSI is responsible for the Smart Applications REFerence ontology (SAREF), which has become a widely adopted semantic model for interoperability in smart energy and IoT applications.
- The **European Committee for Standardization (CEN)** and the **European Committee for Electrotechnical Standardization (CENELEC)** [74] are two distinct private international non-profit organizations. CEN is the officially recognized standardization representative for sectors other than electrotechnical (CENELEC) and telecommunications (ETSI). CEN/CENELEC is a common platform for the development of European Standards and other technical specifications across a wide range of sectors, also ensuring that standards correspond with any relevant EU legislation. Together with ETSI, they form the European Standardization System and play a key role in supporting interoperability, the European Single Market, and the adoption of international standards at European level. CEN-CENELEC-ETSI developed the SGAM model described in Ch. 2.2.3 “The Smart Grid Architecture Model and the Data Exchange Reference Architecture”.

Beyond these standardization bodies, several standards included in the table have been developed in close collaboration with external organizations and industry initiatives:

- **CIMUG** [75] and **61850UG** [76] were formed as subgroups of the UCA (Utility Communication Architecture) International Users Groups to foster collaboration and knowledge among professionals involved in implementing, advancing the adoption and testing of IEC CIM and IEC 61850 standards.
- **buildingSMART** [77] is a global, non-profit organization that develops open, vendor-neutral standards for the construction and infrastructure industry. The organization originated several BIM-related standards and works closely with ISO TC 59 SC 13 on their international standardization. In particular, buildingSMART is responsible for the development and maintenance of the Industry Foundation Classes (IFC) specification and the buildingSMART Data Dictionary (bSDD), and continues to support the evolution of ISO standards such as ISO 16739 (IFC), ISO 12006-3, ISO 23386, and ISO 23387.
- **ENTSO-E** (European Network of Transmission System Operators for Electricity) [78] was established under the European Union's Third Energy Package to support the integration and operation of the European electricity market. ENTSO-E has adopted the IEC Common Information Model (CIM) as the preferred information model for pan-European grid data exchange. To ensure that CIM standards evolve according to transmission system operator requirements, ENTSO-E maintains close collaboration and liaison relationships with IEC TC 57 Working Groups 13 and 16. This collaboration led to the development of the Common Grid Model Exchange Standard (CGMES), which has become the reference model for data exchange among European TSOs.
- **DLMS User Association** [79] is a non-profit organization responsible for the development, maintenance, certification, and promotion of the DLMS/COSEM protocol suite for utility metering. The DLMS/COSEM specifications were subsequently standardized within the IEC 62056 series by IEC TC 13. DLMS UA continues to collaborate with IEC TC 13, particularly Working Group 14, to ensure alignment between industry requirements and international standardization activities.
- **OpenADR Alliance** [80] is an industry consortium established to promote interoperable Demand Response (DR) and Distributed Energy Resources (DER) communications. The Alliance developed the OpenADR specification to enable automated interactions between utilities, aggregators, and end-users for flexibility and demand response services. The OpenADR specification was later incorporated into the IEC standardization framework through IEC 62746-10-1.
- **Industry 4.0,** originally promoted by the German *Plattform Industrie 4.0* [81], aims to enable the digital transformation of manufacturing through interoperable digital representations of industrial assets, processes, and systems. A central

concept of this ecosystem is the Asset Administration Shell (AAS), which serves as a standardized digital representation of physical and logical assets. To ensure semantic interoperability, AAS submodels frequently rely on concepts and property definitions from the IEC Common Data Dictionary (IEC CDD) [82], standardized through the IEC 61360 series. Industry 4.0 activities are closely connected to the work of IEC TC 184 SC 4, which develops standards such as ISO 10303 (STEP), IEC/ISO 62264 (ISA-95), Asset Administration Shell specifications, and the emerging Industrial Data Ontology (IDO), all of which contribute to semantic interoperability and digital twin implementations in industrial environments.

Additional initiatives are also relevant for interoperability and reference architectures in the smart energy domain:

- The **BRIDGE Data Management Working Group**, established under the European Commission's BRIDGE initiative, develops methodologies and guidelines for interoperability and data exchange in energy systems. Its outputs include the Data Exchange Reference Architecture described in paragraph "The Smart Grid Architecture Model and the Data Exchange Reference Architecture", the Reference Framework for Interoperability, a Use Case Repository, and interoperability guidelines for flexibility assets, distributed energy resources, and smart appliances.
- The **Alliance for IoT and Edge Computing Innovation (AIOTI)** [83] was initiated in 2015, with the aim to strengthen the dialogue and interaction among IoT players in Europe. It brings together industry, research organizations, and policymakers to advance the adoption of AI, IoT and edge continuum to support Europe's digitalization and competitiveness. Within the Semantic Interoperability Focus Group, AIOTI has actively contributed to discussions on semantic interoperability, ontology reuse, and cross-domain data integration, and has recently promoted the concept of reusable ontologies through its manifesto [11].

Finally, the role of IEC System Committees in fostering semantic interoperability across domains such as smart energy, smart cities, and sustainable transportation should be highlighted. By coordinating activities across technical committees, they help identify gaps, overlaps, and opportunities for harmonization among existing standards and semantic models. In particular, IEC SyC Smart Energy is leading the development of a roadmap for smart energy ontologies aimed at promoting ontology reuse, cross-domain interoperability, and long-term sustainability. The initiative aims to establish a federated ecosystem of interoperable reference ontologies that can support emerging technologies such as digital twins and artificial intelligence, while providing mechanisms for validation, maintenance, and continuous evolution.