TwinEU Open Reference Architecture

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List of Abbreviations and Acronyms

Acronym	Meaning
ADF	Architecture Description Framework
ADL	Architecture Description Language
AI	Artificial Intelligence
AIoT	Artificial Intelligence of Things
AIOTI HLA	Alliance for IoT and Edge Computing Innovation High Level Architecture
AMI	Advanced Metering Infrastructure
API	Application Programming Interface
AAS	Asset Administration Shell
BDVA	Big Data Value Association
BD4NRG	Big Data for Next Generation Energy
BMO	Balancing Market Operators
BO	Business Objects
BSP	Balancing Service Provider
BUC	Business Use Case
CEEDS	Common European Energy Data Space
CGMES	Common Grid Model Exchange Standard
CIM	Common Information Model
COSMAG	Comprehensive Architecture for Smart Grid
CRoF	Control Room of the Future
DAM	Day Ahead Market
DEPO	Data Exchange Platform Operator
DER	Distributed Energy Resource
DERA	Data Exchange Reference Architecture
DGA	Data Governance Act
DLR	Dynamic Line Rating
DMS	Distribution Management System
DoA	Description of Action
DSP	Dataspace Protocol
DSO	Distribution System Operator
DT	Digital Twin
EFI	Energy Flexibility Interface
EMS	Energy Management System

ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
FACTS	Flexible AC Transmission System
FCR	Frequency Containment Reserve
FDT	Federated Digital Twin
FSP	Flexibility Service Provider
FR	Functional Requirements
FUR	Functional User Requirements
FxR	Flexibility Register
GDPR	General Data Protection Regulation
GE	Generic Enabler
GFUR	General Functional User Requirements
GIS	Geographic Information System
GSUC	General System Use Cases
GWAC	GridWise Architecture Council
HEMS	Home Energy Management System
HPC	High Performance Computing
HV	High Voltage
HVAC	Heating, Ventilation, and Air Conditioning
HVDC	High Voltage Direct Current
IDP	Industrial Data Platform
IDSA	International Data Space Association
IEGSA	Interoperable pan-European Grid Services Architecture
IGP	Intelligent Grid Platform
IoT	Internet of Things
IT	Information Technology
ISO	International Organization for Standardization
LV	Low Voltage
MDP	Measuring Device Provider
MPO	Metering Point Operator
ML	Machine Learning
MO	Market Operator
MV	Medium Voltage

NFR	Non-Functional Requirements
OneNet	One Network for Europe
OPC UA	Open Platform Communication Unified Architecture
panEU	Pan European
PAS	Publicly Available Standard
PDP	Personal Data Platform
PE	Power Electronics
PERT	Project, Evaluation and Review Technique
PPP	Public-Private Partnership
PV	Photovoltaic
TwinEU	Digital Twin for Europe
QoS	Quality of Service
RA	Reference Architecture
RAF	Reference Architecture Framework
RAM	Reference Architecture Model
RES	Renewable Energy Source
RSC	Regional Security Coordinator
SAD	Smart Assistant Developer
SAREF	Smart Applications REFerence
SCADA	Supervisory Control and Data Acquisition
SGAM	Smart Grid Architecture Model
SO	System Operator
SRIA	Strategic Research and Innovation Agenda
SUC	System Use Case
ToC	Table of Content
TRL	Technology Readiness Levels
TSO	Transmission System Operator
UC	Use Case
UI	User Interface
UML	Unified Modelling Language
WP	Work Package
WDS	Weather Data Supplier
WFP	Weather Forecast Provider

Executive Summary

The central goal of the TwinEU project is the establishment of a pan-European federated Digital Twin (DT) ecosystem, underpinned by an open, modular, and interoperable Reference Architecture (RA). This RA serves as the foundational technical framework enabling seamless integration and federation of digital twins across diverse energy domains, facilitating collaboration between Transmission System Operators (TSOs), Distribution System Operators (DSOs), market participants, technology providers, and consumers. By adopting standards and interoperability protocols derived from established European initiatives such as FIWARE, GAIA-X, and IDSA, the TwinEU RA ensures compatibility and scalability across platforms, enhancing the potential for a unified European energy data space. The methodology adopted for developing the RA combines industry best practices and established architectural frameworks, notably variations of the ISO 42010 standard and the 4+1 View Model, ensuring comprehensive coverage of the system's logical, functional, development, and operational dimensions. The architecture integrates insights from relevant EU projects and established reference architectures, consolidating proven models into a coherent design. Through analysis of the Component Catalogue (mainly software components such as middleware, AI models, interoperable services, semantic tools, and digital twin enablers) and Business and High-Level Use Cases, a clear link between user needs and system functionality is established. These use cases were further translated into functional and technical specifications for standardized data access and system integration, forming the basis for a shared reference point across partners and pilots.

In parallel, the RA integrates data governance, cybersecurity, and legal-ethical considerations, ensuring that technical design respects data protection regulations (e.g., GDPR), sector-specific requirements, and trust-by-design principles. Sovereign data exchange mechanisms such as connectors are being employed to enforce access control and usage policies across federated environments. Lessons learned throughout the development emphasize the critical importance of early stakeholder alignment, iterative deployment strategies (such as Minimum Viable Products), strict adherence to interoperability standards, and a decentralized federation approach to maintain scalability, data sovereignty, and security. The resulting RA not only addresses immediate technical and functional challenges but also lays a robust foundation for future innovations in energy management, facilitating improved reliability, economic growth through new business models, and societal benefits such as enhanced grid resilience, transparency, and sustainability. Ultimately, the TwinEU RA serves as a pivotal enabler for Europe’s ongoing digital and energy transitions, offering a blueprint for scalable, federated digital twin integration across the continent.

1 Introduction

This document shows the final version of the Open Reference Architecture of the TwinEU project. TwinEU (Digital Twin for Europe) is a 3-year EU project within call HORIZON-CL5-2023-D3-01 under topic HORIZON-CL5-2023-D3-01-10 - Supporting the development of a digital twin to improve management, operations and resilience of the EU Electricity System in support to REPowerEU [72].

As for the TwinEU project: The evolving global landscape has made the energy transition process more vital for Europe than ever before. Increasing the adoption of renewable energy while enhancing the resilience and cost-efficiency of infrastructure is now imperative. In this context, digital twins (DT) are emerging as a pivotal asset to streamline business and operational coordination for system operators and market participants. To maximize the potential of DTs, it is essential to establish a European-level agreement that promotes a federated ecosystem of DT solutions rather than isolated implementations. This approach allows individual operators to make their own implementation choices while ensuring interoperability and seamless exchange within the broader ecosystem. This vision is at the core of the TwinEU consortium: to enable advanced DT technologies that foster interoperability, data sharing, and model exchanges through standardized interfaces and open APIs for external stakeholders. The envisioned DT system will serve as the foundation of European data exchange, integrating with the emerging Energy Data Space. Leveraging advanced modeling, AI tools, and High-Performance Computing (HPC) infrastructure, it will provide unprecedented capabilities to observe, test, and operate a comprehensive digital replica of Europe’s energy infrastructure. The TwinEU consortium unites an unparalleled network of stakeholders from over 15 European countries, ensuring continuous geographic coverage across the continent. Demonstrations will involve key transmission, distribution, and market operators, showcasing coordinated cross-regional data exchange. The consortium also includes leading industry players, research institutions, and associations with a proven track record in delivering innovative solutions for Europe. By fostering consensus and collaboration, TwinEU aims to redefine the future of Europe’s energy infrastructure with an integrated, interoperable, and cutting-edge digital twin ecosystem.

1.1 Scope

Deliverable D3.1 “TwinEU Open Reference Architecture” is produced within the WP3 “Open Architecture and Design for pan-European Federated Data Space-enabled DT” as part of Task 3.1 “TwinEU Open Reference Architecture”. The purpose of this document is to define the TwinEU Reference Architecture (RA), that supports the implementation and integration of a data-space-enabled DT federated infrastructure. The RA implementation methodology utilizes two models in its design process, namely the use of ISO42010 for architectural communication, and 4+1 Architectural models for a multi-view perspective. The identification and integration of key software and hardware components which are vital for the effective operation of the TwinEU ecosystem is done through the development of a component catalogue. The RA also integrates all use cases extracted within the context of this project into one architectural model. The basis will be the outputs from the activities carried out in WP2 “Digital Twins EU-level cross-stakeholder use cases capitalization and preparation”. In more detail Task 3.1 focuses on the alignment and interactions with the existing relevant EU programs, initiatives and platforms for the digital transformations of the European energy systems, and attempts to align with B2B reference architectures in order to enhance the interoperable connection and integration among smart energy grids, including FIWARE Smart Energy Reference Architecture, IDSA RA Model, IoT/edge AIOTI HLA, as well as BRIDGE DERA 3.0 [29]. Moreover, it considers the most relevant results coming from EU initiatives and relevant projects, as well as the functional and technical specifications for enabling edge-level DT integration. To this end, the deliverable considers the outputs from the activities in other tasks in WP3 and uses them as inputs to develop the RA, through analysis and mapping of the use cases and specifications, to ensure technical convergence and data interoperability.

1.2 Work Package 3

WP3 "*Open Architecture and Design for pan-European Federated Data Space-enabled DT*" oversees the definition of the Twin EU open reference Architecture which will support the implementation and integration of data-space-enabled DT federated infrastructure. In more detail, the main WP3 activities are:

- Design of the TwinEU Open Reference Architecture for the effective and seamless interoperation of DTs in a federated way.
- Alignment of the Open Reference Architecture with the relevant EU initiatives, programs and relevant projects, to ensure that the design of the Open Reference Architecture is up to date with the most recent frameworks and standards of the industry.
- Definition of both functional and technical specifications of pan-European federated DT design together with cybersecurity and data privacy requirements.

1.3 Task 3.1 - TwinEU open reference architecture

The primary activity of Task 3.1 covers the development of the TwinEU open reference architecture, which is a core component of the Twin EU project, with the aim to facilitate an interoperable operation of DTs in a federated energy infrastructure on a pan-European scale. This can be broken down into the following activities:

Table 1: T3.1 Activities

A1: Definition of the TwinEU Open Reference Architecture	Building on the outcome of the work carried within WP2, Task 3.1 creates an open reference architecture, which acts as the foundation for integrating data-space enabled DTs, to support the federated DT infrastructure of the work conducted in WP4.
A2: Integration of similar projects	Taking the relevant frameworks and considerations from the EU regulatory environment to ensure that the open RA is aligned with the most recent and relevant standards. Furthermore, a review of the reference architecture for the following projects will be conducted to see the steps already taken in the field: • OneNet • BD4NRG • BD4OPEM • TDX-Assist • EU-SysFlex • CoordiNet • INTERRFACE • ENERSHARE
A3: Alignment with EU initiatives and platforms	Ensuring interoperability and effective interaction, the RA is aligned with existing EU initiatives, frameworks, and platforms, including:

	• FIWARE Smart Energy Reference Architecture • IDSA Reference Architectural Model • IoT/edge AIOTI High-Level Architecture • IEGSMA Architecture • GAIA-X Federated Architecture • BRIDGE DERA 3.0 • COSMAG • AIOTI • OPEN DEI • BDVA

The above activities of T3.1 aim to achieve the following objectives:

- **Design the TwinEU Open Reference Architecture**, to support the implementation, integration, and interoperable operation of data-space enabled DT federated infrastructure.
- Alignment and interaction with the existing EU programs, initiatives, and platforms for the digital transformation of the European system, to ensure that the TwinEU edge-level DT federated infrastructure can support the project's goals and integrate with other systems and smart energy projects and EU initiatives.

1.4 Connection with other WPs and Tasks

The following PERT diagram shows all interactions of WP3 tasks with WP2 and WP4.

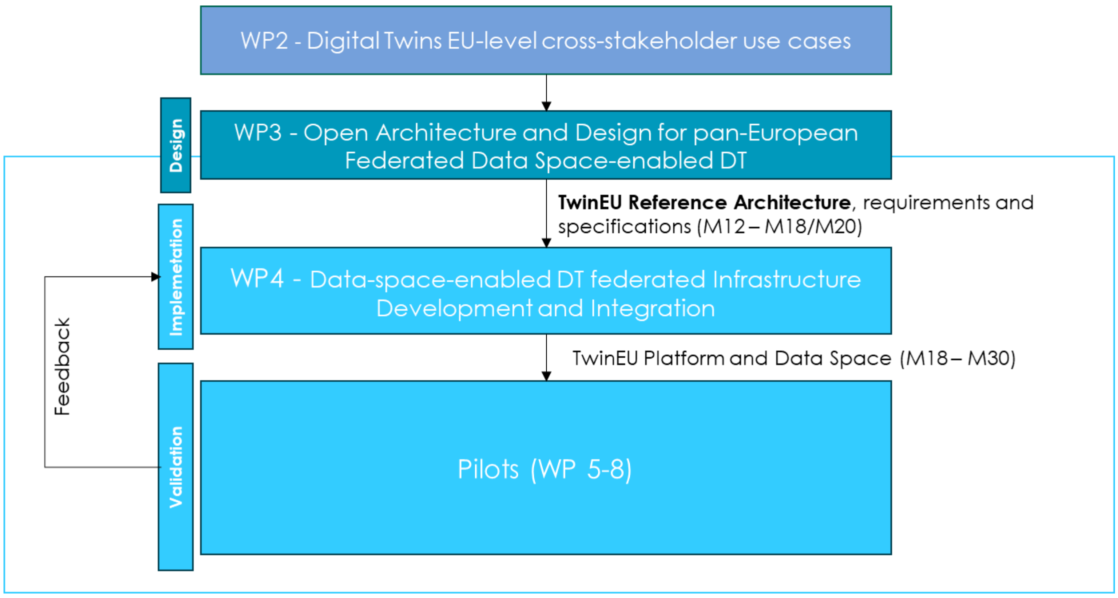


Figure 1: PERT chart for the activities in WP3

WP3 is related to WP2, which will provide relevant outcomes in terms of TwinEU use cases and scenarios, stakeholder requirements, and technology boundaries. This ensures that the architecture meets the requirements of the stakeholders and that it can support their practical applications. Input from WP2 also comes in the form of analysis of relevant EU initiatives and existing smart energy projects, which provide guidance on the best current practices in the industry and ensures alignment with the most recent standards. WP3 is also linked to WP4, which will use the open reference architecture and functional and technical specifications defined in WP3 as input for the implementation of the TwinEU architecture in WP4. This will offer guidance on the effective development and integration of data-space enabled DT federated infrastructure, by ensuring that the implementation is aligned with the architecture in WP3. Conversely, WP4 will provide relevant feedback on the design activities of the open RA in WP3, to provide insights necessary for improving the architecture, and to ensure alignment between design and implementation. The design of the TwinEU open reference architecture in WP3 is validated through the feedback loop between the implementation and validation activities of work packages WP4 and WP5-8 respectively, where the applicability and effectiveness of the TwinEU Platform is validated in different real-world scenarios.

1.5 Outline of the deliverable D3.1

Overall, the deliverable is structured as follows:

- **Chapter 2** describes the methodology to design (develop) the Reference Architecture. We explain the 4+1 views model and its merits. Furthermore, we describe ISO 42010 and how based on it we can extrapolate an accepted vocabulary in the system architecture context.
- **Chapter 3** describes European Architecture Models and relevant RAs that form the basis of the architectural aspects of TwinEU enablers implementation, along with identified related projects. This diverse set of architecture models, project outcomes and demo architectures serve as an inspiration and provide input for a consolidation in RA as required by the Grant Agreement.
- **Chapter 4** presents the Component Catalogue (software modules) and integrated services that are part of the TwinEU architecture.
- **Chapter 5** summarises the Business & High-Level Use Cases based on WP2 in conjunction with the actors, data sources and interoperability interfaces in the digital ecosystem, as depicted in Deliverable D2.2 [27].
- **Chapter 6** includes a methodology for defining the functional specifications for standardised data access & integration. The chapter focuses on creating a standardized approach for the identification of Functional Requirements by mapping them to Business Use Cases in relation to TwinEU objectives, thereby facilitating more efficient and effective use of integrated systems.
- **Chapter 7** presents the technical specifications for standardized Data Access & integration, analyses the technical specifications and maps them similarly into the system use cases.
- **Chapter 8** presents the actual technical TwinEU building blocks convergence, albeit as a high-level architectural concept for this deliverable version. This chapter visualises the Open Reference Architecture with a special focus on Digital Twin federation and Data Space integration.
- **Chapter 9** examines the UCs from the viewpoints of data privacy, cybersecurity, and ethical and legal concerns. Subsequently, adequate RA requirements are derived.
- Finally, **Chapter 10** concludes the deliverable results and outlines the next steps.

1.6 How to Read this Document

For an effective understanding of this deliverable, it is recommended that readers familiarize themselves with Deliverable D2.2 [27], which details the Business Use Cases (BUCs), actors, and initial interoperability considerations foundational to this architecture. This document builds directly upon these prior insights, systematically translating identified use cases and stakeholder requirements into a cohesive Reference Architecture, while also preparing the groundwork for subsequent technical and functional specifications detailed in future deliverables such as D3.2 “Functional and Technical Specifications”.

2 Reference Architecture Methodology

The design of the Open Reference Architecture for the TwinEU project takes into consideration the support of a federated DT infrastructure. The methodological approach which is followed ensures effective problem solving and RA design. This chapter describes in detail this methodological approach, including the steps required to integrate the work carried out from other work packages, and includes the sections on the ISO 42010 and the 4+1 Architectural view model, which are used as tools for the definition and framework building of the RA.

2.1 Methodology Approach

The methodology used to define the initial version of the TwinEU Reference Architecture consists of 4 distinct steps and is built on three foundational pillars: the development of the TwinEU concept and the project's primary objectives (blue pillar); an analysis of existing outcomes from key EU projects, architectures, and initiatives related to Smart Energy for grid operations (green pillar); and the architectures, use cases, and requirements derived from the TwinEU pilots (yellow pillar).

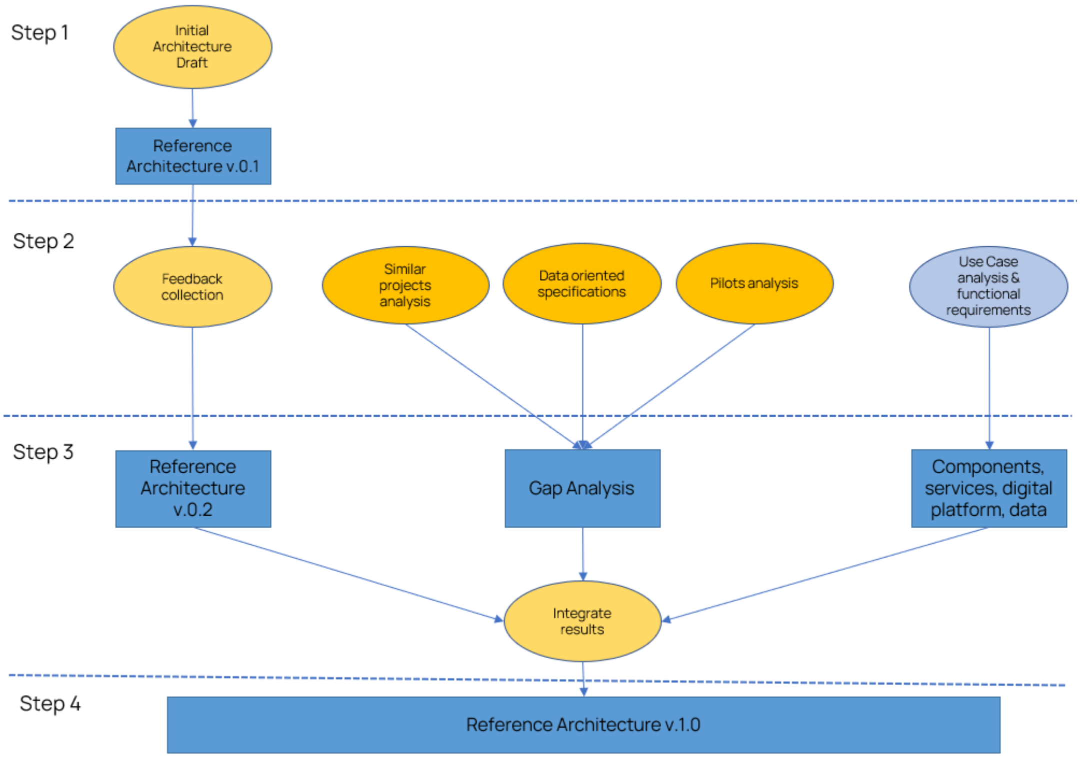


Figure 2: T3.1 4-steps Methodology

Step 1 – Initial architecture draft: The first step involves creating a preliminary version of the TwinEU Open Reference Architecture (v.0.1). This initial version focuses solely on the project's main objectives and the key features outlined in the Description of Action (DoA). It was reviewed during dedicated meetings among the partners in Task T3.1 and at specific Technical Workshops led by the Task Leader. During these workshops, technical and demonstration partners shared their perspectives on the overall concept, the architecture, and stakeholder expectations.

Step 2 – Bottom-Up and Top-Down analysis: The second step of the methodology is likely the most critical part of the entire task, as it involves analysing all relevant information for designing the RA. This analytical approach links a bottom-up method, where the architecture is shaped by use cases, requirements, and specifications with a top-down method that relies on required objectives and results. In this case, the initial version of the architecture served as a foundation for internal discussions and feedback from technical partners and demonstrations, as mentioned above. Concurrently, detailed analyses were conducted based on the outcomes of the most promising EU projects, reference architectures for seamless federation of digital twins with data-sharing and exchange services, and initiatives focused on creating a data-driven ecosystem. The architectures from these projects were mapped, enabling us to gather comparable information from the TwinEU pilots. Lastly, the results from WP2 were examined, which included information on use cases and the associated requirements and specifications that the reference architecture should address.

Step 3 – Results Integration: Step 2 information was analysed (GAP analysis), to identify similarities and differences among projects, architectures, and initiatives, aiming to pinpoint the key characteristics of the architecture. Simultaneously, the initial version of the architecture was updated to versions 0.2 and 0.3, incorporating the first round of feedback and insights from the partners.

Step 4 – Design of the Reference Architecture v1: The final step includes the design of the first consolidated version of the Reference Architecture (v1), taking into consideration all the information, requirements, specifications and concepts expressed during the various phases of analysis and design.

Significant input in the designing process of the TwinEU software ecosystem, is the ISO/IEC/IEEE 42010:2022 “Systems and software engineering — Architecture description” [1]. This is a useful model for creating a clear framework to help describe the architecture of systems like the TwinEU project. In the context of this project, ISO42010 will ensure that the structure of the RA is sound and helps communicate the key design elements and implications to stakeholders. ISO 42010 is discussed in more detail in chapter 2.2. Another key model which is being used in the design of the TwinEU RA, is the 4+1 Architectural View Model. This model was first proposed by Philippe Kruchten, and offers the necessary framework to create the many layers of the RA. The 4+1 Model View breaks down the architecture into five distinct views: Logical, Development, Process, Physical, and Scenarios (the "4+1" view) [2]. Each view is tailored to meet the specific needs of different stakeholders to ensure a holistic understanding of the system's design and functionality. The 4+1 Architectural View Model is further discussed in Section 2.3.

2.2 ISO 42010

The ISO 42010:2022 [3] is an international standard which provides a standardized framework for creating and managing architecture descriptions of complex systems. It is based upon a conceptual model – or “meta model” – of the terms and concepts affecting architecture descriptions. The standard defines the key elements involved in system architecture and specifies how they relate to different stakeholder concerns. It distinguishes between the architecture (system fundamental organization) and the architecture description (the documentation for the architecture), by defining its three critical components:

1. **Architecture Description Frameworks (ADFs)**: Structure how the architecture is described.
2. **Architecture Description Languages (ADLs)**: Provide the language for expressing the architecture.
3. **Architecture Viewpoints and Views**: Organize stakeholder concerns during the architecture design process.

The TwinEU ecosystem is a complex system, which operates within multiple layers of the energy system, and thus introduces complexity that the ISO 42010 standard can manage. The standard’s emphasis on stakeholder driven architecture aligns well with the TwinEU project, which has both diverse actors and a variety of technological systems. The different technologies which are integrated in the project (e.g. IoT devices, edge and cloud systems, AI/ML tools, etc.), can be structured through ISO42010 to address the stakeholder concerns in the architecture of the project. Concerns like interoperability and scalability are managed effectively through well-defined viewpoints and views, to ensure that the design of the architecture is aligned with the expectations of stakeholders, from grid operators to IoT experts. As such, the architecture description will be used to provide a detailed view of how the system components interact to ensure coherence across the project's layers. Within the context of TwinEU, the ADFs (wherever they apply) will structure the architectural description in a consistent and reusable way, making it easier to manage the complexity of the project. By providing proposed predefined structures like viewpoints, perspectives and aspects to manage the design of the TwinEU system, the standard provides important tools for organizing the different elements in the system involved in the project, like AI/ML tools and cloud-edge integration. This will help address the multi-dimensional nature of the TwinEU framework by having consistency across various technological pillars. This approach will ensure scalability and adaptability of the system architecture to accommodate the evolving needs across the project lifecycle.

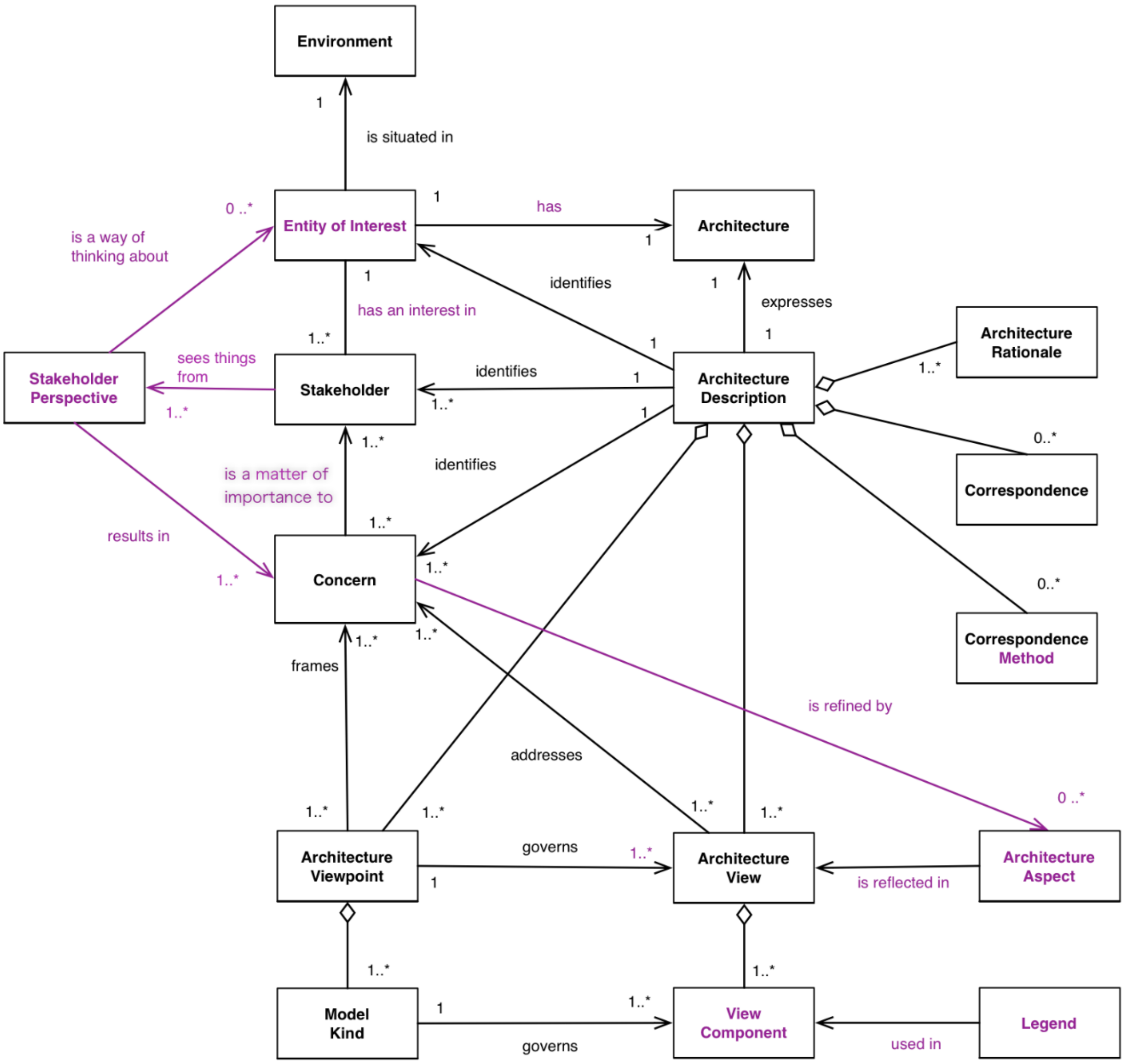


Figure 3: The Core Ontology: ISO/IEC/IEEE 42010:2022 (second edition) [3]

2.3 4+1 Architectural View Model

Software architecture involves designing and implementing the high-level structure of a software system. This process entails assembling various architectural elements in thoughtfully chosen configurations to meet the system's key functional and performance requirements, as well as addressing a range of non-functional requirements. The principles of software architecture are related to concepts such as abstraction, composition, and decomposition, alongside considerations of style and aesthetics. Aiming to accomplish an effective description of software architecture, models are often used that incorporate multiple perspectives of the system. One popular method for modelling system architectures in UML is the "4 + 1" view model. This approach provides a comprehensive perspective on system architecture by breaking it down into five interconnected views, each contributing to a full understanding of the system. Unified Modelling Language (UML) serves as a powerful tool for visualizing and documenting complex structures and descriptions of the "4 + 1" view model. In the TwinEU project, the "4 + 1" view model and its application in modelling system architectures using UML are aligned with the design needs and utilized to implement the TwinEU Architecture. The five main Views of the "4 + 1" model is namely:

- The Logical view, which is concerned with the overall functionality of the system mostly related to the end-user defining objects, components and classes,
- the process view, which focuses on the behaviour of the system and the dynamic flow of the information and control between various components and processes capturing concurrency and synchronization aspects of the system,
- the physical view, which presents the mapping of software onto the hardware elements from a system engineering perspective,
- the development view, which presents the static organization of the software from the software developer perspective,
- the use case scenarios that are used to combine the four views and depict the description of the architecture.

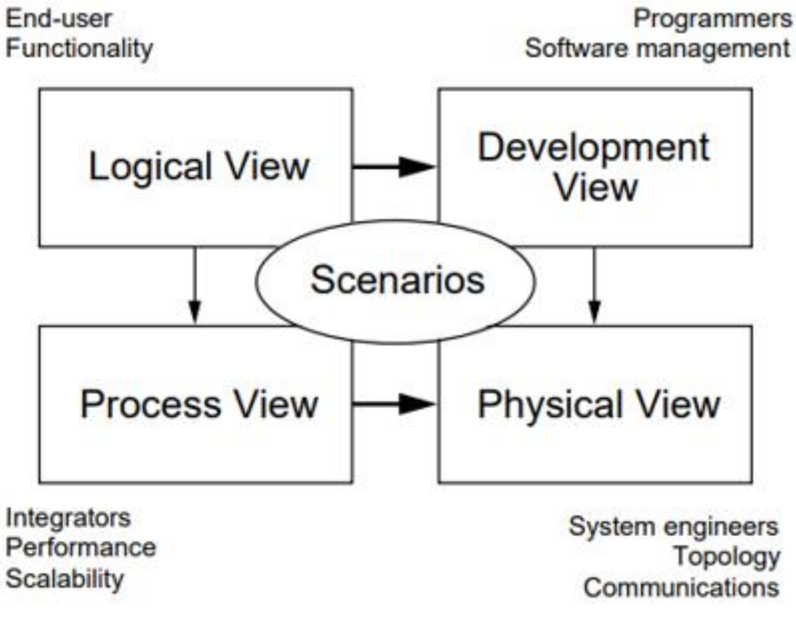


Figure 4: The "4 + 1" view model [2]

More specifically, **Logical View** focuses on the functional requirements of the system and what exactly the system should provide as services and operations to the user. For that reason, the system is decomposed of abstract elements such as objects, classes and components. The Logical view contains a set of UML diagrams such as class, state and component diagrams that illustrate their logical relationships, namely inheritance, usage, association, and composition. The **Process View** focuses on a set of non-functional requirements such as availability and performance. The process architecture presents the sequence of interactions and actions within the system, decomposing it in a set of independently executing logical networks of communicating programs (processes) and their internal tasks and sub-tasks. The Process View contains a set of UML diagrams such as communication, activity, and sequence diagrams.

The **Development View** focuses on the software module organization within the environment that is selected for software development. The software is decomposed in a hierarchy of layers such as program libraries, modules and subsystems. The Development view contains a set of UML diagrams such as components and package diagrams. The **Physical View** also focuses on non-functional requirements such as reliability, availability, scalability, performance and physical constraints. The Physical view depicts the software as a network of computers, servers or processing nodes that relate to various elements such as processes, components, networks, tasks and objects. The Physical View contains a set of UML diagrams such as deployment diagrams.

3 Architecture Models & Initiatives Alignment

This chapter provides a brief overview of reference architecture models and component frameworks for data processing across Europe, which are relevant to form the TwinEU RA.

3.1 Relevant reference architectures

3.1.1 BRIDGE DERA Reference Architecture

3.1.1.1 Introduction & Objectives

BRIDGE [74] is a European Commission initiative that brings together Horizon 2020 and Horizon Europe projects in smart grids, energy storage, digitalization, and energy islands. It fosters collaboration, promotes standardization through frameworks like DERA [29] and HEMRM, and supports EU policy alignment. Acting as a central forum, BRIDGE drives interoperability and cross-sector integration by sharing best practices and addressing regulatory and technical barriers. BRIDGE's structure is articulated through Working Groups (WGs) on:

- **Data Management:** Focused on communication infrastructure, data privacy, cybersecurity, and interoperable data handling.
- **Business Models:** Defines standardised valuation frameworks and explores simulation tools to assess emerging business model viability.
- **Regulation:** Establishes baseline regulatory conditions for smart grids and energy storage, including demand-side response and grid cooperation.
- **Consumer Engagement:** Analyses consumer profiles, motivations, and behavioural triggers to enhance engagement strategies.

These working groups feed into architectural planning, supporting the development of a coherent ecosystem that integrates digital tools and aligns with data space strategies and AI-enabled innovation.

3.1.1.2 BRIDGE Architecture

BRIDGE designs and implements individual structure and planning for each of its activity groups. The sum of these plans constitutes the BRIDGE Architecture.

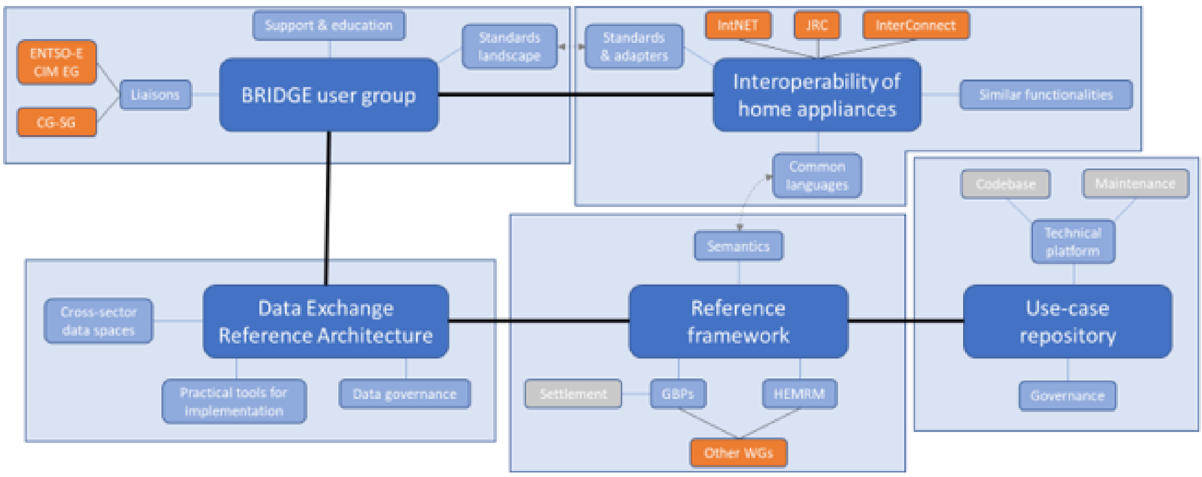


Figure 5: Overall Component Diagram related to the 5 BRIDGE Data Management cornerstones [30]

The Data Management structure and plan for BRIDGE is organized around five core internal actions, which define the purpose, methods, participants, and context of data exchange both within and beyond the initiative. These objectives and actions include the BRIDGE Use Case Repository, the Data Exchange Reference Architecture, the Reference Framework, the BRIDGE User Group, and the Interoperability of Home Appliances. Figure 5 illustrates the overall diagram that integrates and connects these components of BRIDGE Data Management.

The **BRIDGE Use Case Repository** [73] serves as a centralized hub for hosting use case descriptions based on IEC 62559, which includes libraries, role models, and frameworks designed to standardize use case descriptions. The repository incorporates role models and documentation of standards and solutions. It interacts with technical platforms and governance tools to achieve several goals:

- Simplify and standardize the definition of use cases for users with diverse backgrounds.
- Enable the reuse of existing use cases and solutions from past or ongoing projects.
- Provide a detailed dataset for cross-project research.
- Offer a comprehensive overview of all EU project use cases in a unified and accessible format.

Additionally, the Use Case Repository is directly connected to the Reference Framework, ensuring seamless integration and alignment across projects and initiatives.

The **BRIDGE Data Exchange Reference Architecture** (DERA 2.0) outlines the processes necessary to establish a fully interoperable and business-process-agnostic data exchange environment, both within Europe's energy sector and across other domains. This architecture ensures seamless integration with various cross-sector data spaces while addressing data governance, sovereignty, and the practical tools and methods needed for initiation, implementation, and utilization by diverse stakeholders [29]. The high-level SGAM-based reference architecture for European energy data exchange, as adopted by BRIDGE, is depicted in Figure 6.

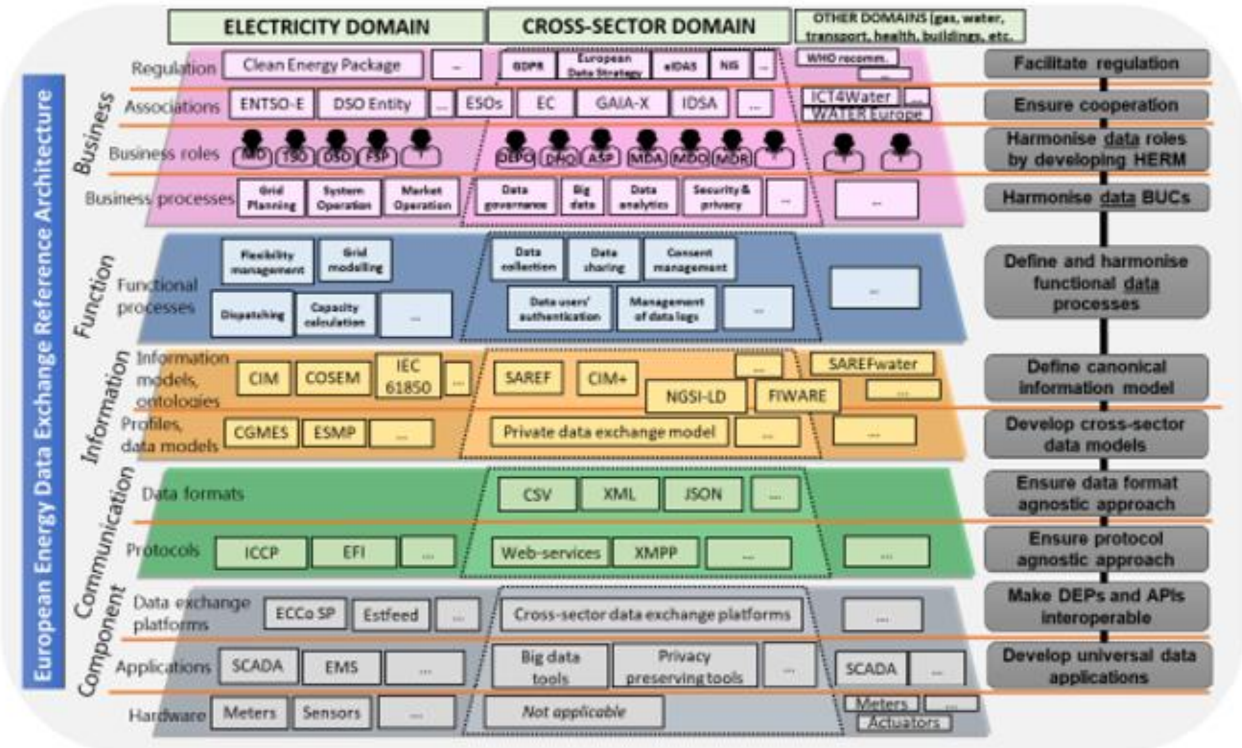


Figure 6: High-level SGAM based reference architecture for European energy data exchange [29]

The **BRIDGE Reference Framework** is the sum of the methodologies that are used to support interoperability of flexibility assets based on the solutions that are implemented in the projects. The Reference Framework [75] aims to add to the number of existing flexibility-related use cases that are applied in EU projects. Specifically, this framework is involved with the definition of flexibility, the generic business processes, and the functions and interfaces that are utilized. Figure 7 shows the position of the Reference Architecture in the methodology to study the interoperability of flexibility assets.

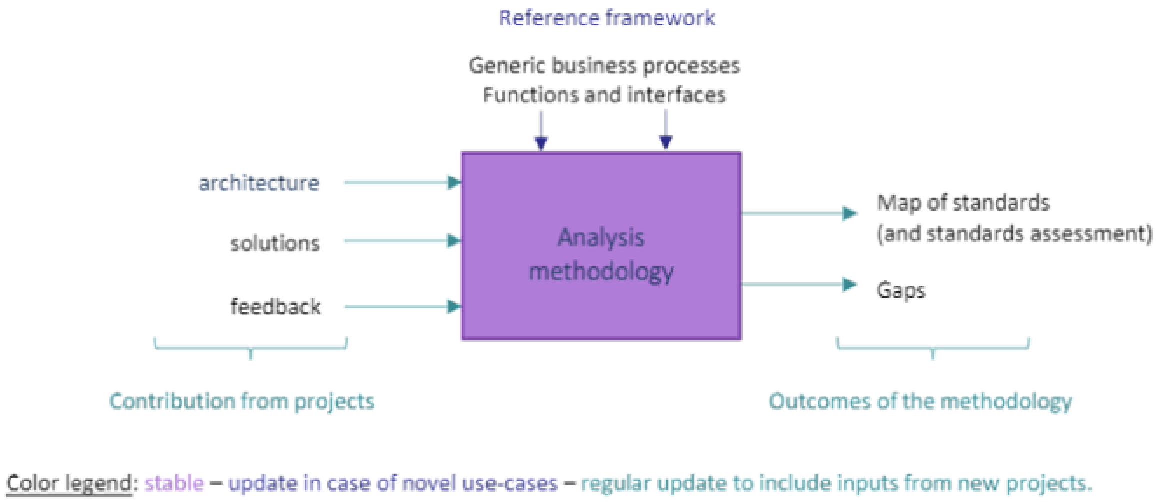


Figure 7: Description of the RA as part of the methodology to study the interoperability of the flexibility assets

The reference architecture focuses on the definition of the generic business processes, identifying seven of them, namely:

- Flexibility for SO through open market
- Flexibility for SO via prior bilateral agreement
- Flexibility for BRP portfolio optimisation
- Flexibility for energy community optimisation
- Implicit flexibility using dynamic steering signals
- Energy monitoring and energy management
- P2P trading in energy community

3.1.1.3 BRIDGE DERA 3.0 Architecture

The Data Exchange Reference Architecture (DERA) 3.0 [29] developed by the BRIDGE Data Management Working Group, aims to foster cross-sectoral, interoperable, and business process-agnostic data exchange in the European energy domain. It builds upon versions 1.0 and 2.0 by incorporating practical implementation feedback, aligning with EU digitalization goals (notably DESAP), and integrating with emerging data space frameworks such as Gaia-X, IDSA, and OpenDEI.

DERA 3.0 provides a layered, modular, and federated approach to energy data exchange that bridges local energy platforms (e.g., DSOs, energy communities) with federated data spaces, supporting a scalable and secure EU-wide energy data ecosystem.

DERA 3.0 is structured around the SGAM (Smart Grid Architecture Model) layers, while introducing clear differentiation between:

- Local platforms: e.g., DSOs, data hubs, metering systems.
- Federated data spaces: data marketplaces and cross-sector collaboration frameworks.
- Data Space Connectors: trusted intermediaries that enable secure, interoperable data flow between local and federated systems.

Key principles include:

- Data sovereignty and role-based access control.
- Protocol and format agnosticism.
- Semantic interoperability via shared vocabularies (e.g., CIM, SAREF).
- Open-source and standard-based integration.
- Cross-sectoral and cross-border reuse of services and data models.

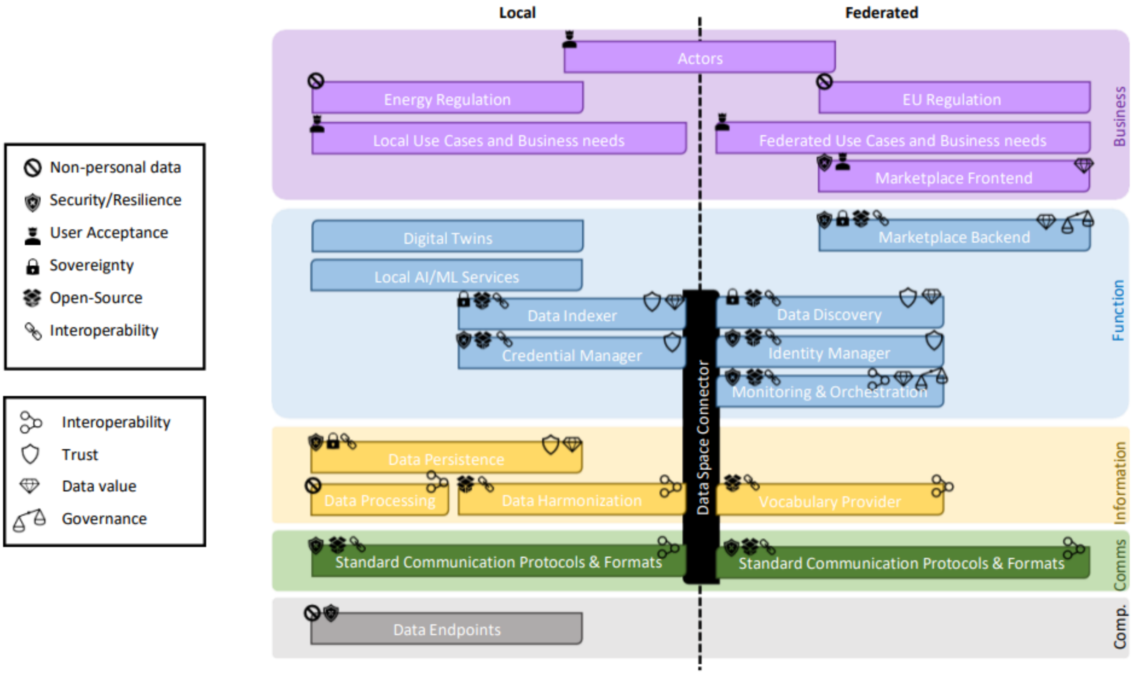


Figure 8: DERA 3.0 Layered Architecture and link to the DESAP and OPEN DEI Building Blocks [29]

3.1.2 SGAM

The Smart Grid Architecture Model (SGAM) is a framework developed to tackle the growing complexity and interoperability challenges in modern energy systems. SGAM offers a structured and holistic approach to conceptualize, develop, and integrate smart grid architectures. This ensures seamless interaction among various components and systems from different manufacturers, thereby facilitating efficient system integration and interoperability.[31]

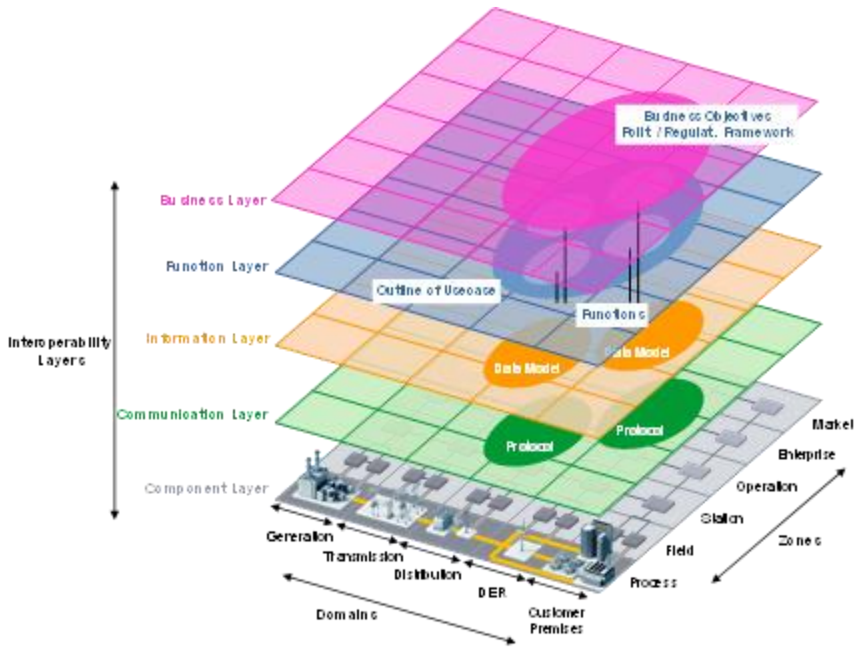


Figure 9. SGAM framework interoperability layers [31]

SGAM is structured into five interoperability layers, which are mapped across different domains and zones of the power system, as seen in Figure 9. These layers help in defining roles, interactions, and data flows within the smart grid ecosystem. The layers are as follows:

- **Business Layer:** Represents the business view on information exchange related to smart grids. SGAM can be used to map regulatory and economic structures, business models, and business processes. It aids executives and regulators in decision-making and market modeling.
- **Function Layer:** Describes functions and services, including their relationships from an architectural viewpoint, independent of actors, and physical implementations. Functions are derived from use case functionalities and are crucial for understanding the operational aspects of the smart grid.
- **Information Layer:** Focuses on the information used and exchanged between functions, services, and components. It includes information objects and canonical data models, ensuring common semantics for interoperable information exchange. This layer is essential for maintaining the integrity and consistency of data across the system.
- **Communication Layer:** Details the protocols and mechanisms for the interoperable exchange of information between components, considering the underlying use case, function, or service. This layer ensures that the communication infrastructure supports the necessary data flows and interactions required for smart grid operations.
- **Component Layer:** Emphasizes the physical distribution of all participating components, including system actors, applications, power system equipment, protection devices, network infrastructure, and computers. This layer provides a detailed view of the physical assets and their deployment within the smart grid.

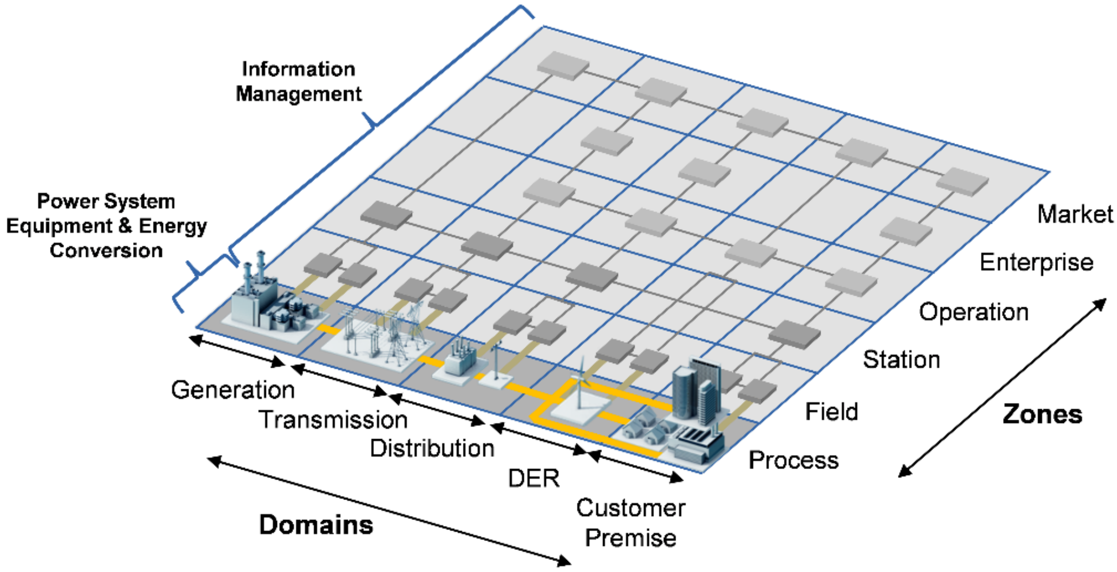


Figure 10. SGAM framework Domains and Hierarchical Zones [31]

These layers are integrated into a three-dimensional model that includes domains and hierarchical zones, see Figure 10:

- Domains:
    - **Generation:** This domain involves the production of electricity, typically at a high voltage, from various sources such as fossil fuels, nuclear, hydro, wind, and solar power plants.
    - **Transmission:** This domain includes the infrastructure and processes involved in transporting high-voltage electricity from generation sites to distribution networks. It encompasses transmission lines, substations, and related control systems.
    - **Distribution:** This domain focuses on delivering electricity from the transmission system to end consumers at medium to low voltage levels. It includes distribution lines, transformers, and distribution substations.
    - **Distributed Energy Resources (DER):** This domain refers to smaller-scale power generation sources that are connected to the distribution network. Examples include rooftop solar panels, small wind turbines, and battery storage systems.
    - **Customer Premises:** This domain represents the end-users of electricity, including residential, commercial, and industrial consumers. It involves the final delivery of electricity and encompasses various customer-side technologies such as smart meters, home energy management systems, and electric vehicles.
- Zones:
    - **Process Zone:** Physical, chemical or spatial transformations of energy (electricity, solar, heat, water, wind, etc.) and the physical equipment directly involved. (e.g. generators, transformers, circuit breakers, etc).
    - **Field Zone:** Equipment to protect, control and monitor the process of the power system, (e.g., protection relays, bay controller, etc).
    - **Station Zone:** Representing the areal aggregation level for field level (e.g. for data concentration, functional aggregation, substation automation, local SCADA systems, plant supervision, etc).
    - **Operation Zone:** Hosting power system control operation in the respective domain (e.g. distribution management systems (DMS), energy management systems (EMS) in generation and transmission systems, etc).

- **Enterprise Zone:** Commercial and organizational processes, services and infrastructures for enterprises (utilities, service providers, energy traders) such as asset management, logistics, work force management, staff training, etc.
- **Market Zone:** Reflecting the market operations possible along the energy conversion chain (e.g., energy trading, mass market, retail market, etc).

The context in which the SGAM framework will be used in this project is for defining the federation of digital twins and the underlying technical requirements. Therefore, the first three layers will be defined: the component layer, the communication layer, and the information layer. These layers define the technical characteristics of the architecture and allow the integration of the various software already used by each of the digital twins and the inclusion of data spaces to have more exhaustive control over the data exchange between the digital twins, forming their federation.

Specifically, the component layer allows for the generalization of all components defined for each use case, enabling the grouping of Digital Twins with similar functionalities and better structuring their federation. The communication layer performs a similar function to the component layer by identifying the current technologies used by each Digital Twin owner and integrating some of them, thereby improving communication management through data spaces. Finally, the information layer allows for the observation of data models and the types of data exchanged, defining what will be exchanged in these data spaces and managing and unifying data models for exchange. This creates new data models for the project and enhances data traceability and visibility.

3.1.3 COSMAG

3.1.3.1 Introduction

The Comprehensive Architecture for Smart Grid (COSMAG) focuses on analysing and consolidating specifications that define potential processes for data exchange among diverse stakeholders [32]. Its design is guided by the following core principles:

- **Alignment with European Goals**: The interactions are crafted to align with the European Commission's vision as articulated in the *Clean Energy for All Europeans* [33] package.
- **Openness for Future Innovation**: The architecture features "open gates" mainly data interaction points designed to accommodate future expansions and innovative use cases.
- **Building on Existing Standards**: COSMAG does not create new standards but instead builds on and integrates the results of previous projects and standardization efforts.
- **Promoting Competitive Markets**: The architecture explicitly avoids interactions that could lead to monopolistic practices or closed market conditions.

3.1.3.2 Data Flow Analysis

Modern grid applications demand seamless collaboration among multiple stakeholders. Figure 11 depicts all the anticipated interactions within the modern electricity market, providing a foundational reference for identifying potential data flows. By examining this diagram, each interaction between stakeholders can be analyzed to evaluate the current state of protocol definitions and data models.

3.1.3.2.1 TSO interactions

The internal data flow for TSOs has been well-established for a long time, requiring no further incremental adjustments.

- TSO-Market Interface: This interface is already standardized, though it continues to evolve, for instance, through updates like the network code on balancing.
- TSO-DSO Interface: This interface is still under development, with significant progress being made in various ongoing H2020 projects, such as SMARTNET [34] and CoordiNet [35].

3.1.3.2.2 DSO interactions

The internal data flow for DSOs is generally well-structured. The IEC61850 standard serves as a cornerstone, functioning both as an automation protocol and a data model for substations. Other key components of data standardization include IEC61970-301 and IEC61968-11, which define the core elements of the Common Information Model (CIM) [36]. CIM offers a comprehensive data model for power systems and facilitates seamless data exchange between grid operators at both the TSO and DSO levels. Embracing these standards within the DSO domain is highly recommended to strengthen TSO-DSO interactions.

- **DSO-Local Market Interface**: This interface is currently non-existent due to the absence of local markets. However, reference solutions for this interface have been proposed in the SMARTNET project.
- **DSO-Prosumer Interface**: While this relationship is still evolving, numerous experiments have been conducted to explore its potential. The primary focus of data exchange at this level involves generation control, with relevant solutions including IEC61850-7 and IEC61400-25, particularly for wind turbines. Communication between DSOs and prosumers (or consumers) also occurs during planned or unplanned service interruptions. Events such as maintenance, outage allocation, and service restoration should prompt data exchanges detailing schedules and estimated recovery times.

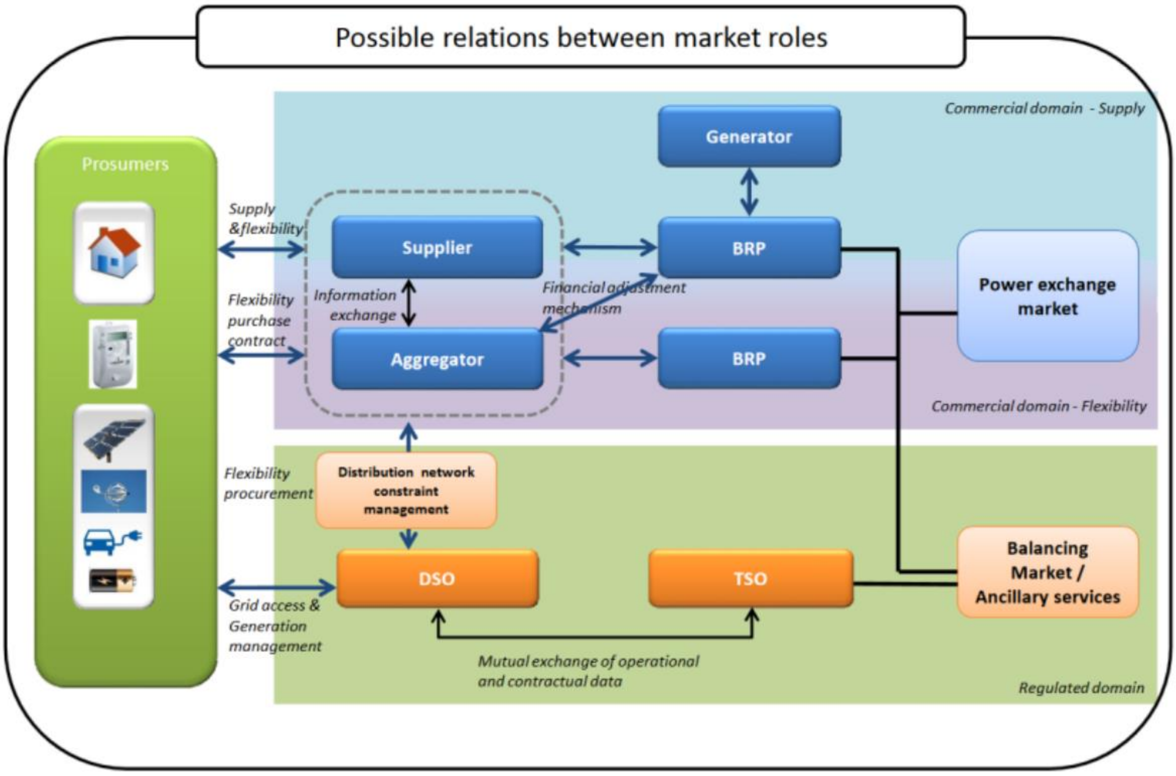


Figure 11: The structure of Market and Actor interactions [32]

3.1.3.2.3 Aggregator interactions

The role of Aggregators is relatively new, with current real-world applications primarily acting as intermediaries to the wholesale market.

- **Aggregator-Local Market Interface**: Standards for this interaction do not yet exist due to the absence of established local markets. However, the FP7 FINESCE [37] project proposed tools for implementing local markets, along with a comprehensive set of open-source APIs compatible with the FIWARE platform [38], which have been made publicly available. An interesting enhancement to these solutions could involve integrating the SAREF data model for improved information exchange.
- **Aggregator-DSO Interface**: This interaction is crucial for incorporating network constraints into aggregator planning. In the FINESCE project, ESB Ireland developed a complete solution using FIWARE technology, although proprietary protocols were employed for network management. Similar data exchanges are outlined in the USEF architecture [39]. The Nobel Grid [39] project demonstrated how aggregators and DSOs could interact through demand response requests to resolve network congestion using a negotiation process based on USEF and the OpenADR 2.0 protocol.
- **Aggregator-Prosumer Interface**: OpenADR has emerged as the leading standard in this domain and has been approved by the IEC as a Publicly Available Standard (PAS) under IEC/PAS 62746-10-1 [41]. The OpenADR data model has been mapped to the Common Information Model (CIM), aligning with the IEC's broader Smart Grid User Interface initiative (PC118). Recent research has explored integrating OpenADR with SAREF, and TNO has introduced the Energy Flexibility Interface (EFI), a model addressing flexibility to support diverse market needs. Additionally, a European Commission study highlights the strong compatibility between the SAREF approach and existing standards.

3.1.3.2.4 Prosumer interactions

- **Prosumer-Retail Interface**: The primary interaction in this interface involves the exchange of metering data. Several standards have been proposed for managing metering data and tariffs. The Open Metering System specification has played a key role in advancing standardization efforts, with three protocols emerging as prominent standards: M-BUS, DLMS/COSEM, and SML. Additionally, open-source Domain-Specific Enablers and APIs were introduced during the FINESCE project, leveraging a FIWARE-based platform. This approach enables the integration of smart metering data into the larger Smart Cities ecosystem.
- **Prosumer-Prosumer Interface**: Recent initiatives have introduced solutions based on peer-to-peer market models, allowing customers to connect directly and establish contracts with one another. Many of these solutions utilize Blockchain technology for contract management. For example, the eDREAM [42] project demonstrates the use of self-enforcing smart contracts to create a price-driven peer-to-peer energy marketplace. This approach supports local trading and consumption of energy generated within micro-grids.

3.1.4 FIWARE Smart Energy Reference Architecture

3.1.4.1 Introduction

The FIWARE Foundation is a non-profit organization founded in 2016 that drives the definition and adoption of open standards to develop smart solutions, based on open-source technologies, in a multitude of industrial domains. It has more than 400 members from all over the world, including large and small companies as well as research and academic institutions. The mission of FIWARE is "*to build* *an open sustainable ecosystem around public, royalty-free and implementation-driven software platform standards that will ease the development of new Smart Applications in multiple sectors*". This is done via the development of open-source software platform components that can be used within a fully FIWARE-powered platform or together with third party components to build hybrid platforms aimed at implementing and deploying smart applications and services in different domains.

3.1.4.2 FIWARE Open Reference Architecture

The FIWARE software architecture builds upon the concepts of Context and Context Information. The Context is the collection of the Digital Twins associated to the system under analysis. Each Digital Twin, in turn, can be defined as the digitalized, virtual representation of either a physical asset or a specific concept belonging to the considered system. The data associated with the different attributes of each Digital Twin represent the Context Information. Handling and sharing, via ad hoc methods, the Context Information is the key aspect of the FIWARE architecture. To this purpose, the FIWARE architecture includes a specific Generic Enabler (GE), the Context Broker, which takes care of this task (GEs are the building blocks of the FIWARE architecture; they can be defined as software components able to provide a well-defined functionality and they expose open APIs for the integration in the platform). Having a FIWARE Context Broker is the only requirement to define a platform "powered by FIWARE" (other platform software components can come from the FIWARE Catalogue of GEs or can be taken from third parties). The central role of the Context Broker is reflected also in the FIWARE Open Reference Architecture. This is a three-layered architecture composed of (starting from the bottom):

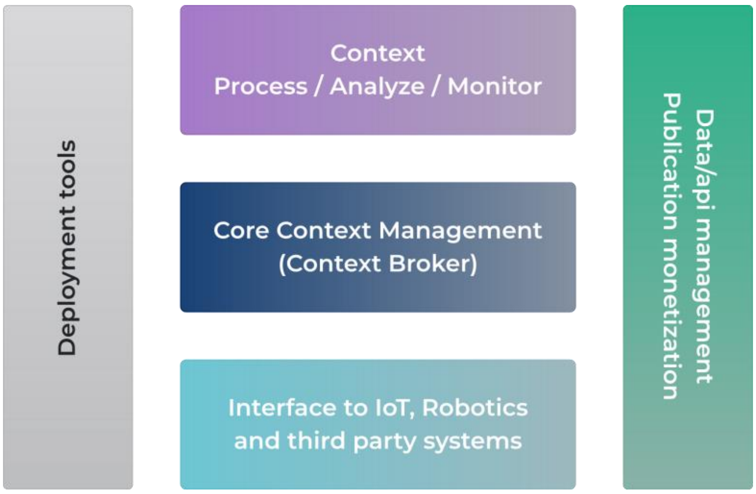


Figure 12: FIWARE Open Reference Architecture [43]

- **Interface to IoT, Robotics and third-party systems**: it is the bottom layer of the architecture; it includes all the agents required for the interconnection to field devices or other systems, from which the data are collected and towards which the actuation commands are sent. The FIWARE catalogue contains several GEs conceived to facilitate the connection to several physical components.
- **Core Context Management (Context Broker)**: as already anticipated, this is the heart of the FIWARE architecture. It keeps, handles and exposes all the information related to the digital twins of the physical (or non-physical) objects in the system.
- **Context Processing, Analysis and Visualization**: it is the upper layer of the architecture; it includes all those GEs or third-party software components employed for the further processing of the

Context Information, for enriching the value of the available information (data analytics tools) or for presenting the information to the user by means of dedicated graphical interfaces.

In parallel to the three layers, the FIWARE Reference Architecture has additional GEs developed to address cross-cutting concerns, such as security GEs. In this regard, the FIWARE catalogue offers a set of GEs aimed at dealing with the aspects related to Identity and Access Management, as well as additional GEs that foster the publication and monetization of data.

3.1.4.3 FIWARE Smart Energy Reference Architecture

Starting from the Open Reference Architecture depicted in Figure 12 FIWARE Reference Architecture has been adapted to specific domains [44]. The FIWARE Reference Architecture tailored to the Smart Energy Management Services domain within the power system sector. Beginning from the bottom of the architecture, you will find physical devices (or objects) relevant to Energy Management, along with other potential sources of information. These devices can be connected to the software platform either through specific agents from the FIWARE Catalogue or via third-party IoT systems, ensuring the necessary connectivity at this level. Data from the physical system, collected through these interfaces, is then transmitted to the Context Broker. As shown in Figure 13, the Context Broker contains digital twins of various power system entities, managing their related data and making it accessible via open APIs. The upper layers include various processing and visualization tools that utilize the Context Information provided by the Context Broker to manage, control, and optimize the energy system. Additionally, specific GEs or third-party components can be integrated across the architecture to ensure security and enable data monetization.

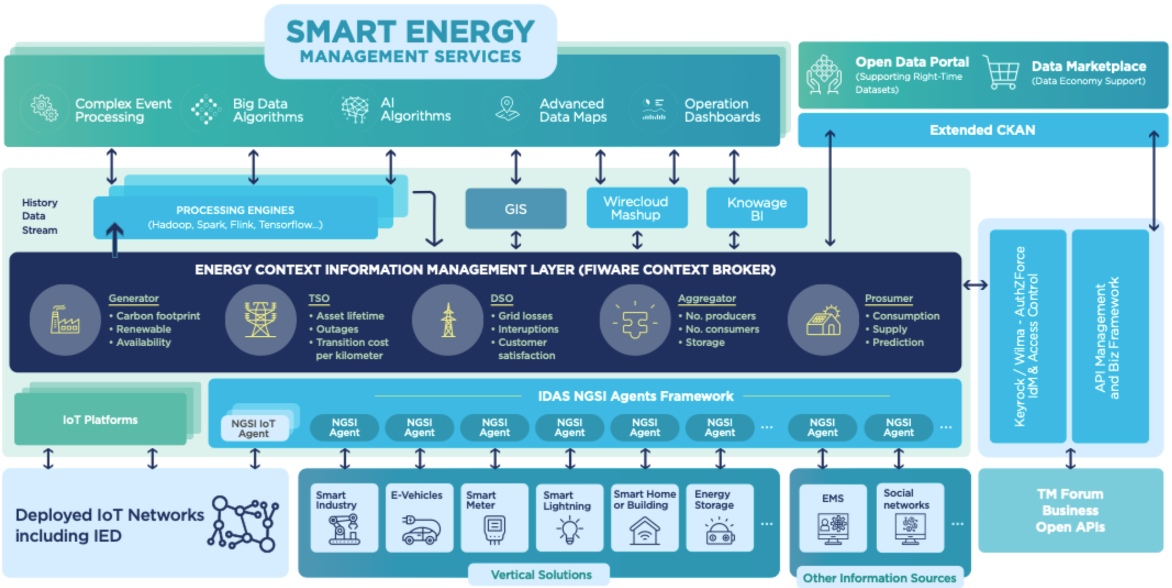


Figure 13: FIWARE Smart Energy RA [44]

3.1.5 AIOTI HLA

The mission of the Alliance of Internet of Things Innovation (AIOTI) is to foster the European IoT market uptake and position by developing ecosystems across vertical silos, contributing to the direction of H2020 large-scale pilots, gathering evidence on market obstacles for IoT deployment in the Digital Single Market context, championing the EU in spearheading IoT initiatives, and mapping and bridging global, EU and Members States' IoT innovation and standardisation activities [4]. The Alliance for IoT and Edge Computing Innovation (AIOTI) is a collaborative initiative that defines a standardized Reference Architecture aimed at providing a unified framework with reusable interfaces and structures for IoT systems and deployments. Furthermore, AIOTI plays a key role in the standardization process, bringing together a range of established standards and protocols to streamline and harmonize their use across the IoT landscape. In addition to offering a Reference Architecture specifically for IoT deployments, AIOTI also provides important considerations related to various architectural aspects of IoT. These include:

1. Interoperability,
2. Data security,
3. Virtualization,
4. Privacy,
5. Data Marketplaces,
6. Edge and cloud computing, and
7. Big Data analysis.

These elements are crucial for effective and secure IoT deployment strategies.

The AIOTI High-Level Architecture places the “thing” (of the Internet of Things) at the centre of value creation. As is depicted in Figure 14, AIOTI initially focuses its recommendations on the Functional and Domain models regarding the set of the Architectural Models introduced by ISO/IEC/IEEE 42010 [28]:

- The Domain Model captures the entities that participate within an IoT domain and the relationships between them.
- The Functional Model describes interfaces and functions within the IoT domain.

The rest of the models are described within future releases of the AIOTI HLA.

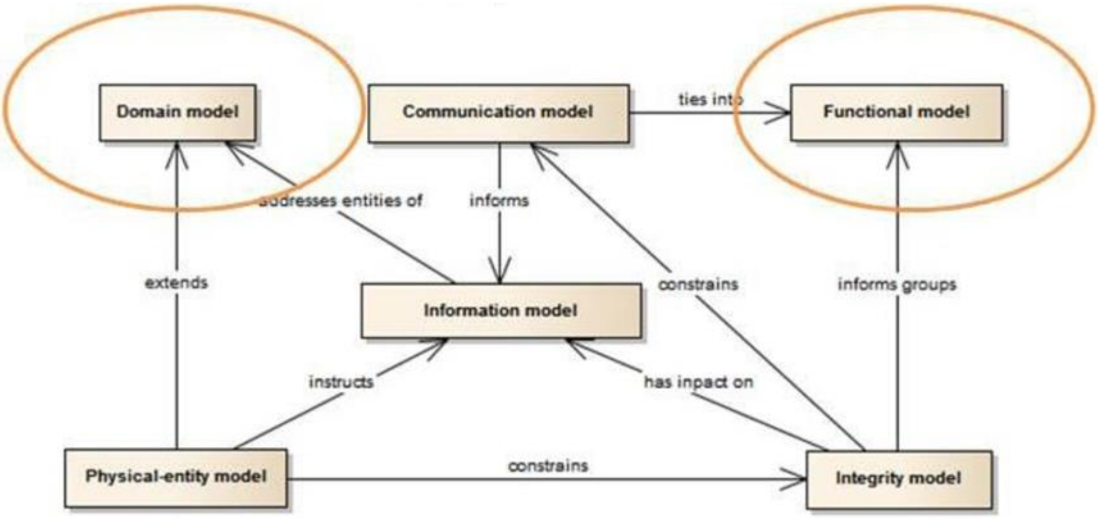


Figure 14: Architectural Models of ISO/IEC/IEEE 42010 standard [28]

3.1.5.1 AIOTI Domain Model

The domain model outlines the key concepts and their relationships within the IoT space at a high level. By defining and naming these relationships and concepts, the model establishes a shared vocabulary, which serves as the basis for other models and taxonomies. In the AIOTI domain, the primary entities include the IoT Device, the User, the Virtual Entity, the IoT Service, and the Things. These entities are designed to represent any IoT ecosystem built with AIOTI's framework. At the heart of the AIOTI domain model is the interaction between a user and a physical entity, or "thing," which is facilitated by the other entities mentioned as depicted in Figure 15.

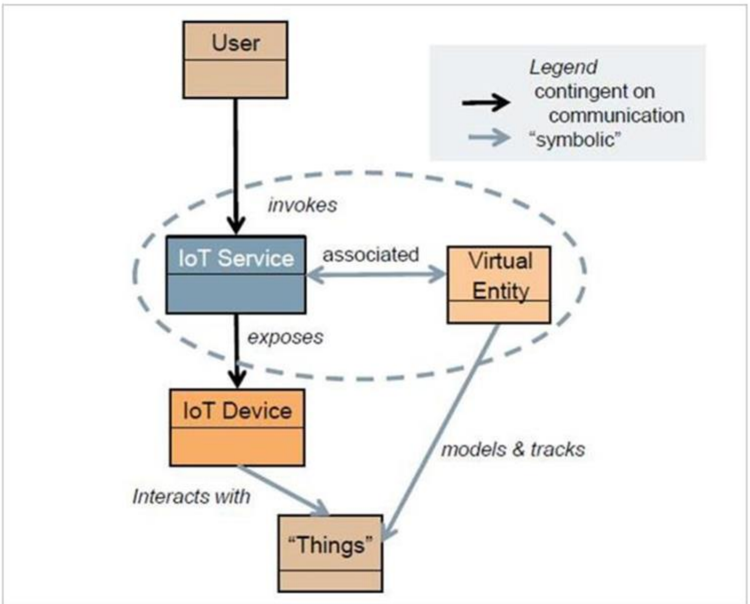


Figure 15: AIOTI Domain Model [28]

3.1.5.2 AIOTI Functional Model

As mentioned earlier, the AIOTI Functional Model outlines the functions and interfaces within the AIOTI framework. Notably, this model also takes into account certain interactions beyond the domain.

The AIOTI functional model is structured into three key Layers:

- **Network Layer**: This layer offers two categories of services. The first is data plane services, which handle both short- and long-range connectivity and manage data forwarding between entities. The second is control plane services, including functions like location tracking, device triggering, and ensuring system determinism.
- **IoT Layer**: Focused on IoT-specific operations, this layer handles data storage, sharing, and interaction with the network layer. It makes these functions accessible to the application layer via APIs (Application Programming Interfaces).
- **Application Layer**: This top layer facilitates process-to-process communications by providing the necessary communication protocols and interface methods.

In this context, "layer" refers to a software architecture concept where each layer groups related modules that offer a consistent set of services.

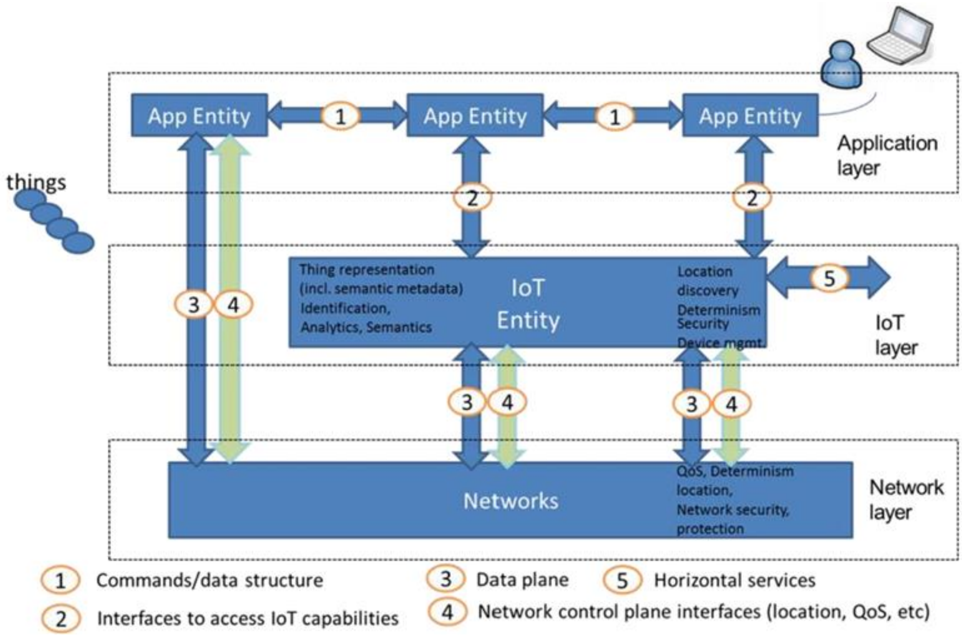


Figure 16: AIOTI Functional Model with its interfaces [28]

Figure 16 illustrates the different interfaces and the corresponding entities involved in each interaction. A brief description of these interfaces is provided below:

1. **Data/Command Structure Interface:** This defines how data is structured when exchanged between App Entities. Common examples include commands, measurements, authentication, authorization, etc.
2. **IoT Capabilities Access Interfaces:** This interface allows entities to access services provided by an IoT Entity, such as subscribing to notifications, consuming or exposing data, and registering for updates.
3. **Network Data Plane Interface**: Responsible for transmitting and receiving data across networks to communicate with other entities.
4. **Network Control Plane Interfaces**: This interface provides access to network control services, like triggering a device, tracking its location, enabling Quality of Service (QoS) bearers, or ensuring deterministic flow delivery.
5. **Horizontal Services Interface**: Facilitates the sharing and requesting of services between IoT Entities. It is used in scenarios such as a gateway to upload data to the cloud, retrieving a software update, or managing a device's software image.

Regarding the entities that participate within the AIOTI Functional Model there are three main categories. The App Entity which an entity in the application layer that implements IoT application logic. An App Entity can reside in devices, gateways or servers. The IoT entity is an entity in the IoT layer that exposes IoT functions to App Entities through the interface “2 IoT Capabilities Access Interfaces” or to other IoT entities through the interface “5. Horizontal Services Interface”. Finally, the networks can be implemented of different network technologies (PAN, LAN, WAN, etc.) and consist of different interconnected administrative network domains.

3.1.6 OPEN DEI

OPEN DEI [4] was developed under the EU Horizon 2020 project between 2019 and 2022, with the aim of proving an important contribution to the implementation of Digitizing European Industry policies. The project focuses on leveraging synergies, identifying gaps, sharing best practices, reinforcing regional/national relationships as well as putting in place the necessary joint measures to implement common dissemination, communication, training and exploitation action plans among the Innovation Actions implementing the EU Digital Transformation strategy [6]. It uses "Platforms and Pilots" to support the implementation of digital platforms in four fundamental industries: Manufacturing, Agriculture, Energy, Healthcare [7]. The work and activities within the project cover the following topics [8]:

- **Platform Building,** comparing different reference architectures and open-source reference implementations, promotes the development of a unified industrial platform that is up to date with the most recent technological innovations.
- **Large Scale Piloting,** creating a set of assessment methods and a migration journey benchmark tool, contributes to the digital maturity model.
- **Data Ecosystem Development:** Enabling an innovation and collaboration platform, forging a European network of DIHs, contributing to industrial skills catalogue and observatory.
- **Standardization:** Conducting cross-domain surveys, performing promotion and implementation, building strives alliances with existing EU and standard developing organizations.

OPEN DEI proposes a conceptual model for integrated data-driven services for Digital Transformation guidelines, to support their planning, development, operation, and maintenance by adopting organizations. The model is modular and includes loosely coupled service components interconnected through a shared common data infrastructure. The OPEN DEI project has defined the approach for designing a common RAF able to describe the Cross Domain Digital Transformation.

3.1.6.1 OPEN DEI Reference Architecture

OPEN DEI is one of the more generic enhancements of the BDVA reference architecture [9]. It aligns the reference architecture of BDVA with the requirements of open platforms and large-scale pilots for digital transformation. The OPEN DEI RA framework is built upon six fundamental principles which are applicable to digital platforms for data-driven services [10]:

- interoperability through data sharing
- openness of data and software
- reusability of IT solutions, information, and data
- security and privacy
- avoiding vendor lock-in and
- supporting a data economy

OPEN DEI's RA is illustrated in Figure 17. It has three dimensions, with the third dimension providing directions for implementation according to the underlying philosophy of the framework. The horizontal layers include Field Level Data Spaces, Edge Level Data Spaces, and Cloud Level Data Spaces in which data is shared. The Smart World Services included in the Field Level Data Spaces enable interaction with IoT, automation systems and humans. The Edge Level Data Spaces provides services for data acquisition, brokering and processing. Cloud Level Data Spaces include different operations on the cloud such as data storage, data integration and data intelligence. These data spaces offer the services to the main orthogonal dimension of the RAF – the X-Industry Data Spaces. The X-Industry Data Spaces provide trustful and secure communication, data sharing and data trading through appropriate technical infrastructure and development frameworks. All these data spaces support the implementation of Digital Transformation X-Industry Pilots for specific business scenarios. The main enhancement of the BDVA reference architecture by OPEN DEI RAF is in embedding innovation and commercialization directly into the architecture through the concepts of data spaces, smart services and industry pilots.

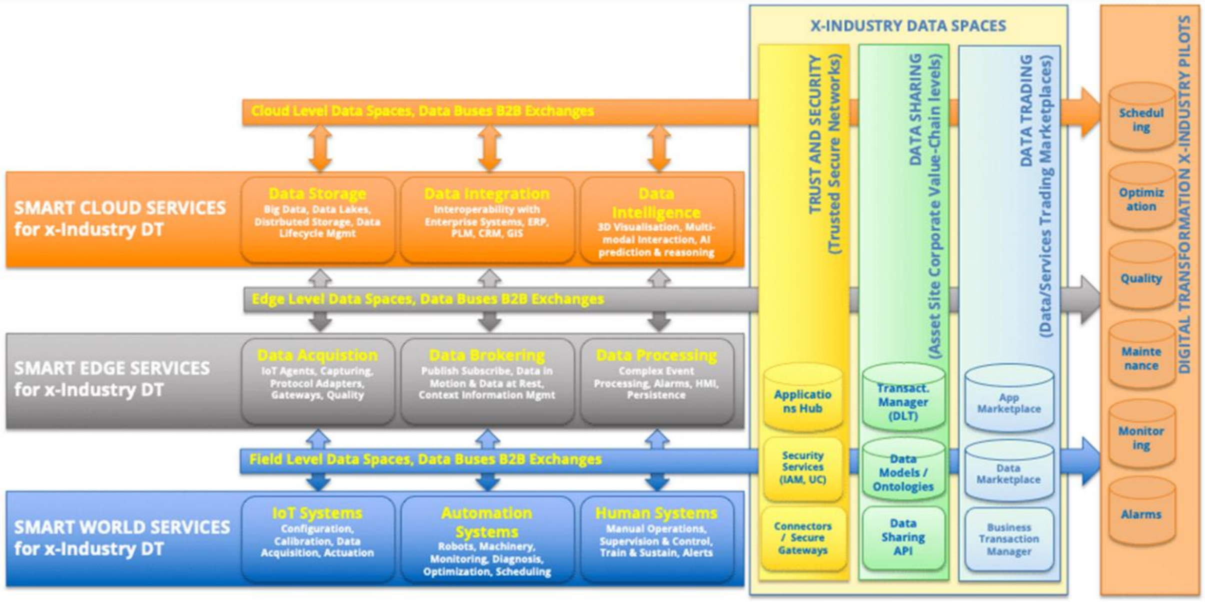


Figure 17: OPEN DEI Reference Architecture [10]

A common scenario in the implementation of many DT solutions and industrial sectors is the extensive use of sensors and interconnected devices. The availability of this huge amount of information coming from different data sources can cover many business applications and scenarios. Data-driven pipelines and workflows management are crucial for data gathering, processing, and decision support. To handle this complexity, OPEN DEI has adopted the so called "6C Architecture", adapted from the one suggested by the German "*Plattform Industrie 4.0 Initiative*" [11]", which is based on i) **Connection**: sensors & networks, ii) **Cyber**: model & memory, iii) **Computing**: edge/cloud and data on demand, iv) **Content/Context**: meaning & correlation, v) **Community**: sharing & collaboration, and vi) **Customisation**: personalisation & value. The six levels mean connection of different data sources and networks, cyber modelling mechanisms, computing of data (in the edge or in the cloud), content/context correlation, community engagement, and customization tailored to the user perspective and expectations. The "6C Architecture" principles have led to the design of the OPEN DEI RAF, developed around the main concept of Data Spaces in which data are published, accessed, and shared. The OPEN DEI RAF may drive the definition of the TwinEU Data Space, providing a set of common models, principles and recommendations, to gather data and process them doing with the purpose of reaching the Digital Transformation using a cross-sector mindset, at the same time ensuring the trust and secure behaviour during the exchange.

3.2 Data-driven initiatives & specifications

3.2.1 IDSA

The International Data Spaces Association (IDSA) [49] is a non-profit organization dedicated to developing and promoting standardized frameworks for data spaces—secure environments where organizations can exchange data while maintaining full control over its usage. Comprised of over 140-member organizations, including industry leaders and innovators, the IDSA envisions a future where data providers maintain complete data sovereignty and maximize the value of their data through secure, equitable partnerships. The IDSA brings together companies, researchers, policymakers, and other key stakeholders in an open, non-profit consortium to establish the technical standards necessary for the emerging data-driven economy. Since 2017, the IDSA has played a crucial role in advancing key technologies for data spaces, leading to important achievements such as the International Data Spaces Reference Architecture Model (IDS-RAM) [47], the IDSA Rulebook, the Dataspace Protocol, standardization efforts, and IDS Certification. These accomplishments provide the foundation for a fair and trusted data economy, establishing clear guidelines for secure and transparent data sharing. With its IDS-RAM (International Data Spaces - Reference Architecture Model), the IDSA association defines a model for the architecture of a data ecosystem. This model has a high level of abstraction and focuses on the generalization of concepts, functionality, and overall processes needed to create a secure network of trusted data. The model is made of five layers and comprises three perspectives that need to be implemented across all five layers, as can be seen in Figure 18:

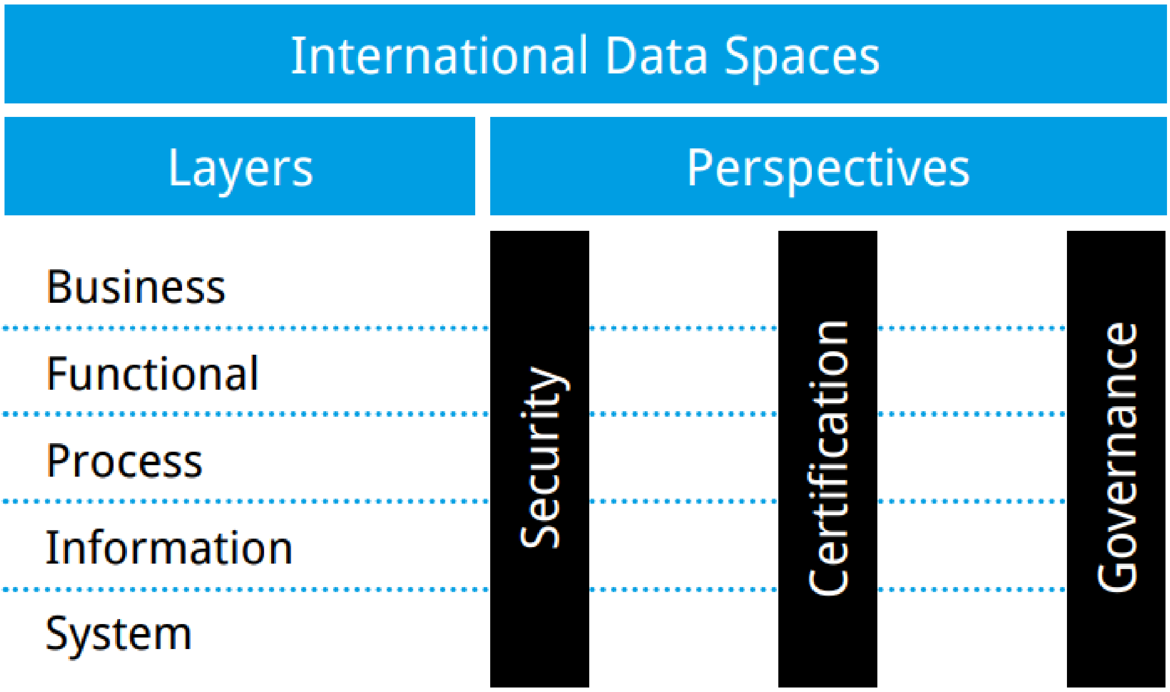


Figure 18: IDSA Reference Architecture Model [47]

- The **Business Layer** defines the different roles and basic patterns of interaction taking place between roles. This layer can be considered a blueprint for the more technical layers.
- The **Functional Layer** defines the functional requirements and the features to be implemented. It comprises six blocks: Trust, Security and Data Sovereignty, Ecosystem of Data, Standardized Interoperability, Value Adding Apps, and Data Markets.
- The **Information Layer** supports the description, publication, and identification of data products and reusable data processing software, which are referred to as Digital Resources or Resources.
- The **Process Layer** specifies the interactions taking place between the different components and provides a dynamic view of RAM. It involves the processes of Onboarding, Data Offering, Contract Negotiation, Exchanging Data, and Publishing and using Data Apps.
- The **System Layer** describes the core technical components of IDS. On this layer, the roles specified on the Business Layer and the processes defined in the Process Layer are mapped onto concrete data and service architecture. These components and their interactions are depicted in Figure 19, which doesn’t show the Identity Provider only for readability purposes.

As for the three Perspectives:

- **Security:** Ensures that security measures are integrated across all layers.
- **Certification:** Confirms standards and procedures for compliance with IDS-RAM.
- **Governance:** Provides guidelines for managing data space operations.

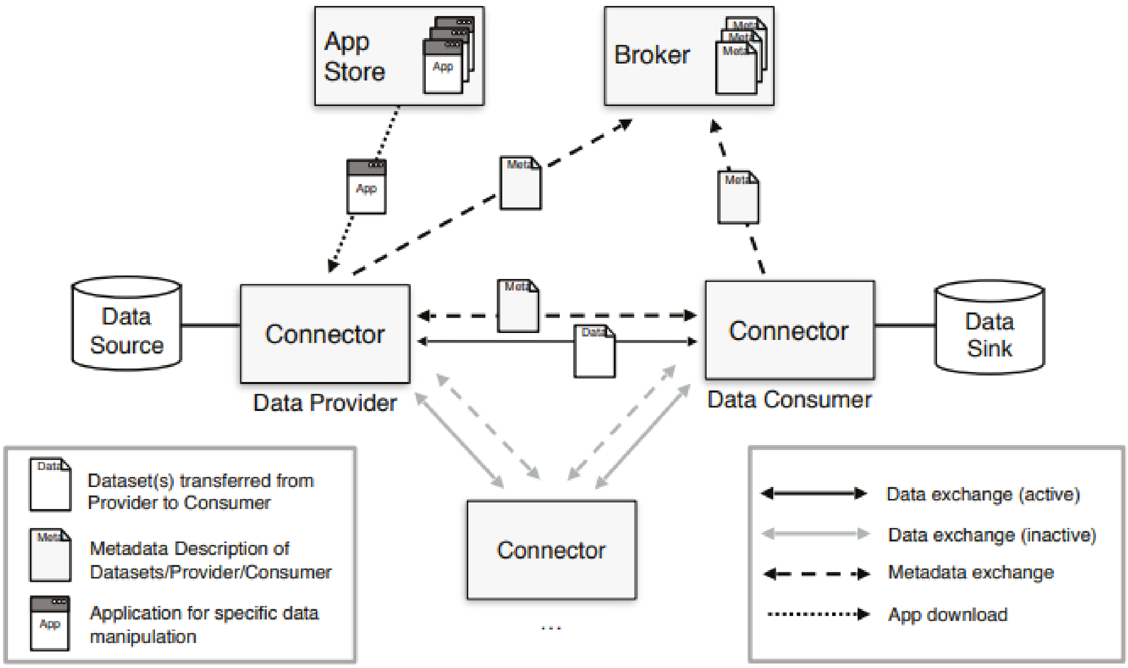


Figure 19: Interaction of Technical Components [47]

The Connector, the Broker, and the App Store are supported by other (4) additional components which are the Identity Provider regarding the Security Perspective, the Vocabulary Hub currently as defined outside the IDS, the Update Repository (i.e. the source for updates of deployed Connectors) depending on the connectors technology, and the Trust Repository (i.e. the source for trustworthy software stacks and fingerprints as well as remote attestation checks) regarding also the Security Perspective. IDS Apps are services for realizing business logic inside the connector. IDS Data Apps are used to process data, connect to external systems, or control the IDS Connector. Therefore, they can be downloaded via the App Store and deployed by the connector.

3.2.1.1 IDSA Connector

The Connector is a software component composed of specific key elements, including one or more physical or virtual machines, operating systems, an Application Container Management system, and the Connector Core Service(s) layer. The elements related with the actual connector concept are the following:

- **Certified Core Container:** This container houses the Connector Routing Core Service, which encompasses vital components such as Metadata Management, Data Management, Contract and Policy Management, IDS Protocols Authentication, IDS App Management.
- **Application Container Management:** The deployment of Connector Core Service(s) and selected IDS Apps relies on application containers. These isolate IDS Apps, preventing unwanted interdependencies. Application Container Management provides enhanced control

over IDS Apps and containers. In development environments or systems with limited resources, this management layer can be omitted.

- **Certified App Container:** A container that is downloaded from the App Store and provides a specific IDS App to the IDS Connector. This container is pre-certified.
- **Custom Container:** A container designed for deploying self-developed Custom Apps. Unlike certified containers, these do not require certification.
- **IDS App:** An application which defines a public API, called by the IDS Connector. The API is formally described in a meta-description imported during the app's deployment phase. IDS Apps can have extensive functionalities and can be developed in various programming languages, for different runtime environments. This allows for the reuse of existing components, easing migration from other integration platforms.
- **Runtime Environment:** The runtime environment for Custom/Certified Apps and Certified Core Containers is determined by the technology and programming language selected. The runtime, along with the application itself, forms the core of a container. Different containers may utilize different runtime environments, and the available runtimes depend on the host computer's base operating system. Service architects can choose the runtime most appropriate for their needs from the available options.

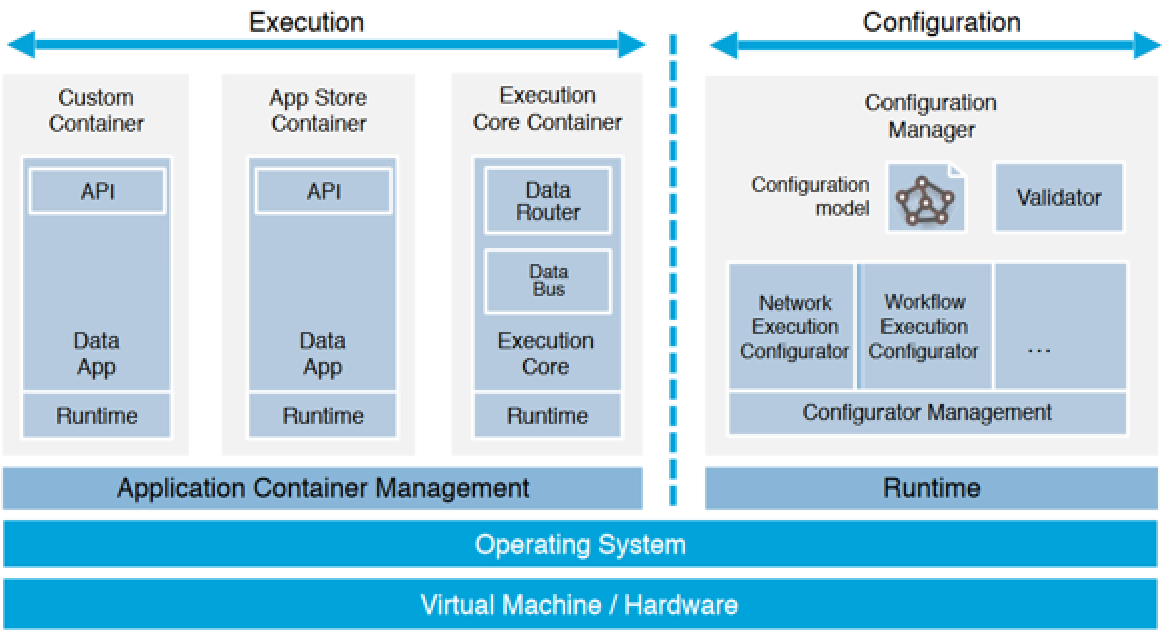


Figure 20: IDS Connector Architecture [47]

3.2.2 BDVA

The European contractual Public Private Partnership on Big Data Value (BDV PPP) [24] [50] was signed in October 2014, marking the commitment of the European Commission, industry, and academia to build a data-driven economy across Europe, creating a competitive advantage for European industry, stimulating economic growth and job opportunities. Its goal is to enable the creation of a European Big Data Value economy, supporting, boosting, and mobilizing stakeholders throughout society, industry, academia, and research, and delivering services and technologies, while providing highly skilled data engineers, scientists, and practitioners along the entire Big Data Value chain. The Big Data Value Association was established in 2014 as the private counterpart of the European Commission in the Big Data Value Public Private Partnership. It is an industry-driven research and innovation organisation with a mission to develop an innovation ecosystem that enables the data-driven and AI-enabled digital transformation of the economy and society in Europe [12], with a focus on areas such as big data technologies, data platforms and data spaces, Industrial AI, data-driven value creation and standardisation. The BDVA has over 240 members from all over Europe representing large, small, and medium-sized industries, research, and user organizations. Its objectives are to create a positive societal impact though influencing policy making and businesses with the use of data and AI, ignite world class research on Data and AI for competitiveness and create new projects and leverage their value, and ultimately contribute the drive towards a sustainable future.

Emerging data ecosystems enable large-scale data to be securely connected, valorised, and shared through the following three complementary technologies [25]:

- **Data Spaces:** Serve as ecosystems that manage data storage, models, lifecycle management, and governance, all while streamlining data exchange and fostering new knowledge.
- **Data Platforms:** Modern systems designed for acquiring and processing data efficiently.
- **Data Marketplaces:** Act as digital hubs where data providers and consumers can connect, trade, and maximize the value of data assets and algorithms. These marketplaces ensure interoperability across different data spaces and facilitate B2B transactions using concepts like Open Data, Monetised Data, and Trusted Data sharing.

To create a successful European data space which can generate value in the economy by broadening data access to AI, a clear plan for iterative implementation strategies is required by all involved stakeholders. Therefore, there is a key requirement and concept of trust and security which must be present in such an ecosystem. This is true across the entire data value chain, from validating the data itself and the algorithms operating on it, to the governance of the data space, and its users. To establish trust, these five pillars need to meet specific criteria [13]:

- **Data:** Promote free movement of data through strategies that embed sharing by design (e.g., interoperability) and clear guidelines for valuing data assets.
- **Governance:** Foster trust with European rules and values, ensuring open participation and transparent, fair rules.
- **People:** Ensure privacy and fair compensation for personal data sharing, while upskilling the workforce to meet new market demands.
- **Organizations:** Encourage a shift towards a data-centric culture, exploring new data-driven business models and value flows.
- **Technology:** Develop safer environments for testing technologies related to trustworthy data and algorithms, with quicker adaptation to emerging standards.

The BDVA highlights two key opportunities that arise from effective data-sharing initiatives in Europe:

1. **Wider Data Access:** Create a secure, decentralized data space to fully harness AI's potential, enabling democratic data sharing and strengthening Europe's data economy.
2. **European-Governed Data Space**: Establish a European-led data space that drives global efforts in AI and data solutions, aligning with European values of democracy, privacy, and equality, and engaging with a broad range of stakeholders [13].

The portfolio of the Big Data Value PPP covers the data platform projects within the Energy Industry include:

- **BD4NRG,** which delivers a reference architecture for Smart Energy, which aligns with the BDVA, IDSA, and FIWARE reference models and architectures to enable B2B multi-party data exchange while providing full interoperability of leading-edge big data technologies with smart grid standards and operational frameworks.
- **BD4OPEM, which** develops an analytic toolbox to improve existing energy services and create new ones, all available in an open innovation marketplace.
- **PLATOON** facilitates deploying distributed/edge processing and data analytics technologies for optimized real-time energy system management in a simple way for the energy domain expert.
- **SYNERGY**, which introduces a novel reference big data architecture and platform that leverages data, primarily or secondarily related to the electricity domain, coming from diverse sources.

Additionally, close cooperation between the AIOTI and the BDVA has brough significant benefits in these key areas:

- Alignment of high-level reference architectures: Developing a shared understanding between AIOTI's HLA and BDVA's Reference Model helps make informed decisions about future tech impacts.
- Understanding Sector Needs: Through the mutual exchange of roadmaps and insights will provide BDVA with valuable input on the drivers and barriers to big data adoption across different sectors.
- **Standardization Efforts**: Aligning standardization activities between IoT and big data tech is crucial. BDVA can also leverage AIOTI’s existing partnerships with standard bodies to address big-data standardization needs more effectively.

3.2.2.1 BDV Reference Model

BDVA has developed the BDV Reference Model, by considering information from technical experts and stakeholders along the entire big data value chain, as well as interactions with the other related PPPs [14]. The BDV Reference Model acts as a common reference framework to identify big data technologies on the overall IT stack and addresses the main aspects and considerations for any big data value system. An overview of the BDV Reference Model is shown in Figure 21. It is structured into horizontal and vertical concerns:

- **Horizontal concerns** cover specific areas along the data processing value chain, from advanced visualization approaches for improved user experience [15], data analytics which ranges from descriptive, through predictive, and to prescriptive analytics [16], to data processing for low latency real-time computations, data management and cloud [17] and HPC for faster computational decision-making.
- **Vertical concerns** address cross cutting issues which can impact all horizontal concerns, data types to support both syntactical and semantic aspects, standards to facilitate data integration, sharing and interoperability for the construction of a Digital Single Market and foster Data Economy [18], Market places and Industrial and Personal Data Platforms (IDP and PDPs) [19]for efficient usage of the horizontal concerns, and cybersecurity for security and trust elements that go beyond privacy and anonymisation. Additionally, vertical concerns may be pure technical but also include non-technical aspects.

This reference model provides a very high-level view of data processing without imposing any restrictions on the implementation, regardless of the area of applicability. The BDV Reference Model has no ambition to serve as a technical reference architecture. However, it is compatible with such reference architectures. There are more specific reference architectures developed with application areas in focus, such as the hierarchical model “*Industrie 3.0*” and the three-dimensional model

"*Industrie 4.0*", which account more detailed relationship between the business processes, but they are focused entirely on the needs of industry.

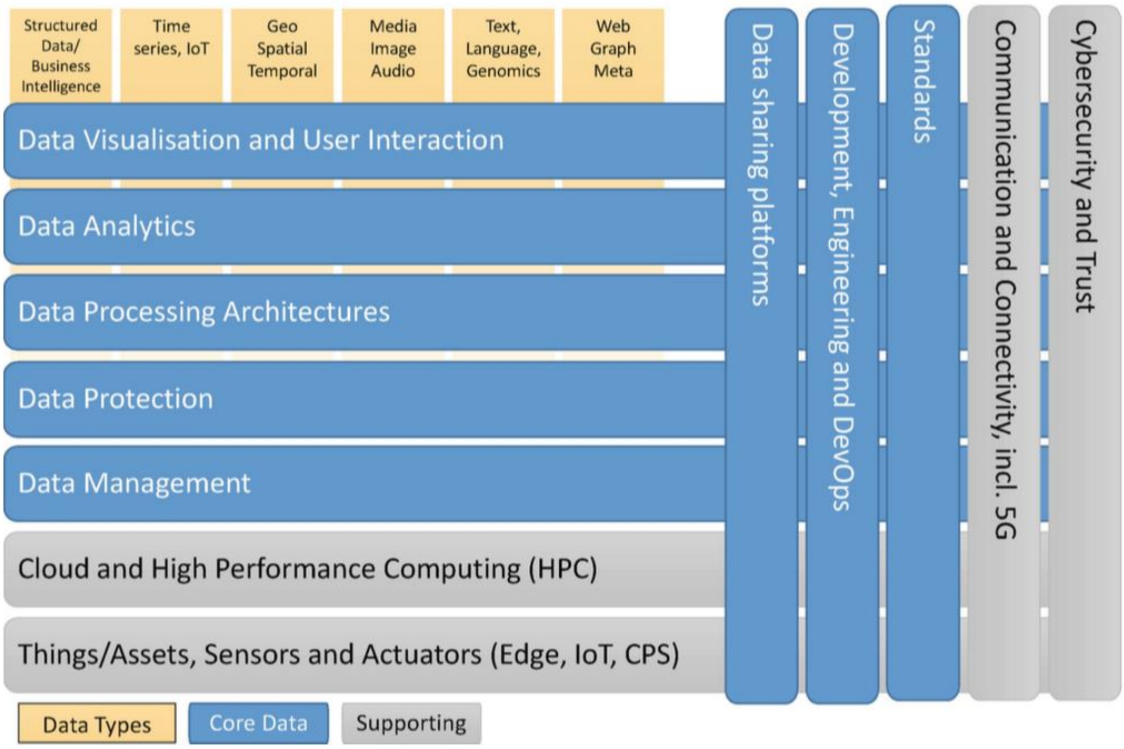


Figure 21: Big Data Value Reference Model [10]

Complementing this application of the reference model, it has also been used to systematically monitor the technical progress of the Big Data Value PPP. To determine how well the technical priorities and challenges are covered by ongoing research and innovation activities, the BDVA performed a systematic collection of data, where the BDV Reference Model provided the structure for a common data collection template and frame for data analysis [4]. One of the more generic enhancements of the BDVA reference architecture has been developed under the EU Horizon 2020 project OPEN DEI [4]. It aligns the reference architecture of BDVA with the requirements of open platforms and large-scale pilots for digital transformation.

3.2.3 GAIA-X

The GAIA-X project [51] aims to advance the development of a sustainable and innovative data economy across Europe. Its primary goal is to establish a secure and federated data infrastructure in Germany and Europe, enhancing data sovereignty for businesses, research, governments, and society, particularly in the context of data storage, exchange, and utilization of data and services. The GAIA-X ecosystem extends domain-specific knowledge among European stakeholders, facilitates data sharing and exchange within and across sectors, and enables the development of innovative business models in the digital market. GAIA-X integrates federated centralized and decentralized infrastructures (cloud and edge services) into a cohesive, user-friendly system. These infrastructures make data and services available for AI applications while protecting rights, interests, and intellectual property. Each node within the federated infrastructure operates as an autonomous unit, adhering to the reference architecture and uniquely identifiable and accessible. The node's self-description provides transparency regarding specific features and capabilities, such as statements on the location of data storage and processing, on the technologies used, on calculation and storage performance, and on the functionality made available. Additional characteristics include real-time capabilities, data sovereignty based on certified protection levels, consumption models, etc. The GAIA-X ecosystem is structured into the Infrastructure Ecosystem and the Data Ecosystem. The Infrastructure Ecosystem focuses on providing or consuming infrastructure services, represented in GAIA-X by the asset called Node. In the Data Ecosystem, the main asset is Data. Participants, typically organizations active within these ecosystems, assume two primary roles: Provider and Consumer. A Participant can serve as both Provider and Consumer simultaneously. The Data and Infrastructure Ecosystems are interdependent, with services acting as the linking element between Providers and Consumers, also connecting Data and Nodes. The GAIA-X ecosystem relies on a common and solid foundation built upon Policy Rules and an Architecture of Standards for interconnection. Figure 22 below presents a high-level overview of the GAIA-X reference architecture.

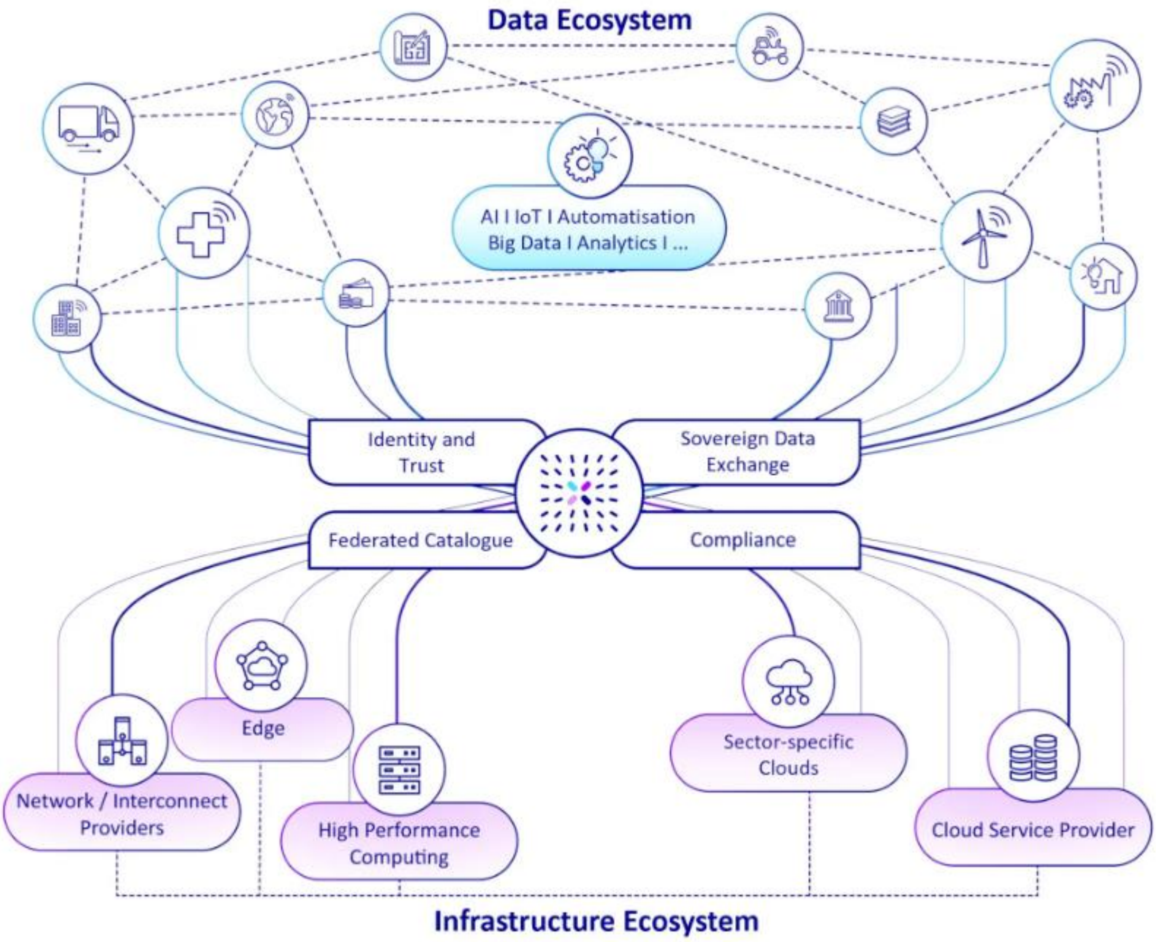


Figure 22: High-level overview of the GAIA-X architecture [52]

1. A Node refers to a computational resource or infrastructure component, such as an edge resource, a virtual machine, a container, a data centre, or any other generic infrastructure component where services can be deployed. Nodes are placed within the Infrastructure Ecosystem.
2. A Service describes a cloud offering, including all types of cloud services provided by a Service Provider. When a service relies on a GAIA-X Node, it is referred to as a Service Instance. Services can be combined, enabling the creation of service cascades. Throughout all Service executions, GAIA-X ensures interoperability, allowing Services to be migrated from one Node to another.

3. A Data Asset refers to a dataset available or hosted on GAIA-X Nodes and provided to consumers through GAIA-X Services. Data Assets can be integrated with each other, forming data spaces according to the federated characteristics of the ecosystem.
4. A GAIA-X Participant, typically a business organization, individual, or any legal entity engaged in the ecosystem, assumes the role of provider, consumer, or both, depending on the specific business case. Each Asset is associated with a GAIA-X Provider within the GAIA-X ecosystem, prohibiting external contributions without self-descriptions. Other roles within the GAIA-X ecosystem include Service Provider, Service Instance Provider, and Node Provider.
5. Participants and Assets express their attributes and characteristics via mandatory GAIA-X Self-Descriptions, which contain structured and searchable metadata, detailing aspects like data ownership and usage policies.
6. The core of GAIA-X is represented by Federated Services, which interconnects the Infrastructure and Data Ecosystems. The Federation Services include both infrastructure-level functionalities and organizational support features, such as Federated Catalogues, Identity and Trust Services, Compliance Services, and Sovereign Data Exchange Services.
7. The GAIA-X Federated Catalogue is an open mechanism that enables existing and emerging ecosystems to incorporate domain-specific catalogues into the GAIA-X Federation, if they adhere to the transparency, fairness, security, and trust requirements of a GAIA-X Catalogue. GAIA-X is responsible for the verification and certification process of these catalogues. Asset discovery occurs via the Federated Catalogue, using an open and transparent query algorithm to locate appropriate Self-Descriptions that meet consumer requirements. GAIA-X Data Connectors are part of the Federated Catalogue.
8. Identity and Trust Federated Services ensure verifiable identities for Participants and foster trust in their capabilities and Assets. Additionally, federated identity management ensures the interoperability of identities across different domains by linking various national and international identity providers.
9. Sovereign Data Exchange Services are established by GAIA-X to enable and ensure individuals or legal entities with exclusive control over how their data is used. This is predicated on metadata-level interoperability, enabling self-determined decision-making regarding data usage and processing. A crucial element of data sovereignty is the enforcement of Usage Policies, referred to as Usage Control.

Figure 23 illustrates the main relationships between GAIA-X Assets and GAIA-X Participants, where Participants may assume multiple roles.

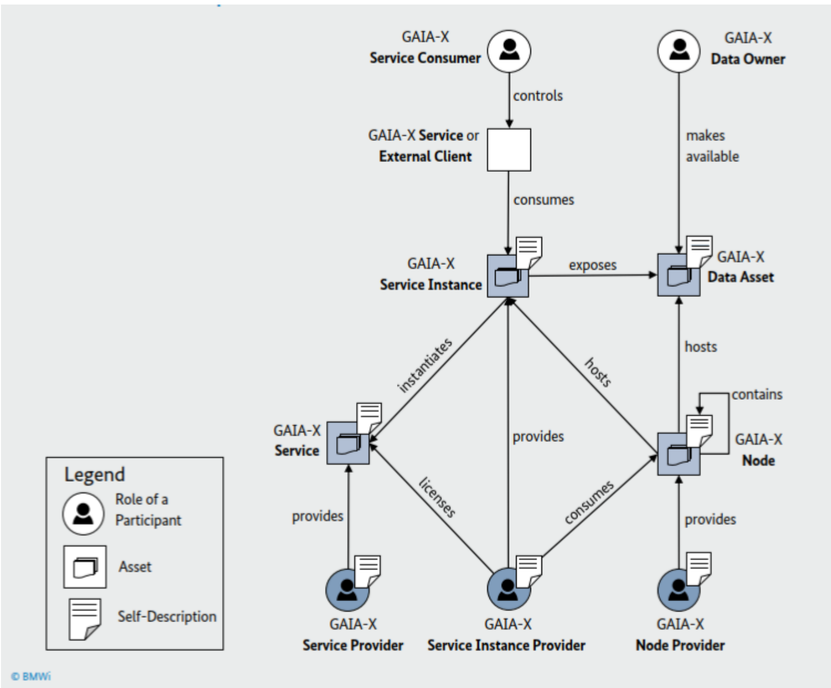


Figure 23: Top-level Self-Description Ontology [53]

3.3 Related Projects

3.3.1 OneNet

The project OneNet (One Network for Europe) [45] provides a seamless integration of all the actors in the electricity network across Europe to create the conditions for a synergistic operation that optimizes the overall energy system while creating an open and fair market structure. The key elements of the project are:

- Definition of a common market design for Europe: this means standardized products and key parameters for grid services which aim at the coordination of all actors, from grid operators to customers.
- Definition of a Common IT Architecture and Common IT Interfaces: this means not trying to create a single IT platform for all the products but enabling an open architecture of interactions among several platforms so that anybody can join any market across Europe.
- Large-scale demonstrators to implement and showcase the scalable solutions developed throughout the project. These demonstrators are organized in four clusters coming to include countries in every region of Europe and testing innovative use cases never validated before.

3.3.1.1 Reference Architecture

In the context of data-driven architecture, the OneNet Reference Architecture [46] represents a very innovative solution that leverage on IDS reference model and FIWARE interfaces, bring to a hybrid solution using both the standard models for implementing the OneNet Decentralized middleware and the OneNet Connector. The usage of IDS Connector and FIWARE Context Broker ensures a high level of standardization, interoperability, scalability and reuse of OneNet solution. The OneNet Reference Architecture [46], shown in Figure 24 consists of three logical layers:

OneNet Participants: Any kind of actor is involved in the OneNet ecosystem. Can be divided into data source, data provider, data consumer and service provider.

OneNet Network of Platforms: Any Platform (e.g., DSO platforms, Market platforms, DEPs) able to connect to the OneNet Middleware using the OneNet Connector.

It aims to be a P2P fully decentralised ecosystem for interoperability. In the OneNet Network of Platforms, two systems (OneNet Participants) can interact directly with each other, without intermediation by a third party.

OneNet Framework: The core of the OneNet Architecture. It consists of three main components:

- OneNet Decentralized Middleware
- OneNet Orchestration Workbench
- OneNet Monitoring and Analytics Dashboard

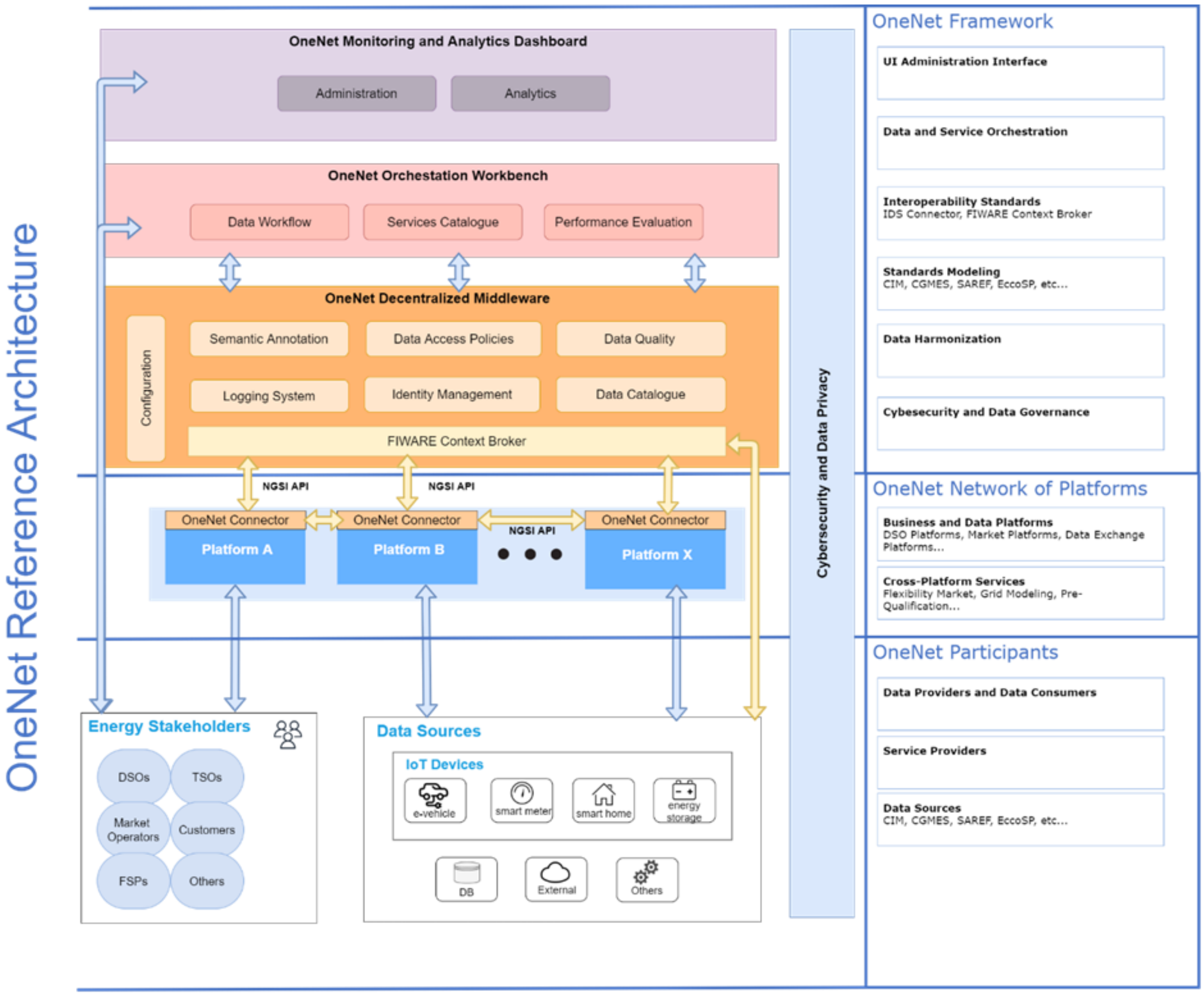


Figure 24: OneNet Reference Architecture [46]

OneNet Participants: Data Sources and Business Actors

The bottom layer of the OneNet Reference Architecture, the OneNet Participants layer includes Business Actors and Data Sources. The Business Actors are named according to their business role, and this can be DSO, TSO, Market Operator, FSP, Customer or others possible Energy Stakeholders. Due to the focus of the architecture in the Data exchange, these actors are classified following a data-driven set of roles such as Data Owner, User, Consumer, Provider, and others. The following data-driven Business Actors and Roles were identified in OneNet:

- Data Provider is a specific OneNet participant that provides data to the system. To submit metadata to a Broker, or exchange data with a Data Consumer, the Data Provider uses software components (OneNet connector) that are compliant with OneNet Framework. To facilitate a data request from a Data Consumer, the Data Provider should provide proper metadata.
- Data Consumer receives data from a Data Provider. From a business process perspective, the Data Consumer is the mirror entity of the Data Provider; the activities performed by the Data Consumer are therefore like the activities performed by the Data Provider. Before the connection to a Data Provider can be established, the Data Consumer can search for existing datasets in a data catalogue.
- Service Provider is a specific OneNet participant that provides services or tools. The Service Provider registers its services in the OneNet Framework in order to be used, integrated, and tested within any cross-platform integration or orchestration process.

The Data Sources refer to all the assets that produce or process data. These can be sensors, actuators, gateways, edge computing nodes, and they can come from various energy sectors like electric mobility, energy storage, and residential energy monitoring. This layer relates to the OneNet Network of Platforms layer since it represents the source of data for all the business and data platforms, as well as any integrable services or applications. It could be also directly connected to the OneNet Framework, since based on needs and requirements, there may be a need to integrate a data source directly into the OneNet Framework, using the OneNet Middleware and its interoperability mechanisms based on the FIWARE architecture and on the FIWARE Orion Context Broker. Furthermore, the business actors will have the possibility to access the Orchestration Workbench for the evaluation and testing of apps, tools and services and the OneNet Monitoring Dashboard for exploiting monitoring and analytics features offered by the OneNet Framework.

OneNet Network of Platforms: Business and Data Platforms, Application, Services

The OneNet Network of Platforms layer focuses on the integration of external platforms, such as DSO platforms, Market platforms and other data exchange platforms into the OneNet Framework. This integration is to be made regardless of the technology of these platforms to remain platform-agnostic. From a technical point of view, the term platform means any software environment (e.g., applications, services or tools) able to connect with the OneNet Middleware using the OneNet Connector. The main goal of this layer is to create a P2P fully decentralised system for interoperability. In such an infrastructure, two systems (OneNet Participants) can interact directly with each other, without intermediation by a third party. The results of this fully decentralised approach will create the OneNet Network of Platforms. The more important component included in this layer is the OneNet Connector, described in Ch. 3.3.1.2.

3.3.1.2 OneNet Framework

The OneNet Framework is the core of the OneNet Architecture. It consists of three main components: the OneNet Decentralized Middleware (including OneNet Connector), the OneNet Orchestration Workbench and the OneNet Monitoring and Analytics Dashboard [54].

OneNet Decentralized Middleware and OneNet Connector

The OneNet Decentralized Middleware is the main component of the OneNet Framework which enables the creation of the data space ecosystem. It implements some crucial centralized features for setting up the data space and provides central information to the OneNet Participants. In the OneNet Decentralized Middleware are implemented:

- Identity Management
- Data Catalogue and Data source discovery
- Vocabulary Provider

The OneNet Connector is the entry point for OneNet Participants to be part of the data space ecosystem. It is a plug-and-play solution, ready to be deployed inside each platform environment. It allows easy integration and cooperation among the platforms, maintaining data ownership and preserving access to data sources. The OneNet Connector is essential for connecting and integrating a platform within the OneNet ecosystem. As shown in Figure 25, the OneNet connector has been developed following a decentralised approach, ensuring the necessary scalability for the near real-time data integration and management enabling multi-country and multi-stakeholder near real-time decision-making services. The OneNet connector is based on the IDS connector concept and follows all the IDS specifications and requirements. The Broker included in the OneNet Connector is implemented using the FIWARE Orion-LD Context Broker. The FIWARE context Broker offers the FIWARE NGSI APIs and associate information model (entity, attribute, metadata) as the main interface for sharing data by the OneNet Participants. Data Providers can use the FIWARE APIs to publish or to expose the data they offer, and Data Consumers can retrieve or subscribe (to be later notified) to the data offered. Figure 26 presents the OneNet Connector Architecture.

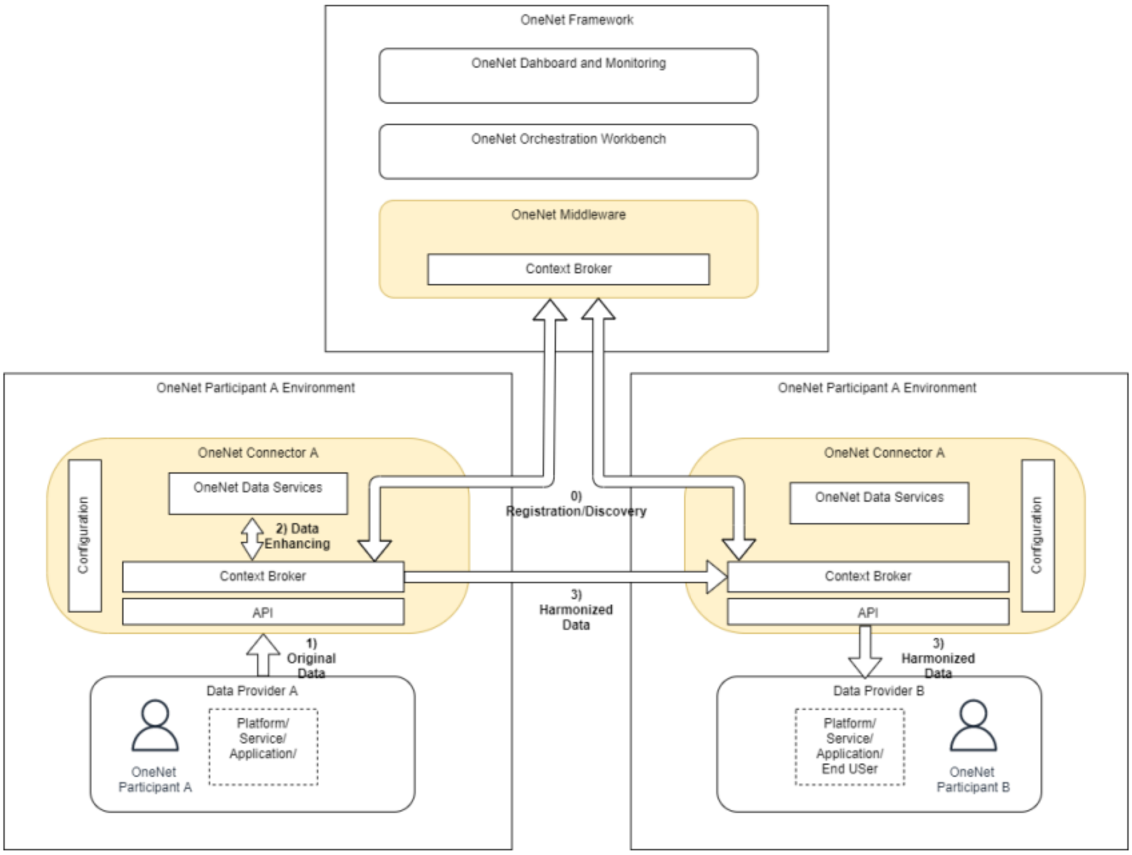


Figure 25: OneNet Decentralized approach [46]

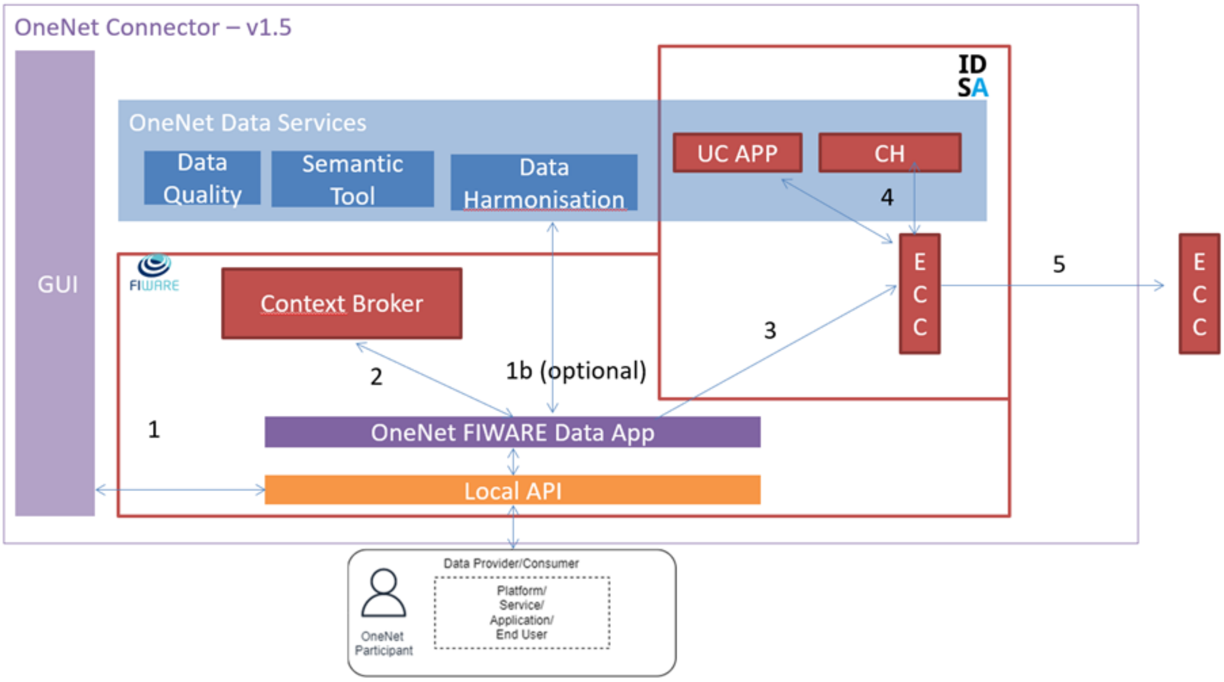


Figure 26: OneNet Connector Architecture [54]

OneNet Orchestration Workbench

The OneNet Orchestration Workbench [55] is the component able to orchestrate and evaluate the performance and scalability of the cross-platform services that will be integrated and implemented in the OneNet System. Any OneNet Participant and in particular the Service Providers will be able to test and evaluate their own service by exploiting the OneNet Orchestration Workbench, that allows to integrate data coming from the OneNet Middleware and to implement a data pipeline orchestration. From a functional perspective, it supports the integration and evaluation of the performance and scalability of the AI, IoT and Big Data cross-platform services for market and grid operations. The OneNet Orchestration Workbench allows data coming from the OneNet middleware and interaction with the service providers which can register and evaluate their own services, implementing services orchestration, data pipeline and evaluation schema. The OneNet Orchestration Workbench also include:

- Job Scheduling.
- App/Service registry and discovery.
- Error/Retries management.
- SLAs tracking, alerting, and notification.

OneNet Monitoring and Analytics Dashboard

The OneNet Monitoring and Analytics Dashboard [55] is the component that offers a GUI for facilitating the OneNet Participants in the management, monitoring and analytics of the data exchanges.

The OneNet Monitoring and Analytics Dashboard is the main User Interface that allows access to the OneNet Participants for monitoring and data analytics features, as well as for the OneNet Administrators for configuration and administration tools.

The main features of the OneNet Monitoring and Analytics Dashboard are:

- administrative and configuration tools.
- easy integration with the OneNet Orchestration Workbench and OneNet Middleware.
- data-analytics dashboard.
- monitoring and alerting dashboard for data processes and platform integrations.
- user-friendly selection of data sources and services from the catalogues.

3.3.2 BD4NRG

The BD4NRG [20] project was started on January 1, 2023, with the aim to confront big data management challenges for the energy sector, giving a competitive edge to the European stakeholders to improve decision making and at the same time to open new market opportunities [21]. It consists of 32 companies and research institutions from the EU, Horizon 2020, spanning a duration of 36 months.

The key objectives of this project are:

1. To develop a reference architecture for Smart Energy systems, by integrating BDVA, SRIA, IDSA, and FIWARE architectures.
2. Progress technological solutions for data management, pipeline management and IoT, achieving a TRL 5-6 and further integrating to TRL 7-8.
3. Create modular analytical tools (TRL 8) for mass data analysis combining legacy and third-party systems.
4. Implement predictive and regulatory advanced mass data analysis on 13 large-scale pilots covering the entire energy value chain.

3.3.2.1 Reference Architecture

The BD4NRG RA [76] is depicted in Figure 27, and considers recent developments and architectural initiatives and models, including BRIDGE, CSMAG and RAMI, while highlighting the aspects that need to be taken into account for creating decentralized energy data spaces, following initiatives and approaches provided by IDSA, OPEN DEI, AIOTI, FIWARE and BDVA/DAIRO [8]. The architecture considers four main layers of the data value chain and a vertical pillar focusing on data space enablers that allow decentralized energy ecosystems to make their data available, in a trusted and sovereignty-preserving manner, to analytics services providers so that value can be generated [8].

1. **The Data Sources Layer**, which focuses on identifying and understanding the Big Data provided by numerous sources. including energy sensors and meters, data monitoring and acquisition platforms such as SCADA systems or Building Energy Management systems, databases with historical or real time data, smart grid data exchange platforms and cross-domain information such as environmental information and data coming from public administration services.
2. **The Data Interoperability Layer**, which focuses on identifying the communication interfaces with the data sources and corresponding data formats, as well as on providing a set of data and information models which could be followed or used for data transformation, aiming to ensure interoperable data exchange and use. This layer integrates the “Communication” and “Information” layers of the BRIDGE architecture.
3. **The Innovative Data Analytics Services Layer**, which comprises of four sublayers which specify: (i) the processing infrastructure required for Big Data processing, (ii) different types of analytics that are employed depending on user requirements and data analytics use cases, (iii) the analytics services that take as input the energy and cross-sector Big Data and (iv) the functional process which are supported by the analytics services and receive the value extracted from Big Data. This

layer represents the "Function" layer of the BRIDGE architecture by consolidating aspects related to data analytics and correspondingly supported functions.

4. **The Business Actors and Ecosystems Layer**, which identifies stakeholders who participate in the data analytics ecosystem and corresponding energy data spaces. They include data providers and analytics services users / data consumers, analytics applications providers and providers of data space enablers and related platforms.

There is major influence of BRIDGE RA on the BD4NRG RA. The BD4NRG RA adapts the BRIDGE RA and aligns it to the needs of Big Data analytics value chains. Under the BD4NRG view, the focus lies on data driven services in all aspects of energy ecosystems, including smart management of building environments as well as energy performance contracts. The vertical pillar of BD4NRG Data Space Enablers identifies the components and functions required to realize the distributed BD4NRG data space and is aligned with the design principles specified by OPEN-DEI [22]. The main element for smooth data space operation is specification and provision of a set of rules or agreements which should be followed by all stakeholders. This set of rules essentially define how the data space is governed and clarified how stakeholders interact within it on organizational, operational and business levels. IDSA has already provided a rule book [23] specifying blueprints of agreements which should be considered when implementing a data space.

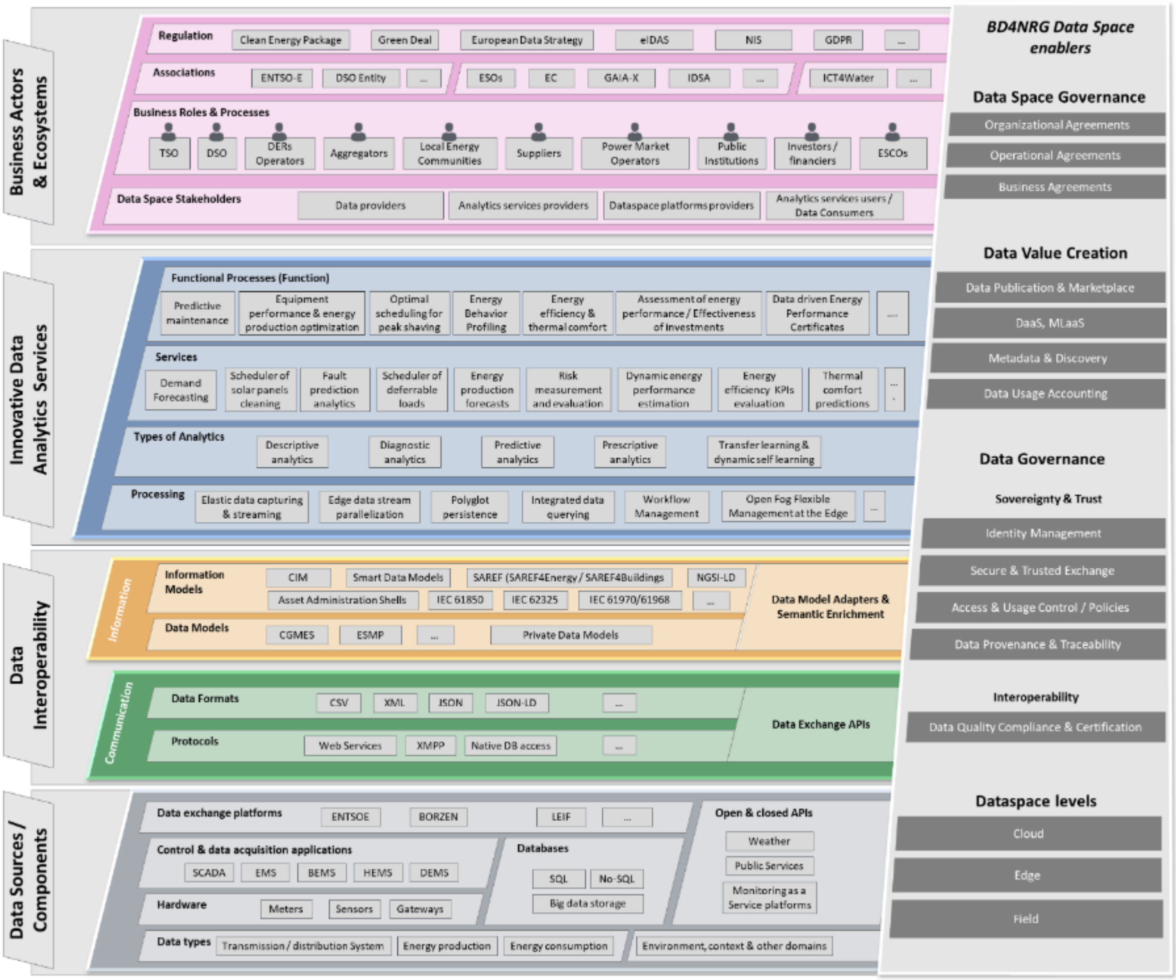


Figure 27: Overview of the BD4NRG Reference Architecture [76]

The Data Space governance is complemented by a set of technical components for data governance that need to be in place in order to ensure data sovereignty and trust, track the origin (provenance) and usage of data, and enforce the interoperability specification by applying measures for data quality compliance and/or certification. Data value creation within a data space is accomplished through data publication and marketplace services, which facilitate the exchange or transaction of data and the use of data analytics services. Marketplaces are spaces where data producers, analytics services providers and users of the services meet with the purpose of creating value from the available data. An efficient data marketplace is supported by services that allow data and metadata discovery as well as data usage accounting. Moreover, analytics services are provided in "as a service" manner.

BD4NRG RA considers the various dataspace levels as specified by OPEN DEI, which can be:

- Cloud: data storage, integration and analytics services operate on the cloud.
- Edge: mission critical processing is performed at the edge or in the organizations' premises, whereas the cloud is used for long term Big Data storage and/or for offloading analytics tasks than can be executed on the cloud.
- Field: data analytics services are deployed at the user premises and are used in locally deployed infrastructure. Such an approach may be advantageous for organizations that are reluctant to make the transition to the cloud due to business, organizational, or other restrictions.

3.3.2.2 Alignment between TwinEU and BD4NRG

BD4NRG shares similar focus with the TwinEU project in their emphasis of creating a decentralized federated energy ecosystem. The RA of BD4NRG is intended to support seamless data exchange across different distributed systems, to enhance interoperability. This is done with data spaces that allow for trusted data sharing between stakeholders. Another example of similarities in the two projects of RA, is the use of the same common standards and EU initiatives as part of the literature review for the design process of both RAs. This is because of the shared goals of achieving interoperability in combination with data governance, as discussed earlier. More specifically, both projects adopt principles for data governance, and FIWARE reference architecture standards to guide the design process for achieving interoperability. Moreover, there are similarities in the alignment of both projects with other EU initiatives. BRIDGE's reference architecture significantly influences the design of both projects in aligning data value chain with bog data analytics, while both projects integrate principles from OPEN DEI, to manage and analyse big data efficiently. Finally, both projects share common objectives in design the reference architecture for the projects, in the sense that there is a focus on standardized data models for cross domain data integration, cross-platform communication and leveraging AI to optimize computing and decision-making processes.

3.3.3 BD4OPEM

BD4OPEM (Big Data for Innovative and Sustainable Energy Solutions) [56] is a project aimed at developing an open innovation marketplace. This marketplace integrates an analytic toolbox powered by artificial intelligence to provide products and services for enhancing the monitoring, operation, maintenance, and planning of electrical distribution grids. These solutions are made available to various stakeholders. The project has been completed. The BD4OPEM project developed an IT architecture to support interfaces and data interoperability platforms, focusing on enhancing flexibility and improving business processes. The architecture includes several "device adaptors" as part of the data layer, alongside modules for data harmonization (using standards such as CIM), context brokers, data cleansing, storage, data lake management, unified APIs, and data monitoring. Data harmonization is achieved through the implementation of standards and ontologies, including SAREF, SAREF4NER, FIWARE, and CIM, which provide a common structure for data. The purposes of interfaces are specified in terms of information models and interaction sequences. Interaction sequences are detailed in sequence diagrams for the project's use cases, including 10 Business Use Cases (BUCs) and 24 Specific Use Cases (SUCs).

The BD4OPEM architecture is mapped to the SGAM model, showcasing its alignment with various layers of the Smart Grid Architecture Model. The project focused on distribution-level use cases at low voltage (LV) and medium voltage (MV), addressing areas such as power quality and disturbance, flexibility forecasting, topological representation, SCADA information mapping, and electric vehicle (EV) grid flexibility. The project made significant contributions to data interoperability platforms and data-sharing frameworks by creating a data layer that integrates with analytics, marketplace, and security layers. This architecture hosts independent tools tested at demo sites and is compatible with various systems, including AMI, SCADA, GIS, EV charging, HVAC with KNX, and PV control with Wibeee.

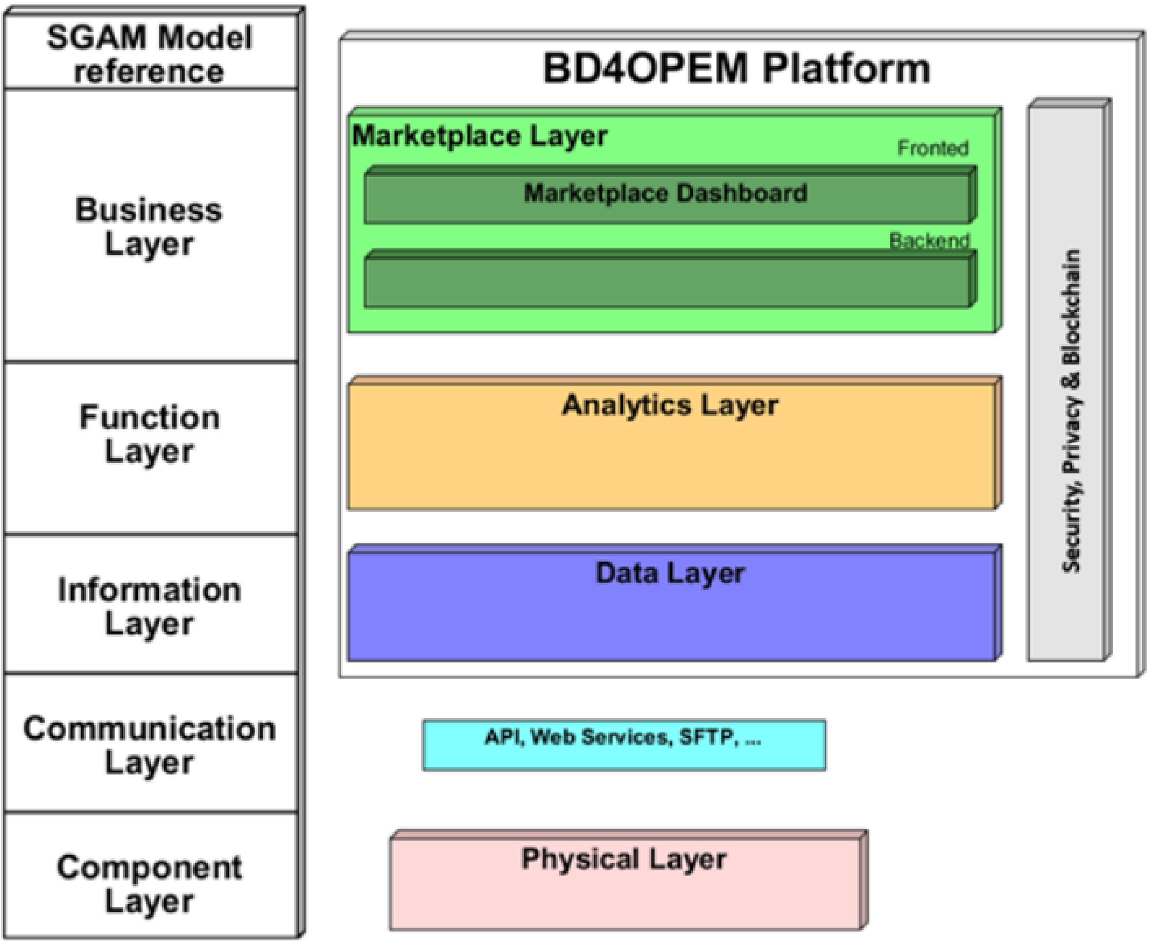


Figure 28: The BD4OPEM Platform [57]

3.3.4 TDX-Assist

The TDX-ASSIST project [58] "Coordination of Transmission and Distribution data eXchanges for renewables integration in the European marketplace through Advanced, Scalable and Secure ICT Systems and Tools", funded by the EU Horizon 2020 research and innovation program, was implemented between 2017 and 2020. Its primary objective was to design and develop innovative ICT tools and techniques to enable scalable and secure information systems for data exchange between TSOs and DSOs, thereby supporting the integration of renewable energy sources in the European energy market. Three key innovations in ICT tools and techniques were introduced in the project:

- Scalability: Ensuring the capacity to accommodate new users and managing increasingly larger volumes of information and data efficiently.
- Security: Providing robust protection against external threats and cyberattacks.
- Interoperability: Facilitating seamless data exchange using international standards and interoperable information systems.

The project built upon the RA defined in the *IEC TC 57 62357-1* [59] standard and utilized the *Common* CIM as a semantic data model to ensure interoperability between TSOs and DSOs. The most important aspects that TwinEU would leverage from TDX-ASSIST are:

- A **systematic approach to use case development**, enabling the derivation of technical specifications that were validated in both pilot demonstrations and simulations.
- **CIM profiles** specifically developed to enhance TSO-DSO data exchange.
- A **reference architecture** leveraging cloud-based solutions for data exchange between TSOs, DSOs, and other electricity market stakeholders.

3.3.4.1 Use Cases

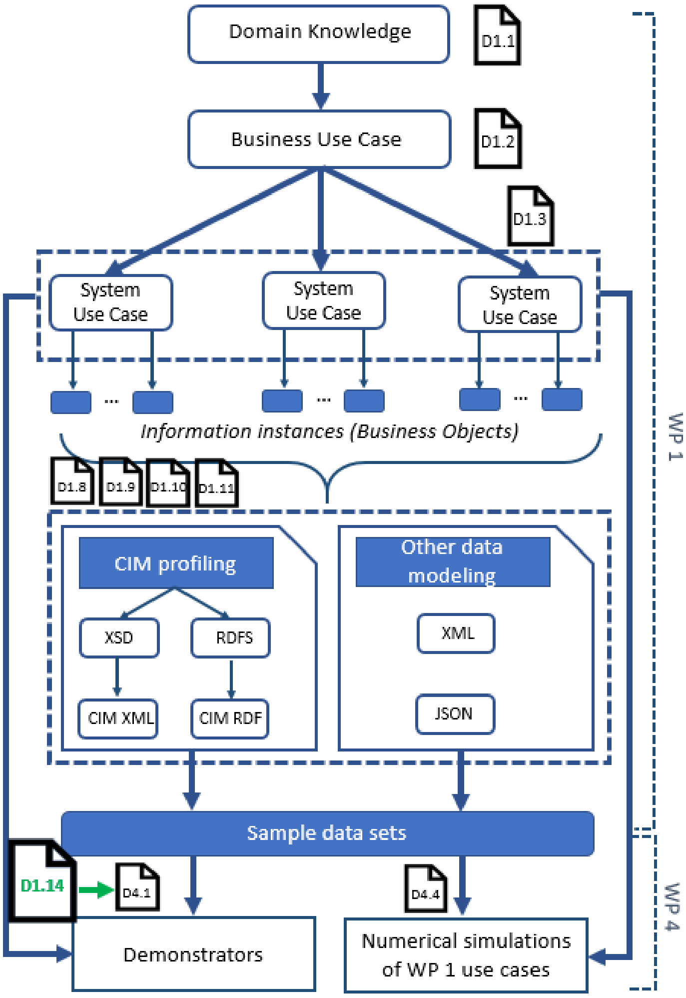


Figure 29: TDX-ASSIST approach for development and usage of use cases [62]

The TDX-ASSIST use cases have been developed using the "Systems of Systems" methodology, as defined by the IEC System Committee on Smart Energy. This methodology encompasses BUCs and SUCs to derive the requirements for data exchange among stakeholders [62]. While BUCs describe business processes and define business roles, SUCs provide the corresponding technical details. Each

BUC is linked to one or more SUCs. Figure 29 below illustrates how these use cases have been utilized for data modelling, pilot demonstrations, and numerical simulations. It also includes references to specific TDX-ASSIST deliverables, which can be consulted for further information.

3.3.4.2 Data modelling

TDX-ASSIST utilized the CIM as a semantic data model to facilitate information exchange between TSOs and DSOs. Each SUC includes a detailed description of the exchanged information, organized into "Business Objects (BOs)" [60]. A comprehensive gap analysis was conducted to compare the BOs from all SUCs in the TDX-ASSIST BUC/SUC repository against the Common Grid Model Exchange Standard (CGMES). Based on this analysis, a CIM profile was developed for each SUC, incorporating proposed extensions derived from the identified gaps. An example is an approach to model observability area between TSO and DSO in CGMES, which can be of potential use for TwinEU demonstrators.

3.3.4.3 TDX-ASSIST architecture in the cloud

The cloud-based data exchange platform design for exchange of information between TSOs, DSOs and other electricity market stakeholders has been proposed within TDX-ASSIST project [63]. The input requirements for the platform have been extracted from BUCs and developed market services. The platform architecture, leveraging microservices, is given in Figure 30. The data exchange platform has been deployed in cloud mainly due to on-demand availability of computer system resources, data storage and computing power, without direct active management by a user.

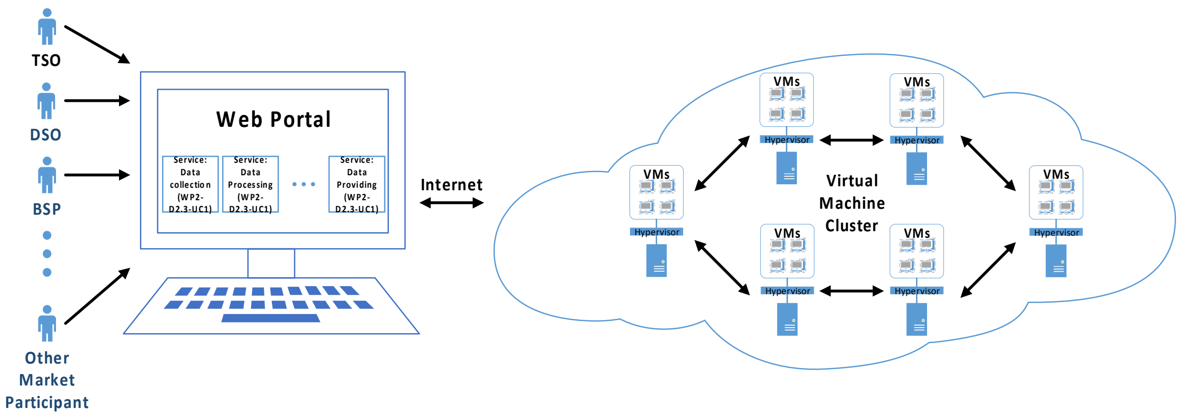


Figure 30: TDX-ASSIST architecture of the data exchange cloud platform [61]

3.3.5 EU-SysFlex

EU-SysFlex [64] was a Horizon 2020 project funded under Grant agreement 773505 from 1st November 2017 to 28th February 2022 composed of 34 partners from 14 European countries. The goal of EU-SysFlex was to provide efficient system services to support high levels of renewable electricity (RES-E) while maintaining the resilience expected by European consumers. This involved three key steps:

1. Identifying the technical needs of a pan-European system with over 50% RES-E and translating them into services within an improved market design,
2. Enhancing market design and regulations to efficiently procure these services,
3. And removing barriers to competition by clarifying the roles of all stakeholders, including generators, flexibility providers, TSOs, DSOs, and regulators, across all system levels.

For the TwinEU project, the two aspects of data exchange standards and the data exchange conceptual model are of interest.

3.3.5.1 Data Exchange Standards and Protocols

As shown in the Project deliverable "Proposal for data exchange standards and protocols" [66], the EU-SysFlex project worked on the continuous standardization of data exchange in the energy domain. The focus was set on standardization needed for flexibility market operations, aligned with the project's goal of integrating large-scale renewable energy. The aim was to assist European power system operators by addressing data exchange requirements and promoting further standardization.

As a result, they propose "CIMification", which emphasizes the benefits of adopting a unified CIM to enhance interoperability, regulatory compliance, and vendor adoption across the European energy sector. Expanding and refining CIM through new profiles, tools, and cross-sector integration supports data exchange, compliance testing, and interoperability among diverse systems and vendors. As an outcome, they recommend for additional CIM coverage in the field of data hubs, private data portability, authentication, access permission, erasure and rectification between data owners, data logs, sub-meter data, data aggregation and -anonymization, flexibility services, and for the communication between smaller DERs and system operators.

TABLE 1: STANDARDS AND SPECIFICATIONS USED FOR EU-SYSFLEX DATA MODELS

Data models	WP6 Germany	WP6 Italy	WP6 Finland	WP7 Portugal VPP	WP7 Portugal FlexHub	WP8 France	WP9
CIM							X
CIM CGMES	X						
ENTSO-E Reserve Resource Process (ERRP)	X						X
IEC 62325-503 (MADES)							X
IEC 60870-5 (101 or 104)	X	X	X			X	
IEC 61850		X	X			X	
IEC 60870-6 (TASE.2 ICCP)				X			
OPC UA			X	X			
Modbus						X	
Estfeed							X

Figure 31: Table 1 of the Deliverable "Proposal for data exchange standards and protocols": Standards and specification used for EU-SysFlex data models [65]

3.3.5.2 Recommended data exchange conceptual model for Europe

In the deliverable "Recommended data exchange conceptual model for Europe" [67] the problem of existing obstacles in the exchange of data between sectors and countries is addressed. They start by reviewing the legal framework for data access and exchange, particularly through Data Exchange Platforms (DEPs), and conclude that this is critical for developing a European data exchange model. A review of ten EU energy sector legal texts highlights the role of DEPs in facilitating secure, non-discriminatory access to energy data and services like flexibility services. DEPs enable consent management, GDPR-compliant data sharing, and cross-border exchange while supporting TSO-DSO cooperation and digitalization. Generic EU regulations on data management, personal data protection, and open data further inform DEP requirements, aligning with use cases such as transferring, aggregating, and anonymizing energy data, and enabling compliance with the free flow of non-personal data regulations. They also conducted several interviews with data platform operators and found that data platforms are owned and operated mainly by TSOs and DSOs. In contrast to data platforms, they also review data exchange formats and highlight the importance of Common Information model, IEC 61850, DLMS/COSEM, Green Button, Estfeed, EEBUS, CIM CGMES, CIM ESMP, IEC 60870, and OPC UA. The EU-SysFlex consortium recommends the usage of the data exchange conceptual model which consists of the data exchange reference architecture proposed by the BRIDGE initiative together with its own addons.

3.3.6 INTERRFACE

The IEGSA platform is developed by the INTERRFACE project [68] to perform as a common platform to connect multiple actors such as Market Operators, Systems Operators (i.e. TSOs and DSOs), Flexibility Service Provides (i.e. Balance Service Providers or Aggregators), Settlement Responsible Parties, along various energy markets focusing on providing support on the procurement of services (such as balancing, congestion management and ancillary services) from assets connected to the network both at transmission and at distribution level, in a coordinated way. This is achieved by implementing multiple coordination schemes between TSOs and DSOs. Therefore, IEGSA provides a channel that establishes seamless coordination between system operators towards their efficient communication on procuring network services by enabling flexibility from all levels. The increasing participation of energy stakeholders (i.e., providing or trading available flexibility), implies the need for a channel to allow the secure information and data exchange, a fact which is well addressed by the IEGSA platform.

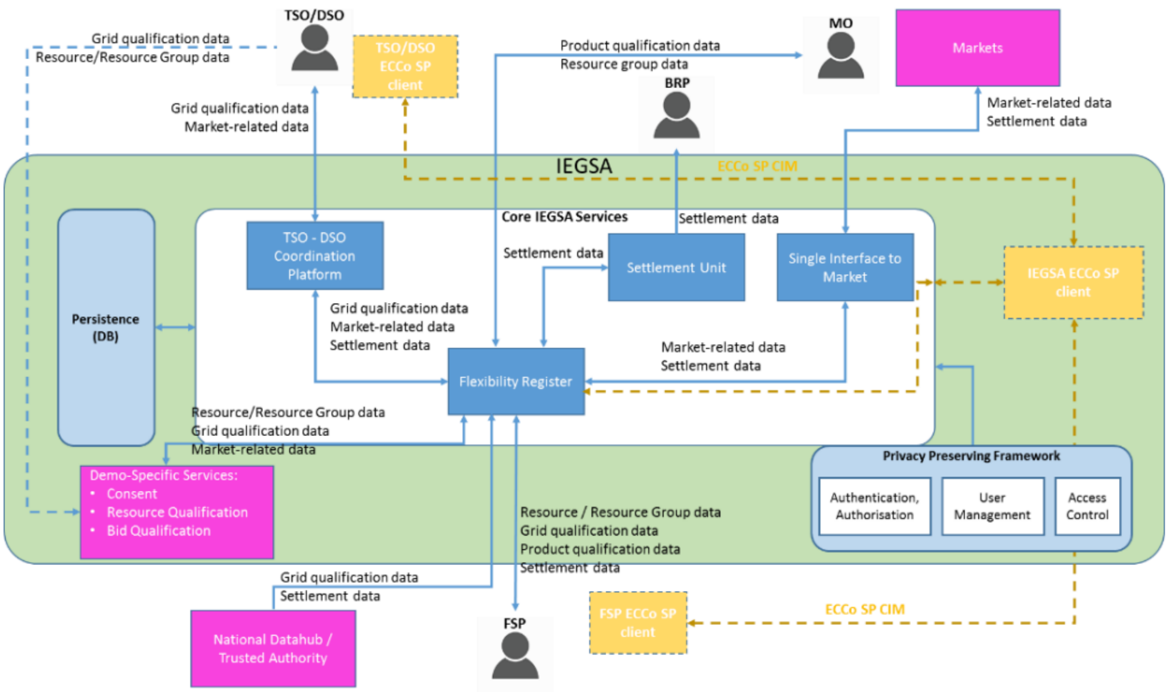


Figure 32: IEGSA Logical Architecture [69]

IEGSA proposes a modular architecture platform which enables data exchange with existing hubs in Europe, facilitating the interconnection of different actors such as TSOs, DSOs, and other market participants or customers connected to the system. The conceptual and logical architecture design of the IEGSA platform essentially allows the interactions among system operators as well as flexibility providers. Therefore, IEGSA comprises a data exchange platform enabling the digitalisation of the energy value chain ensuring data security and privacy requirements by design. Effort is given to engage flexibility services from multiple types of Balancing Service Providers (BSPs), and facilitating access and interconnection with various market platforms, covering different timeframes, enhancing also the coordination among TSOs and DSOs with the introduction of standardized services and market designs. The IEGSA platform encompasses advanced tools and technologies as a matter of integrating multiple actors and systems to serve various business requirements, focusing mainly on flexibility procurement in a coordinated way among TSOs and DSOs. The logical and conceptual technical composition of the IEGSA platform is demonstrated in Figure 32. IEGSA's design follows the SGAM Framework and has been implemented in its different layers, called: business, function, information, communication and components layer respectively. The combination of the communication, information and function layers from a technical standpoint acts as the middleware between the Business Layer with the needs of users and their BUCs; and the Component Layer where the demo specific implementation meets the business layer requirements. There are four main functional blocks that lie in the architecture which follow a modular approach to integrate complementary services and functionalities within the IEGSA framework.

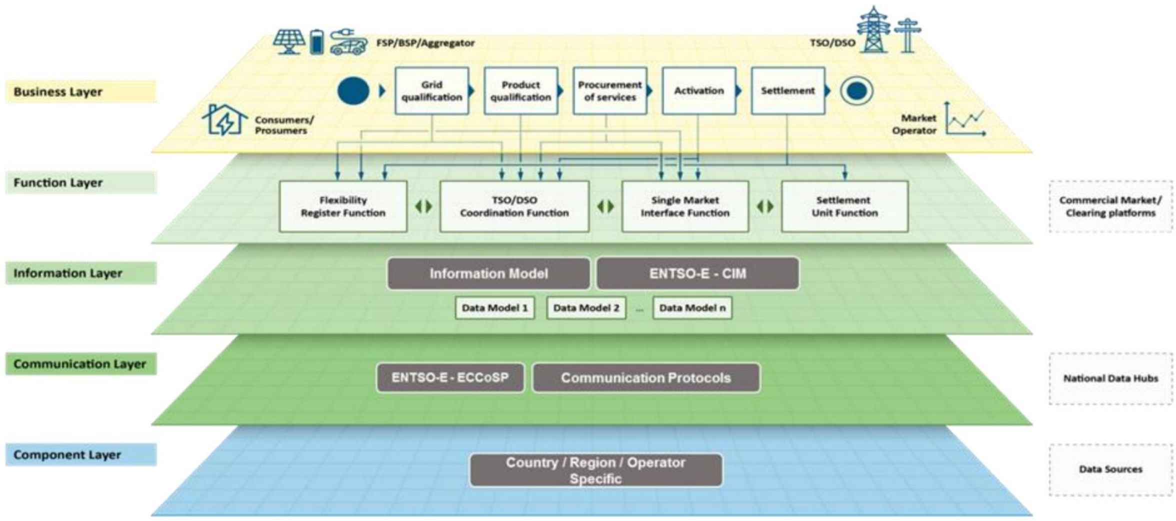


Figure 33: SGAM-Based IEGSA Architectural Representation [69]

Those functional modules are the following:

- **Flexibility Register (FxR),** acting as the core component; processes that are performed within this module include: user management, resource/resource group registration, interaction with consent manager, product definition, trigger of product, grid and bid qualification. The FR module can be accessed by all users of IEGSA such as FSP, Market Operator (MO) and the System Operators (SOs). Each of them has different rights when accessing it. Several UI functionalities reside in FR to ease resource registration (i.e., view and update existing, add new), resource groups definition (i.e., view and update existing, add new), qualification status tab (preview resources and resource groups qualifications status), product definitions and product qualification requests.
- **TSO-DSO Coordination platform** which essentially is the module that enables coordination among SOs. Therefore, this module interacts with the bid and grid qualification services and market-related processes (e.g., merit-order list documents) via the flexibility register. Subsequent User Interface (UI) functionalities are implemented to support SOs to view resources and resource groups. Regarding Resources, the SOs may proceed with changes to the qualification status. A dashboard for the merit order lists of all IEGSA integrated markets is also available for SOs which also may allow the activation of certain bids directly from IEGSA. Activated bids can be previewed on the "Trades" environment of the TSO-DSO Coordination platform.

- **Single Interface to Market** is essentially a backend component that acts as the gateway to connect energy markets with IEGSA, essentially allowing the exchange of market related data. The Single Interface Market is a set of standardized REST APIs, which handle the communication of IEGSA with the various markets that it relates to. This component lies on the back end and there is no dedicated UI. The APIs that comprise the Single Interface to Market are responsible for the transfer of data that facilitate all the processes in IEGSA that surround market integration. The scalable and standardized design of the APIs allows for agnostic connection to different market platforms and seamless data exchange. Thus, IEGSA can exchange bids, Merit Order Lists and Activation Orders with all interconnected markets. The connection to different markets gives a more holistic overview of the available offers and bids to the System Operators, allowing for more efficient and secure grid management.
- **Settlement Unit** which performs the energy settlement of all trades. The FSP may upload documents related to metered and/or sub-meter readings along with activated volumes for all the metering points affiliated with the resource object for all metering points.

3.3.7 ENERSHARE

ENERSHARE [71] aims to develop a European Common Energy Data Space adapted to the energy sector which will deploy an 'intra-energy' and 'cross-sector' interoperable and trusted Energy Data Ecosystem. This Data Space will give the capability to private consumers, businesses, (energy and non-energy) stakeholders and regulated operators to access, share and reuse, based upon voluntary agreements (or legal obligations where such obligations are in force): Large sources of currently fragmented and dispersed data; (b) Data-driven cross-value chain (energy and non-energy) services and Digital Twins for various purposes. The result of the project will be the implementation of a technological, social, and business/governance framework which leverages on, adapts, evolves, and specifically adheres to established Data Space architectures, as well as underlying open-source technological implementations for domain agnostic data-oriented technology components. ENERSHARE project development efforts will:

- create a Reference Architecture for a European Energy Data Space, which combines SGAM, IDSA and GAIA-X architectures, with a special focus on the energy data value chain perspective.
- advance interoperability, security, trust, data value and governance building blocks to TRL 6-7 IDSA-compliant ones, adapt them to energy sector, and deploy:
    - across-energy and cross-sector data enhancement technology enablers and standardisable interfaces and open APIs by leveraging on open Standards (e.g. ETSI Context Broker) and ontologies (e.g. SAREF 2)
    - dataspace connectors, to guarantee confidentiality, privacy, cybersecurity, trust, sovereignty and full data control
    - a DLT/Smart contract-enriched marketplace for several assets (data, energy assets, services) which allows coordination, exchange, sharing, and financial compensation
    - cross-value chain value-added services and Digital Twins, by leveraging on privacy-preserving federated learning
- develop and deploy a Reference Implementation of an EU Energy Data Space, which will be demonstrated along 7 pilots and 11 intra-electricity, intra-energy and beyond energy use cases
- co-design SSH-based consumer-centric business models for energy data sharing enabling data beyond-financial value creation and spreading along value chain
- advance the initiatives for the European Energy Data Space setup, through technological alignment and adherence (GAIA-X, IDSA, BDVA, ETIP SNET, BRIDGE), contributing to standardization and data sharing.

Enershare Data Space Reference Architecture is based on BRIDGE DERA 3.0, and the Deliverable 2.1 building blocks, which are in turn based on OpenDEI (Figure 34).

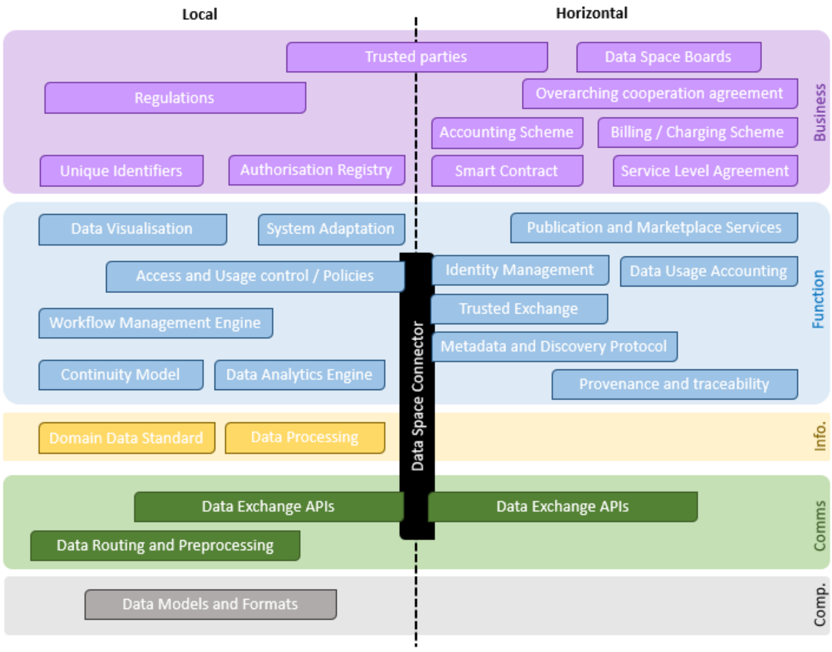


Figure 34: Enershare Data Space Reference Architecture [70]

The five horizonal layers include the Business, Function, Information, Communication and Component Layers. The vertical split distinguishes between local building blocks that facilitate the functionalities local to a use case, and the horizontal building blocks that allow requirement-abiding participation in the Data Space. The central Data Space Connector integrates the local and horizontal domains into the Data Space. The building blocks are identified based on the use case descriptions and the process steps within the business scenarios, information handling or fulfilment of requirements in the pilot use cases. According to the use cases within Enershare, there is a strong focus on data and trust exchange. Data used in the use cases should include data models and formats, possibly aligned with domain data standards, and enriched with metadata and discovery mechanisms through publication services and marketplaces. Trusted exchange makes use of the identity management within the data space and the access and usage control and policies and will be implemented across all use cases. These building blocks form the core of the requirements from the current bottom-up use case perspective.

4 TwinEU Component Catalogue

This chapter presents the TwinEU Component Catalogue, which outlines the key software components underpinning the TwinEU ecosystem. These components are structured as modular, interoperable units that each serve a specific function within the broader system architecture. They are developed in alignment with the project's task structure and are linked to the different technical work packages, ensuring that each component addresses well-defined needs across the ecosystem.

A component refers to a reusable and maintainable module that encapsulates a particular capability or service. Within TwinEU, these software components collectively support the development and integration of digital twins, data exchange mechanisms, AI-based analytics, and other enabling technologies.

4.1 Initial Identification of Component Catalogue

Table 2 below attempts to list the identified components which will be part of the TwinEU digital ecosystem.

Table 2: TwinEU Software Components

a/a	Component	WP	Task	Partner
TWC_01	Services Workbench	4	T4.1	UBE
TWC_02	Big Data management	4	T4.1	UBE
TWC_03	TwinEU AI Models Integration	4	T4.1	UBE
TWC_04	Interoperable Marketplace	4	T4.1	UBE
TWC_05	Interactive augmented exploration of TwinEU DT framework (3d Authoring - Unity Engine - GUI)	4	T4.2	ENG
TWC_06	TwinEU Middleware (GUI – Identity & Access Management)	4	T4.4	ED
TWC_07	DT Federator (OneNet Connector)	4	T4.5	ENG
TWC_08	Semantic Interoperability Enablers	4	T4.5	ENG
TWC_09	Digital twin for cybersecurity of cyber-physical systems	5	T5.2	TUD
TWC_10	Digital Twin for power system training simulator	5	T5.5	RTE
TWC_11	Digital Twinning Validation Tool	6	T6.2	ENEL
TWC_12	Digital Twin for Defence Use Case System	6	T6.3	TRI
TWC_13	Dynamic monitoring tool	6	T6.6	envelio
TWC_14	AI Security Assessment tool	6	T6.7	ELES
TWC_15	Digital twin for applied line monitoring sensors	6	T6.8	BME

TWC_16	Development of a detailed grid-constrained unit commitment model	7	T7.2	UPRC
TWC_17	Development of an enhanced, multi-product optimization tool	7	T7.3	F4STER
TWC_18	Digital twin for the Bulgarian electricity grid -1-	7	T7.4	SC
TWC_19	Digital twin for the Bulgarian electricity grid -2-	7	T7.5	SET
TWC_20	Digital Twin for HVDC interconnection between two power system digital twins	7	T7.6	UCY
TWC_21	Digital twin for stability of power systems	8	T8.2	TUD
TWC_22	Digital twin for operation and planning of the TSO	8	T8.3	REE
TWC_23	Control Centre support decision for the TSO	8	T8.3	CIRCE
TWC_24	Planning studies application	8	T8.3	CIRCE
TWC_25	Digital twin for operation and planning of the DSO	8	T8.3	ETRA/ANELL
TWC_26	Digital twin for operation and planning of the DSO	8	T8.3	ADAION/CUERVA
TWC_27	Digital Twin for cross-border probabilistic capacity allocation and flexibility assessment	8	T8.4	R&D NESTER
TWC_28	High-level Digital Twin of the Iberian Electricity System	8	T8.4	INESC TEC

4.2 TwinEU Pilots Component Information & Integrated Services

4.2.1 Iberian Pilot

The components and integrated services of the Iberian demo are:

Table 3: Iberian Pilot Components & Services

Scope & Challenges	To strengthen the security and resilience of the Iberian Power System in a context of high renewable energy penetration and a significant increase in the number of participants in the energy system. This will be achieved by implementing and coordinating various Digital Twins across the regional energy value chain, thereby improving grid planning and operational processes. The goal is to adapt to a future where electricity generation shifts from predominantly centralized production to a more decentralized model, with a growing number of energy producers connected at all voltage levels and actively participating in various electricity markets. Additionally, electricity consumption is evolving from traditional passive use to active management of consumption assets, integrating diverse energy sources.
Component	**Services**
DT of the transmission system as the DT facilitator	1. New algorithm development based on the combination of power system physical models with AI to enhance transmission

	system operation in presence of high penetration of renewable generation and uncertainty by: • Supporting the decision of control centre operator under specific events • Supporting operational planning activities 2. Tool development which will generate different probabilistic scenarios in different timeframes, considering high integration of renewable generation and demand uncertainty, by leveraging AI techniques.
DT of a distribution network based on ETRA's ÉTER distribution network management system	1. The DT at operational level will include automated topology identification with deep learning, which will be the basis for an AI-based state estimation module and indirect DLR functionality, eliminating the need for field measurement equipment deployment. 2. The DT at simulation level will incorporate grid planning features linked to higher RES penetration in MV-LV including open communication channels with market and TSO's DTs 3. The new dynamic model of distribution networks will be able to capture the whole active behaviour of the grid. To maintain data discretion and simulation computational burden within reasonable limits, this demo will implement an equivalent, reduced dynamic model able to capture the transient response of the distribution networks when facing large disturbances occurring at the transmission side. 4. Based on European Energy Markets SDAC- SIDC, the Iberian Electricity Market System DT will allow the Market Operator to simulate different scenarios such as high-RES penetration and the inclusion of new technologies (i.e., storage including electric vehicle and H2, etc.) predicting the effects on wholesale markets, thereby helping the energy system anticipate these impacts. Moreover, the DT will simulate the integration of new markets, such as local flexibility markets or other flexibility solutions, into the current electrical system and use new procedures to take advantage knowledge of the situation of each RES in the grid
DT Cell of the Iberian system interconnected with Central Europe (dynamic multi-area system)	1. Identify the needs on ancillary services: Use of properly tuned DT of a large multi-area control system (INESC TEC) will provide the dynamic behaviour assessment that enables the identification of the type and volume and characterization of frequency ancillary services (including innovative ones like FFR, virtual inertia) needed by the system. 2. Exploit in a common manner RES generation units and dynamic loads within a VPP concept providing both reserves upward and downward without de-loading the generation units and the loads. 3. Optimal sizing and location of grid forming converters by INESC TEC in an equivalent Iberian system for grid scenarios of 2030 and 2040 with large scale integration of power converters and reduced number of synchronous units

4.2.2 Eastern Mediterranean region pilot

The components and integrated services of Eastern Mediterranean demo are:

Table 4: Eastern Mediterranean pilot

<table>
<tr><td>Scope & Challenges</td><td>Through the development of an integrated balancing market optimization model, the Demo aims at providing actual and realistic scenarios for enabling the interconnection of digital twins between the mainland and Greece’s main insular power system (Crete), as well as the islanded Cyprus power system.</td></tr>
<tr><td>Component</td><td>Services</td></tr>
<tr><td>Integrated Balancing market optimization model</td><td rowspan="3">1. Prototype and scenarios simulator tool development for the balancing market operation
2. Provision of a mathematical formulation for the balancing market, considering distributed energy resources
3. Quantification of the impacts of different cybersecurity threats to determine the optimal operational response to them
4. Recommendations for TSOs and DSOs to incentivize consumers, prosumers, storage, and flexibility service providers to participate in the integrated energy and reserves
5. Enhancement of the flexibility and efficiency of the system through extensive scenario simulations
6. Dynamic monitoring of the interconnected regional power system
7. Foster the implementation of market coupling for regional electricity markets</td></tr>
<tr><td>Development of digital twin of the interconnection of the Cyprus power system with Crete</td></tr>
<tr><td>Enhancement of the digital twin of the Cyprus power system</td></tr>
</table>

4.2.3 Hungarian pilot

The components and integrated services of the Hungarian demo are:

Table 5: Hungarian pilot

Scope & Challenges	Previous projects, such as FARCROSS and FLEXITRANSTORE, have demonstrated that thermal parameters calculated using traditional physical models often differ significantly from actual sensor measurements. This highlights the need for Digital Twin-based approaches to calculate phase conductor temperatures. Such solutions not only offer more accurate thermal assessments compared to conventional models—which are typically limited to ampacity calculation, sag-clearance monitoring, and anti-icing—but also present opportunities to reduce asset costs and enhance the economic efficiency of network operations. The MARI and PICASSO platforms aim to support the development of an integrated, near real-time balancing energy market. While supply for this market is based on capacity procurement, it remains on a national or per-TSO basis. The co-optimized day-ahead market design facilitates multi-product trading using existing cross-border transmission capacity, serving as a critical enabler for full European market integration. By incorporating Dynamic Line Rating, which allows real-time

<table>
<tr><td></td><td>adjustment of transmission capabilities, the current network constraint framework can be evolved. This enhancement enables the cross-border optimization algorithm to better utilize additional ampacity, thus improving power flow on congested lines. The ICT market platform for co-optimized day-ahead energy and balancing capacity auctions, along with its underlying architecture and demonstrative implementation, ensures the protection of commercially sensitive data. It integrates current TSO and MO processes while meeting the specific requirements of co-optimized day-ahead market mechanisms.</td></tr>
<tr><td>Component</td><td>Services</td></tr>
<tr><td>Digital twin-based ANN conductor temperature monitoring</td><td rowspan="3">1. To provide a reliable and cost-effective alternative to line monitoring sensor measurements, digital twins based on an artificial neural network (ANN) will be designed for each sensor. Sensors will be installed on a transmission line, which collect weather, load, and thermal parameters for a specified period. An ANN, whose input parameters are the environmental and load parameters, while its output is the phase conductor temperature, will be selected and trained for all sensor locations.
2. Digital twin as a cutting-edge technology can be an authentic solution not only for the harmonization of the so far existing experiences, but also to achieve synergy between the TSOs and DSOs electric grid. The concept of digital twin is the modelling of the European high voltage power system on which the flow-based electricity market capacity auction algorithm runs besides the dynamic thermal rating calculation. Therefore, the capacity allocation and auction of the power flows means an optimized solution from an economic point of view as the ampacity of the lines is adjusted to their thermal state instead of the conservative static constraints.
3. The market platform for co-optimised day-ahead energy and balancing capacity auction will be used in combination with automatic bid-forwarding to/from other (usually continuously traded) markets. The platform will allow enhanced observability for operators to keep dynamic network limits as fully utilized as feasible and beneficial from the market stakeholders.</td></tr>
<tr><td>Co-optimisation algorithm with dynamic transmission line ampacity and intraday products</td></tr>
<tr><td>Market auction platform for transmission capacity auction within day-ahead/intraday timeframe</td></tr>
</table>

4.2.4 Bulgarian pilot

The components and integrated services of the Bulgarian demo are:

Table 6: Bulgarian pilot

Scope & Challenges	The primary aim of the pilot is the examination of some of the most prominent challenges that the system operators, regardless of the voltage level of the system itself, face in the environment shaped by rapidly increasing levels of penetration of the DER. The pilot foresees the evolution of the existing solutions into the next high Digital Density era, to offer adequate responses to resilience, proactivity and robust design. It will simultaneously allow the

	energy market actors located at the lowest voltage levels (consumers, prosumers, EV chargers, aggregators, energy communities or DERs) the non-discriminatory opportunity to participate in the process of providing the services necessary for the proper operation of the system. To address the above challenges demo will focus on optimal DER integration with advanced forecasts and capacity planning methods, including the development and testing of DTs and forecasts of RES operation. It also aims to support frequency and voltage control, congestion management and DERs' utilization. Another goal is to find optimal connection points of DERs and storages by using digital twins made beforehand. Both the technical capabilities of the grid and the relevant geographical characteristics will be considered to reach the best state for all parties.
Component	**Services**
Digital twin for the Bulgarian electricity grid • Increased data exchange from prosumers, including new services • AI-based predictive congestion management, load balancing and demand forecasting • Localised DERs energy production forecasts (prosumer energy production/consumption predictions) • Predictive consumer behaviour regarding demand side flexibility resources usage utilizing big data and AI • Improved identification of the available flexibility resources • FSPs planning and management of the flexibility resources	1. Collection of sufficient data related to both the market functioning and the limitations of the electricity network in the selected area and creation of the network model of the area that will be utilized for future analyses 2. Creation of the market model that will envelop different aspects of the electricity market functioning in Bulgaria 3. Obtaining the real-time reliable weather forecasts for the chosen region and the analysis of the influence that the climatic conditions have on the state of the power system in that area 4. Producing forecasts of the production of the renewable energy sources and of the behaviour of the demand based upon the obtained predictions of the relevant climatic conditions 5. Grid connection optimization via digital twinning simulations to satisfy grid connection requirements and agility in grid reconfiguration and provide ancillary services 6. Analysis of the impact that the previously mentioned forecasts may have on the congestion management and the frequency and voltage stability of the system 7. Incorporation of the optimization methods to determine the best possible locations, development projects and connection points for the new DERs, while optimizing asset use for efficient infrastructure services 8. Creation of the physical georeferenced network model based on the existing TSO and DSO grid models, with advanced weather and energy predictions

4.2.5 German Pilot

The components and integrated services of the German demo are:

Table 7: German pilot

Scope & Challenges	The most important component inside the German pilot is a cloud-based digital twin tailored specifically to the needs of DSOs, with a particular emphasis on low- and medium-voltage networks. Unlike other solutions that often focus on transmission-level modeling or individual asset management, the Intelligent Grid Platform (IGP) targets data-intensive mass processes at the distribution level. It integrates and validates data from previously siloed systems such as GIS, MDM, and CRM into a central network model. Based on this, it enables modular use cases such as transparency on LV hosting capacity, scenario-based grid development planning, and streamlined connection request evaluations. Moreover, by leveraging this central digital twin, it introduces a PlanOps approach, which connects planning and operations teams through real-time data exchange. This ensures that both departments collaborate efficiently, share insights, and make informed decisions. For example, when a new heat pump is connected to the grid, the operations team can immediately assess its impact, providing valuable feedback to the planning team for refining long-term assumptions. In terms of the TSO-DSO interface, with the deployment of an instance of the TwinEU dataspace (i.e., TwinEU connector and middleware) and the deployment of DPsim and VILLASnode (described in the next section), there will be a development and testing of interfacing components that enable real-time communication in simulation scenarios for Digital Twins in the context of dataspaces. In addition to this, a service for semantic interoperability will be explored in the same context.
Component	**Services**
IGP • Modern & flexible Python/JS/TS stack based on Django, FastAPI, Vue, and more • Large-scale data processing using industry-standard backing services such as PostgreSQL, TimescaleDB, RabbitMQ, and Redis • Infrastructure as Code and multi-cloud deployment with Gitlab	1. Dynamic Grid Monitoring (Task 6.6) • Live monitoring in the German demo region • Combination of static grid model with live monitoring data • State estimation with changing grid topology • Identification of current grid states and potential bottlenecks 2. End-to-End Flexibility Solution (Task 6.4) • Development of a congestion management solution considering grid and market operator requirements • Specification of cross-domain data models for DSO-TSO interactions • Support of flexibility aggregation for forecast mechanisms in the distribution grid 3. Grid Connection and Hosting Capacity (Task 6.5) • Integrated visualization of grid capacities (installed and planned)

CI, SaltStack, Terraform, and Kubernetes **DPSim** It is a solver library for dynamic power system simulation. The simulation core is implemented in highly efficient C++ code. It can load network data and models using the IEC61970 CIM / CGMES XML format. For data exchange it can be interfaced to a variety of protocols and interfaces via VILLASnode **VILLASnode** Is part of the VILLAS framework, a toolset for local and geographically distributed real-time co-simulation. VILLASnode is the interface component for coupling independent components that exchange data in real-time via various protocols and data formats. It is a manufacturer-independent tool that is extensible to new protocols, interfaces, and data formats. It provides a remote API for control via HTTP. Deterministic and low jitter due to low level C/C++ implementation. Easily deployable via Precompiled standalone binaries, Docker image or from source	• Visibility of connected assets in the demonstrator • Connection requests and online connection assessments for DSO, TSO and third parties 4. Data exchange, i.e. for TSO/DSO cooperation • Explore simulation using real-time capabilities and semantic interoperability in a data space environment.

4.2.6 Italian pilot

The components and integrated services of the Italian demo are:

Table 8: Italian pilot

Scope & Challenges	The core concept is to develop a unified Italian pilot that accommodates various use cases tailored to the specific needs, expertise, and available infrastructure of the different Italian partners. The DT will be designed to reflect the interconnection between transmission and distribution networks, enabling the

	integration and testing of these use cases. This setup will allow for the simulation of the individual behaviour of both transmission and distribution systems, as well as their coordinated operation. In this context, the two system operators play a crucial role in enhancing TSO/DSO collaboration, particularly through the incorporation of emerging technologies and innovative operational paradigms. A variety of use cases can be tested within this demo framework.
Component	**Services**
South Italy Power System Digital Twin (DSOs, TSOs interconnection)	1. Digital Twinning as validation tool • Design Validation will allow for active and shared participation, enabling real-time communication among multiple specialists (operators, engineers, other relevant stakeholders) – namely users – who will share a common virtual space, resulting in a more realistic perception of what the built environment should look like and therefore in a reduction of the risk of occurrence of errors during the construction phase 2. Self-Qualification over Digital Twin • In the context of flexibility and energy transition, the Digital Twin will be valuable for the qualification phase of energy resources connected to the grids 3. Improvement of the TSO/DSO interaction with special focus to the defence system • The study will be focused on a portion of the Sardinian grid. The procured RTS simulator will be interfaced with software able to manage system models and perform grid simulations. In addition, Terna has defined a program (called Tyrrhenian-Lab), and create new Labs in Cagliari, Palermo and Salerno, that will be equipped with additional RTS units. Additionally, the well-established ENET-RTLab is connected, through Politecnico di Torino, to the Real-Time Laboratory of the Institute for Automation of Complex Power Systems within the E.ON Energy Research Center at RWTH Aachen University, to carry out real-time co-simulations on a multi-site scheme

4.2.7 Slovenian pilot

The components and integrated services of the Slovenian demo are:

Table 9: Slovenian pilot

Scope & Challenges	In the coming years, Slovenia is expected to see a significant rise in the share of electricity generated from distributed and renewable energy sources, particularly wind and solar. To manage power flows and maintain voltage levels, the TSO, ELES, has already deployed Flexible AC Transmission System (FACTS) devices at the transmission level. Additionally, a considerable amount of battery storage is available to support ancillary services. All these technologies are integrated into the grid via power-electronic (PE) converters. Since most PV systems and battery storage are connected at the distribution level, gaining a deeper understanding of the static and

	dynamic characteristics of load and generation profiles at this level will become increasingly important for evaluating transmission system performance. Although data exchange between the TSO and the DSO currently enables the monitoring and forecasting of renewable generation and consumption, it does not provide sufficient insight into distribution system behaviour under voltage or frequency disturbances. A more integrated approach to the operation and planning of DSO-TSO networks is essential. Such coordination would enhance the security of energy supply and enable the integration of more RES into the distribution network than is currently possible. The main goal of the demonstration project is to modernize network operation and stability management by improving system observability—through advanced monitoring—and controllability—by leveraging the capabilities of PE-interfaced devices. This improved controllability will include the development of a new fast-frequency response service designed to boost system flexibility, which is vital for maintaining resilient operations. National energy plans project a sharp increase in renewable generation capacity, especially from PV, exceeding 50% of the installed capacity of synchronous generators. This trend will lead to higher variability in power flows. In response, fast-acting PE-interfaced devices, capable of responding within two seconds, are seen as a key solution for enhancing system stability. Developing such services will require closer cooperation between DSOs and TSOs, as well as among TSOs themselves, with active involvement from market participants playing a critical role in this evolution.
Component	**Services**
Real-time static and dynamic security assessment tools (SSA and DSA)	1. Upgrade of the existing network operation and stability management process which will be based on increased system observability and controllability 2. Development of a new fast-frequency response service, which will increase the system flexibility, which is essential for ensuring resilient operation 3. Development of a methodology for scenarios-based modelling of future network operating conditions and for network planning, allowing for analysis of the system with high shares of renewables and PE-based devices. This methodology will include the developed SSA and DSA tools and the fast-frequency response service in the network planning process with the aim of optimizing the investments in the network infrastructure 4. Within the project, static and dynamic security assessment tools will be developed and tested in the actual environment of the TSO. The tools will enable a more reliable operation of transmission systems in highly dynamic operating conditions and better utilization of primary network infrastructure. Distribution system operator and distribution company will enhance network planning by increasing data exchange with transmission system operator and development of dynamic transmission network equivalent

4.2.8 French/Dutch pilot

The components and integrated services of the French/Dutch demo are:

Table 10: French/Dutch pilot

Scope & Challenges	Dutch/French Pilots recognize the challenge of developing separate digital twins for the transmission and distribution systems and their applications. Consequently, a unified, integrated digital twin will be developed for the manageability and effectiveness of DT applications. Due to the significant computational resources and limited access required to accurately depict the complete Dutch electrical power system, standard dynamic model templates were applied. These methods are designed to refine the models, particularly to enhance details in key areas such as the integration points of significant variable RES. **Dutch pilot:** To achieve comprehensive system models, the partners in Dutch pilot collaborate closely, beginning with developing models for the transmission system. It will be followed by integrating dynamic, reduced models of the remaining system components, thereby providing a detailed and synthetic presentation of the physical system. This involves using specialized equivalent models to effectively represent interconnections with adjacent networks, ensuring a cohesive and interconnected digital twin ecosystem. This pilot aims to understand the operational dynamics of future power systems, particularly in evaluating the impact of cyber-attacks (by proposing methods to prevent cyber-attacks) and active power disturbances (more common due to the increase of renewable's intermittency and lack of physical inertia). This is crucial for ensuring the resilience and reliability of power systems against evolving conditions and cyber threats. **French Pilot:** The objective is to improve the training of system operators on realistic network scenarios, involving power network as well as communication network events. The DT should be able to play scenarios and record the results for debriefing with trainees. The digital twin is meant for training system operators on stability-critical scenarios and for testing new components (automata, software decision modules). It will include several modules within a co-simulator interfaced through an orchestrator module: Cyber-physical simulators represent physical and cyber networks. SCADA will display network state to operators and send orders from the operators to cyber-physical simulators. A game master will supervise all the modules and will have the ability to run training scenarios.

Component	Services
Integrated Dutch Digital Twin **Integrated French Digital Twin** **Cybersecurity Assessment: Attack Detection Module** **Cybersecurity Assessment: Cascading Failure and Impact Analysis Module** **Stability Assessment: Active Power Disturbance Analysis Module.** **Control Room of the Future (CRoF)** **Game Master** **Cyber Physical Simulator** **SCADA** **Smart Assistant**	DUTCH PILOT: 1. **Transmission and Distribution System Modelling and Cyberattack Simulation:** The Dutch 380kV transmission system dynamic model is being modelled in the DIgSILENT PowerFactory with various controllers, and protection schemes. This model represents as the synthetic model for the Dutch transmission system. Various types of use cases will be performed to study the dynamic behaviour on the system under various physical and cyber-attack cases which represent the cascading failure system dynamics. 2. **Conduct real-time cyberattack simulations on digital twins of interconnected power grids:** Different cyberattack scenarios will be designed and executed on the digital twins, aiming to understand their effects on grid stability and resilience. Mininet will be utilized to simulate the network environment, providing a realistic platform for network configurations and attack scenarios. Additionally, this task will use an Open Platform Communication Unified Architecture (OPC UA) as an interface between the physical and cyber simulated layers for data exchange and interactions within the power grid, enhancing the simulation realism. OPC UA Client and Server are modelled as interacting components in the OPC UA architecture. Preparing attack datasets will further enhance the realism of these simulations and provide valuable data for further analysis. 3. **Anomaly detection using machine learning:** Machine learning method will be used to continuously monitor network traffic and operational data, identifying deviations from normal patterns. By analysing deviations in communication network traffic, the system can promptly detect potential cyber threats and operational anomalies. This integrated approach, leveraging Mininet for network simulation and an OPC UA server for protocol simulation, will enhance the ability to protect power grids from cyberattacks and ensure stable and reliable power system operations. 4. **Analyse how cyber-attacks can initiate cascading failures and cause a blackout:** Cyber-attacks can cause multiple contingencies, e.g., N-k. The probability of occurrence of such contingencies is rare when caused by physical disturbances. However, cyber-attacks can trigger them simultaneously. This significantly speeds up the point of no return, leading to cascading failures and blackouts. A computational method and tool will be developed and demonstrated that is used to assess the cascading failure mechanism and analyse how cyber-attacks can cause a blackout. 5. **Assess in real-time the impact on the operation of interconnected power grids:** Cyberattacks will be simulated in real-time on the digital twin of the interconnected power grids, which can result in loss of generation and interconnectors, and disconnection of multiple transmission lines. The impact on

	power system operations will be evaluated by computing impact indices based on the loss of load, frequency, voltage deviations, surviving islands, and affected power system components. 6. **Simulate and analyse system stability under active power disturbances:** This service evaluates the power system's dynamic response to events such as short-circuits, generator outages, and sudden load variations in real time. It assesses frequency behaviour and voltage recovery using real-time simulation models under scenarios with high penetration of converter-connected renewable sources. FRENCH PILOT: 1. **Game Master:** Oversees scenario execution and operator training 1. Configured system modules (grid model, asset mapping, telecom characteristics) 2. Provides a State View for trainers (unfiltered network visibility) 3. Includes Game Master KPI functionality for monitoring system performance and decision-making during simulation. **2. Cyber-Physical Simulator:** This component consists of three sub-modules: 1. Grid Simulator: Models the physical power network using Dynawo, ensuring dynamic simulation of electrical events 2. Asset Simulator: Maps physical system states to Cyber representations for SCADA-based control 3. Information Flow Model: Simulates telecommunication behaviour and cyber contingencies, including data delays and loss. **3. SCADA** SCADA acts as an interface between the operator, the game master, and the cyber-physical simulators. This SCADA displays the GUI and receives the operators' orders as they would be sent/received as in the real world. **4. Orchestrator** 1. Acts as the central event handler, coordinating actions from the Game Master, SCADA and external systems 2. Ensures event-based execution with real-time updates every second 3. Interfaces with SCADA and external replay for KPI analysis 4. Logs all system interactions, enabling replay for KPI analysis

5 Business & System Use Cases

This chapter presents a comprehensive overview of the TwinEU project's business and system use cases, highlighting the diverse actors, their roles, and their contributions to the project's objectives. The chapter is structured to provide a clear understanding of the interconnected elements that drive the project forward, starting with the key actors and their functionalities, followed by the high-level and business use cases, and concluding with an analysis of the data sources supporting these activities.

5.1 TwinEU Actors

The TwinEU Actors section identifies and describes the main stakeholders involved in the project, spanning various roles across technical, operational, regulatory, and research domains. These actors—ranging from TSOs to software providers and research centres—constitute the foundation of the TwinEU ecosystem. Each actor plays a distinct role in ensuring the project's success by contributing expertise, tools, and services essential for advancing DT technology and its applications in energy systems.

Table 11 provides insights into the actors' high-level responsibilities and relevance to specific demonstrations within TwinEU project. This overview serves as a reference point for understanding the collaborative framework of the project and the synergies between different stakeholders. This is presented in Table 11 below.

Table 11: TwinEU Use Case Actors by Actor Type

a/a	Actor Type	Short Description	Demos
1	**Academic Institute**	The Academic Institute owns the CRoF, housing a real-time simulator (RTDS) and additional hardware, where the Dutch digital twin pilot for stability assessment will be demonstrated at TU Delft. Additionally, the institute actively supports all technical challenges and is responsible for independent evaluation of the DT models.	Dutch Hungarian
2	**Asset owner/ User/ Customer**	The owner/user of an asset or micro-flexibility.	German
3	**Data Exchange Platform Operator (DEPO)**	The Data Exchange Platform Operator provides and manages platforms for secure and efficient data exchange across distributed systems or organizations. These platforms facilitate interoperability without centralizing data, ensuring compliance with regulations, and maintaining data security. Key functionalities include: • Coordinating and managing data exchanges between systems. • Supporting federated architectures to enable secure data sharing and integration across multiple stakeholders. • Implementing standardized data formats, access control, and communication protocols. • Acting as middleware to streamline interoperability while allowing organizations to retain control over their datasets.	German Slovenian

4	**Digital Twin (DT) Operator**	The DT Operator, which could be part of the engineering department of any System Operator, is responsible for validating the N-1 contingency characteristics of the distribution grid (DSO DT Operator). This role involves leveraging DT technologies to ensure grid reliability and stability under various scenarios.	Iberian
5	**Distributed Energy Resources (DER)**	DERs refers to energy resources that include generation, storage, and/or controllable loads connected at the low or medium voltage distribution level. A DER may represent a single unit or a collection of units, which can also be referred to as a DER plant or facility. These assets include rooftop solar, energy storage, electric vehicles, and demand response systems. DER plants can function as microgrids, typically connected to the main grid but capable of disconnecting and operating autonomously when necessary.	EM Greek Italian
6	**Distribution System Operator (DSO)**	A DSO is a natural or legal entity responsible for operating, maintaining, and developing the distribution system in each area and its interconnections with other systems. DSOs ensure the long-term ability of the system to meet electricity distribution demands. They act in compliance with EU regulations, including Directive (EU) 2019/944 and other relevant provisions, defining tasks such as electricity transport at HV, MV, and LV levels, grid maintenance, and integration of new technologies like digital twins. In specific regions: • Bulgarian DSOs contribute their knowledge and experience in the pilot alongside TSOs. • German DSOs manage extensive operations across multiple areas, adhering to EU market rules. • Cypriot DSOs ensure proper operation of the distribution grid to prevent congestion cost-effectively by coordinating DER flexibility. • Greek DSOs balance supply and demand, integrate distributed energy resources, and oversee infrastructure development to support the transition to decentralized, low-carbon energy systems. They procure congestion management products, prequalify resources, and ensure the balancing market's efficient operation. • Iberian DSOs oversee market participants at MV/LV levels and integrate maintenance activities validated by DT-based simulations. • Italian DSOs fulfil similar responsibilities, focusing on long-term system demands and EU-defined roles. • Slovenian DSOs also manage electricity distribution and interconnections, with roles detailed under Directive 2007/72/EC for electricity and 2007/73/EC for gas.	Bulgarian German EM Cypriot EM Greek Iberian Italian Slovenian

7	**Flexibility Service Provider (FSP) / Balancing Service Provider (BSP)**	A Flexibility Service Provider (FSP) offers flexibility services to energy stakeholders, including DSOs and TSOs, through bilateral agreements or flexibility markets. FSPs participate in flexibility markets and Frequency Containment Reserve (FCR) markets, providing congestion management and balancing services based on activation signals and system frequency measurements. They aggregate flexibility capabilities, often from DERs, to support grid stability and efficient operation.	Belgian EM Cypriot EM Greek German Iberian
8	**HEMS Provider**	A HEMS (Home Energy Management System) Provider is a legal entity that aggregates and controls flexible assets behind the meter, enabling efficient management and optimization of residential energy resources.	German
9	**HVDC Operator**	The HVDC Operator is responsible for the operation and maintenance of HVDC links, which transfer large amounts of electricity between interconnected countries or regions. Their tasks include monitoring and controlling HVDC equipment, ensuring power transmission reliability and stability, and compliance with constraints imposed by interconnected power systems. In this context, the HVDC Operator participates in electricity markets, offering grid support services such as FCR. They control HVDC links to deliver cleared FCR services during frequency events.	EM Cypriot
10	**Market Operator (MO)**	A MO is responsible for matching offers to sell electricity or electricity flexibility with bids to buy them, ensuring the efficient operation of electricity markets. MOs award market products related to congestion management services and play a key role in integrating DERs into electricity markets. In specific regions: • Cypriot MOs facilitate electricity and flexibility trading, and award market products related to congestion management. • Greek DAM (Day-Ahead Market) Operators conduct pan-European electricity trading for next-day delivery, optimizing social welfare and integrating DER technologies. • Greek Balancing Market Operators (BMO) ensure real-time balance of supply and demand, manage reserves and ancillary services, and integrate renewable energy and DERs while coordinating market participants. • German MOs operate energy exchanges, matching bids and offers on trading platforms. • Hungarian MOs handle technical operations related to the transmission network and market operations. • Iberian MOs manage the Spanish electricity market operations across High Voltage (HV), Medium Voltage (MV), and Low Voltage (LV) levels, ensuring alignment with DT capabilities.	EM Cypriot EM Greek German Hungarian Iberian
11	**Measuring Device**	The MDP is a natural or legal person responsible for operating, maintaining, and collecting data from measurement devices in the field, such as those installed in LV/MV stations.	German

	Provider (MDP)		
12	**Metering Point Operator (MPO)**	An MPO is a natural or legal person responsible for operating, maintaining, and collecting data from Smart Meters. MPOs ensure the reliable and accurate collection of consumption and grid data for effective energy management.	German
13	**Regional Security Coordinator (RSC)**	The RSC ensures the security and reliability of the electrical grid within a specific geographical area. Their responsibilities include real-time monitoring of cross-border interconnections, coordination of cross-border electricity flows, ensuring compliance with grid codes, and facilitating communication among TSOs and stakeholders. The RSC is crucial for maintaining a continuous and secure electricity supply across regions.	EM Cypriot
14	**Regulatory Authority**	The Greek Regulatory Authority for Energy, Waste and Water (RAAEY) oversees and enforces regulations related to grid operations, tariffs, and system reliability. It ensures that energy systems comply with established rules and operate efficiently.	EM Greek
15	**Research Centre**	The Research Centre (e.g., CIRCE) focuses on algorithm development and advanced research, contributing to innovative solutions for grid management and optimization.	Iberian
16	**Smart Assistant Developer (SAD)**	The Smart Assistant Developer is responsible for debriefing and analysing the results of training sessions, providing insights for improvement and validating outcomes.	French
17	**Information Technology (IT) and Software Provide**	Technology and Software Providers play a pivotal role in delivering the information technologies and advanced solutions necessary for pilot operations. They ensure the integration and execution of functionalities through innovative tools and support infrastructure. Their responsibilities include: • Belgium: Providing the IT technologies required for implementing the functionalities in the pilot work. • Hungary: Developing neural network-based conductor temperature calculations and Dynamic Line Rating (DLR) DT technologies as active project partners. • Iberian Peninsula: Creating AI-driven tools for digital twin self-discovery and debugging to enhance DT accuracy and reliability. These providers enable the deployment of advanced tools and solutions, contributing significantly to the success of digital twin implementations and operational reliability.	Belgian Hungarian Iberian
18	**Trainee**	The Trainee participates in training sessions by running the prepared scenarios, gaining experience and knowledge to enhance their operational capabilities.	French
19	**Trainer**	The Trainer is responsible for building the scenarios used during training sessions, preparing participants for practical exercises and simulations.	French

20	**Transmission System Operator (TSO)**	A Transmission TSO is a natural or legal entity responsible for operating, maintaining, and developing electricity transmission systems within a designated area. TSOs ensure grid stability, reliability, and adequacy while connecting all grid users at the transmission level and coordinating with DSOs. Their role aligns with Article 2.4 of the Electricity Directive 2009/72/EC, emphasizing the ability to meet long-term system demands and support interconnections with other systems. In specific regions: • Bulgarian TSOs bring critical knowledge and experience for pilot outcomes alongside DSOs. • Greek TSOs (IPTO) maintain, develop, and operate the Hellenic Electricity Transmission System, ensuring reliable electricity supply and market operations in line with transparency and competition principles. • Hungarian TSOs manage the distribution network and related technical tasks for the relevant BUC. • Iberian TSOs (REE) utilize their expertise and data to align with EU Smart Grid Task Force guidance for grid development and interconnections. • Italian TSOs adhere to the EU Directive, ensuring efficient grid operation and interconnection management. • Slovenian TSOs maintain compliance with EU standards, focusing on interconnection and grid development. • Dutch TSOs are responsible for maintaining and operating transmission networks, including providing records, historical data, and verifying digital models for synthetic data generation.	Bulgarian EM Greek Hungarian Iberian Italian Slovenian Dutch
21	**Weather Data Supplier (WDS)**	The WDS is a natural or legal person that provides weather data through APIs. This data supports grid operations and forecasting models.	German
22	**Weather Forecast Provider (WFP)**	The WFP supplies high-resolution weather data essential for implementing advanced functionalities in developed tools. This role may be fulfilled by an individual entity or a designated unit within a TSO or DSO.	Belgian

5.2 High Level Use Cases and Business Use Cases

This chapter presents a comprehensive overview of the TwinEU project's business use cases as part of T2.4 "Setting priorities and development of use cases" [27] input.

Table 12: High Level UCs description

Use Case ID	Use Case Name	Scope
BG01	Establishment of the data exchange between the Digital Twins	Establishment of the desired level of communication between the DTs that will be made in the scope of both tasks falling under the Bulgarian pilot. This will be one of the necessary prerequisites

		before the initiation of the procedures included in those tasks. As stated in Deliverable 2.2 in which the communication flows between the DTs are defined, this will mostly be done by using Python codes fit for purpose.
BG02	AI-Improved Forecast of WPP Production	The scope of this task will be the usage of the fit-for-purpose AI techniques to improve the quality of the forecasts of the production power of selected capacities in the grid. In this case, those will be WPPs. This is bound to provide the system operators with a much clearer image of the potential FSPs in the grid, all that while allowing them to evaluate offers for services made by those FSPs.
BG03	AI-Improved Forecast of SPP Production	The scope of this task will be the usage of the fit-for-purpose AI techniques to improve the quality of the forecasts of the production power of selected capacities in the grid. In this case, those will be SPPs. This is bound to provide the system operators with the much clearer image of the potential FSPs in the grid, all that while allowing them to evaluate offers for services made by those FPS
BG04	AI-Improved Forecast of OHL Ampacity	This Use Case will focus on the benefits of the accurate determination of line rating based on the weather conditions that are valid in the locations of interest. It will be revolving around two main points – the ways in which the additional capacity that the dynamic line rating enables (compared to the static approach) can help in the proper utilization of the power system infrastructure and the development of the AI-boosted tool that will be able to calculate those ratings swiftly and reliably.
BG05	Increase of power flow on cross border transmission lines	This Use Case will be rather like the Use Case Bg04, focusing, instead of the general approach, on the possibility of applying the created AI-based algorithm on the cross-border lines to enhance energy and flexibility exchange between the neighbouring systems for the sake of system stability and security
BG06	Determination of optimal locations for RES connection	This Use Case will focus on the determination of the optimal connection points for the RES capacities (either WPPs or SPPs) in the region of interest. An attempt will be made to take into consideration both the interest of the investors in the RES and the interest of the system operators (meaning that the reliable operation of the system cannot be put at risk due to the work of RES at any point)
BG07	N-1 assessment on the DT level	This Use Case will be created around the idea of detecting those elements in the transmission grid of

		Bulgaria whose outage could cause severe issues in the normal operation of the system. This can be used for the risk assessment and, in turn, can be an indicator of the potential action that would need to be taken by the Bulgarian TSO in the next couple of years to ensure the proper work of the system.
BG08	DT-based Maintenance plan of TSO grid	This Use Case will deal with one of the major issues frequently spotted in the work of the transmission system operator – the problem of properly planning maintenance of the grid so that the minimal strain is put on the remaining elements of the grid. For that to be done, the N-1 analysis will be conducted for the situations in the grid in which some other element is already under maintenance. By doing this, the elements during whose maintenance the issues are the most likely to appear will be pointed out. This can be used for performing the proper risk assessment afterwards.
BG09	Flexibility Requirements to Avoid Congestions	The Use Case will revolve around the situation in which congestion is spotted in the distribution grid, after which the potential solutions of this issue that are based on the application of the FSPs in the same region will be examined. The FSPs that will be considered here will be the ones connected to the distribution grid. The type of the FSP will depend on the analysed part of the grid, but can potentially include the WPPs, SPPs (both paired with ANN-based forecast) or controllable demand.
BG10	Inter-SO Flexibility Exchange	The Use Case will revolve around the situation in which the congestion is spotted in the transmission grid, after which the potential solutions of this issue that are based on the application of the FSPs in the same region will be examined. The FSPs that will be considered here will be the ones connected to the distribution grid. The type of the FSP will depend on the analysed part of the grid, but can potentially include the WPPs, SPPs (both paired with ANN-based forecast) or controllable demand.
NL01	DT-enabled real-time cyberattack impact analysis on the operation of integrated power grid	The scope of this use case is to analyse the impact of cyberattacks on stability and cascading failures in real-time on the operation of interconnected power grids
NL02	DT-based dynamic stability assessment under active power flow changing events.	This use case aims to develop and implement a DT to assess and enhance the stability of power systems under various active power flow disturbances. The DT will model and simulate the real-time dynamics of the power grid, including interactions between DSOs and TSOs. The study will focus on understanding the impact of events such as

		generation tripping, load shedding, transmission line faults, large-scale renewable integration fluctuations, and demand response events on system stability.
FR01	Power system training simulator for complex and critical situations	The scope of this use case concerns: • Cooperative training sessions for system operators. • Testbed for software or hardware modules.
EM-CY-01	Congestion management in distribution grids through ancillary services	
EM-CY-02	Frequency support management of HVDC-interconnected systems in a regional level	
EM-GR-01	Congestion management in transmission and distribution grids through TSO-DSO coordination	
EM-GR-02	Fast Frequency Response for Effective Frequency Control through TSO-DSO coordination	
Ge01	Utilization monitoring on LV-level	
Ge02	State estimation under changing topology on LV-level	
Ge03	Development of advanced monitoring & control tools for congestion management	
Ge04	Development of a concept for a preventive congestion management	
Ge05	Optimal utilization of the flexibility potential in the network feeder by aggregation of flexible assets within the household via HEMS	
Ge06	Development of advanced tools for preventive congestion management through regional aggregation of flexible assets	
Ge07	Conceptual description of interoperable solutions that support efficient TSO-DSO data exchange on the interface level.	
Ge08	Connection request and online connection check applications for the DSO, TSO as well as for third parties.	
HUN1	Digital twin for power line monitoring	
HUN2	Co-optimizing the energy and balancing capacity market coupling with dynamic flow-based auction	
Ib01	AI Agent for probabilistic grid status forecast and remedial actions identification for the TSO’s Control Centre Operator	
Ib02	DT for generation of synthetic series of renewable resources	
Ib03	DT-enabled multi-area system dynamic behaviour assessment	
Ib04	Abnormal market participation detection and protocol activation for mitigating the risk and consequences	
Ib05	DT-based N-1 contingency analysis	
Ib06	DT-enabled new RES integration validated plan in the MV grid	
Ib07	DT-based grid maintenance planning activities	
Ib08	DT self-discovering and debugging based on IA	

Ib09	Optimal planner for massive DERs deployment (EV, PV) at the LV Grid
Ib10	Advanced Planner for LV Operation
Ib11	Long term flexibility in MV
Ib12	Flex Connections
Ib13	Probabilistic cross-border capacity allocation
Ib14	Cross-border assessment of flexibility and pre-qualification
Ib15	Integration of TSO-DSO-MO-Prosumer coordination schemes as well as market coordination
Ib16	Enhancement of short-circuit models and TSO/DSO information exchange for operational planning
Ib17	DT-endorsed permanent flexible connection grant through the settlement of a Local Flexibility Market to internally balance the production surplus in congestion-creation hours/scenarios.
IT01	Analysis through DT of the TSO defence system
IT02	Analysis through DT of the behaviour of aggregated distributed resources during a grid event in the TSO system
EACL-IT-01	Digital Twin for definition of data model
EACL-IT-02	Digital Twin for design validation
EACL-IT-03	Scalability of Digital Twin for design validation
SLO-UC-1	Dynamic RMS Analysis with Upgraded Transmission System Model
SLO-UC-2	Real-time Dynamic RMS Analysis with Transmission System Model improved with the dynamic parameters of generators and control models of the neighbouring TSOs

5.3 Data Sources & Data Formats

This section outlines the data exchanged, as reported in the Use Cases (UCs). This data is essential for defining the functional specifications of the TwinEU platform and guiding the development of the data management platform. The content presented here represents a consolidated overview of the data sources and formats identified in the project up to the time of this deliverable. Following the consolidation process, the information was systematically categorized. The categorization framework is based on OneNet catalogue [46], with certain categories broadened (*OneNet (extended scope)*) to capture additional types of activities and data required for digital twin and project-specific use cases. New categories were also introduced to accommodate data types unique to the identified UCs. The categories and their descriptions can be found in Table 13, while the number of data exchanges identified per category is depicted in Table 14. It is important to note that some data items may fall into more than one category, so these results may be reviewed and further improved if appropriate.

Table 13: OneNet Exchanged Data Categories

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
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 14: Information exchange per Category

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

Data formats were not consistently included in the information exchange descriptions. Nevertheless, some descriptions referenced formats such as JSON and XML (e.g., Market data of Day Ahead and Intraday), and the CIM RDF/XML file format, compliant with the CGMES profile for the distribution grid model. Additional data relevant to the project were identified from two key sources. First, from the SGAM Information Layers, a wide range of data formats and communication protocols were noted, including JSON Web Signature, Modbus, IEEE C37.118, EN 60870 (102/104), IEC 62056 (DLMS/COSEM), and various specific models tailored for DTs of TSOs, DSOs (e.g., CITRIC Data Model), Market Operators, and Aggregators/DER Operators. Standards such as IEC 61970 (CGMES), IEC 61968-9, and IEC 62541 were also present. Second, data models and sources were collected through a project-wide questionnaire. These included PMU data exchanged via IEEE C37.118, renewable generation data (wind and PV) accessed through HTTPS APIs in JSON format, and models based on the IIDM format as used in the PowSyBl framework and in simulators like Dynawo and OpenModelica. CIM standard is used in network representations.

5.4 Interoperability interfaces

5.4.1 Data Space interoperability interfaces

Data spaces can be established based on varying domains, goals, architectures, business models, and governance structures. This is why interoperability must be supported by common standards and principles that allow participants to interoperate in the same data space (i.e., intra data space) or between different data spaces (i.e., cross or inter data spaces). Interoperability [77] is required at different levels, and the European Interoperability Framework [48] identifies four main levels.

- **Technical interoperability**: covers system connectivity, including protocols, and defines the requirements of interfaces and services with security aspects.
- **Semantic interoperability**: ensures shared understanding of data meaning through concepts, relationships, and ontologies.
- **Organizational interoperability**: involves aligning processes, roles, and agreements for effective data sharing.
- **Legal interoperability**: addresses the mutual recognition of contracts across ecosystems, despite differences in regulations, laws, or interpretations.

These levels of interoperability can be addressed by aligning the TwinEU federation to the Data Spaces specifications. For interoperability to occur at a technical level, there is a need to define common protocols and interfaces, typically using secure network connections like HTTPS and uniform APIs that all participants can access. For cross data spaces, the basis is the Dataspace Protocol (DSP), which provides a set of specifications designed to facilitate interoperable data sharing between entities that are connected to different data spaces and have a different governance. Organizational interoperability is achieved by defining clear data sharing processes, roles for data consumers and providers, and agreements for data subscription, which together ensure a structured and transparent data exchange. Semantic interoperability can be enabled by providing a common vocabulary through standardised data models used consistently across services. For legal interoperability, contracts must be designed to comply with specific local regulations while remaining valid across different jurisdictions. It is crucial that participants understand the mapping of the data space policies to legal constructs. It is important to enable participants to share their data and models in a way that aligns with their specific processes and services. This can be facilitated by a component that offers an interface where participants can browse and discover services listed in a predefined catalogue. Once a relevant service is identified, the participant can define the corresponding data schema—or even provide a concrete data example instance—to specify what will be shared. The OneNet connector has already implemented an interface that can be extended to new data offering services and to another model catalogue. For the Digital Twins to integrate their platform into the TwinEU data space, a connector is needed to be installed at their premises. Besides that, a central platform or middleware should take care of centralised features, ensure governance, maintain shared vocabulary, and monitor compliance with established agreements. In this scenario, data exchange will be possible through uniform and standard interfaces based on REST API.

5.4.2 SGAM interoperability interfaces

The TwinEU Architecture Interface Model independent of the TwinEU RA can be visualized as a three-dimensional architectural framework that can be used to model interactions (mostly exchange of information) between different entities located within the smart energy and especially storage arena. In more detail, the design process will focus on the i) Business aspect (domains), ii) Architecture aspect (zones), and iii) Interoperability aspect (levels) as defined in SGAM. To maintain interoperability between any two components in TwinEU, interoperability needs to be considered on five different Interoperability Layers. The first two layers are related to functionality, whereas the lower three layers can be associated with the intended technical implementation. The interoperability layers being used are basically derived from the GridWise Architecture Council (GWAC) interoperability stack [78].

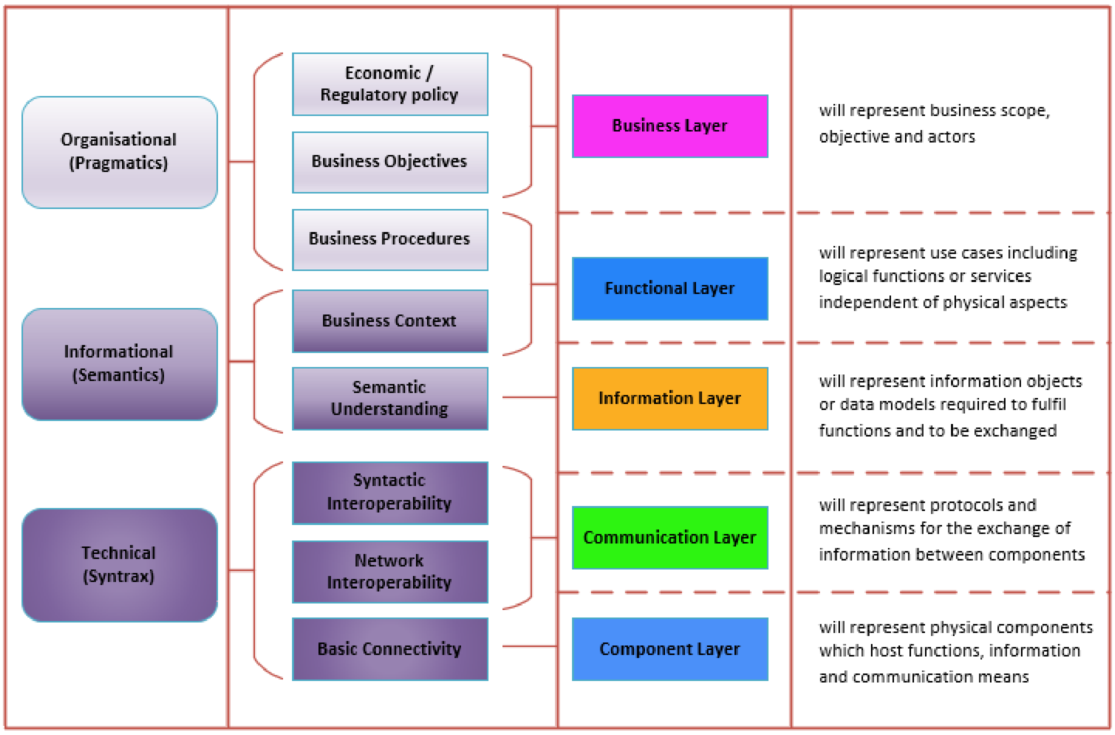


Figure 35: GWAC to SGAM to TwinEU interfaces

5.5 System Use Cases Analysis

This section describes the current state of the art regarding the identification and definition of the General System Use Cases (GSUCs) within the context of the TwinEU project. The content presented reflects the status of the work conducted under Task 3.2 at the time of writing and is subject to further refinement. The GSUCs constitute the conceptual and technical foundation for the design and implementation of interoperable digital twins for the European energy system. A final and detailed version of this activity will be provided in Deliverable D3.2. The current section offers a synthesized overview of the methodology adopted and the main activities carried out so far. The definition of the GSUCs required the adoption of a structured and systematic methodology involving several coordinated phases, methodological tools, and collaboration among key project stakeholders. The process began with a comprehensive analysis of the project's objectives and requirements, aligned with technical guidelines, European strategies, applicable standards and pre-existing initiatives and projects. This initial step was essential to establish the framework for identifying relevant high-level system use cases. Subsequently, a series of dedicated workshops and meetings were conducted with WP2 and WP4 to collect relevant feedback from key partners, including domain experts, pilot representatives, technology providers, and developers. These sessions were aimed at gathering detailed functional requirements, as well as validating key assumptions regarding system behaviour, digital twin federation, and interoperability needs.

Based on the outcomes of these consultations, specific technical functionalities, operational workflows, and interoperability challenges related to the planning and operation of the digital twin for the energy system were identified and analysed. To support this effort, a combination of established methodologies was employed, including scenario-based engineering, business capability mapping for identifying core functionalities, and formal use case modelling using UML diagrams.

The resulting GSUCs, listed in the Table 15, represent a structured set of system use cases specifically designed to support the implementation of the TwinEU platform for federated DTs for Energy system, emphasizing core system functionalities, interoperability mechanisms, and the definition of technical and data flows required to enable seamless data exchange across DTs.

Table 15: GSUCs summary table

General System Use Cases	GFURs
GSUC_01 - Federated Digital Twin (FDT) ecosystem for Energy System Integration	18
GSUC_02 - AI-Driven Big Data ad IoT Data Orchestration and Marketplace for Cross-Platform Digital Twin Services	28
GSUC_03 - Integration with IoT devices and other data sources to TwinEU	23
GSUC_04 - Regulatory Compliance Exchange and Reporting	10
GSUC_05 - Resilient Energy Infrastructure Planning including Dynamic Renewable Energy Integration and Digital Twin-Driven Grid Resilience and Anomaly Detection	10
GSUC_06 - TwinEU XR Framework for DTs visualization and validation	8

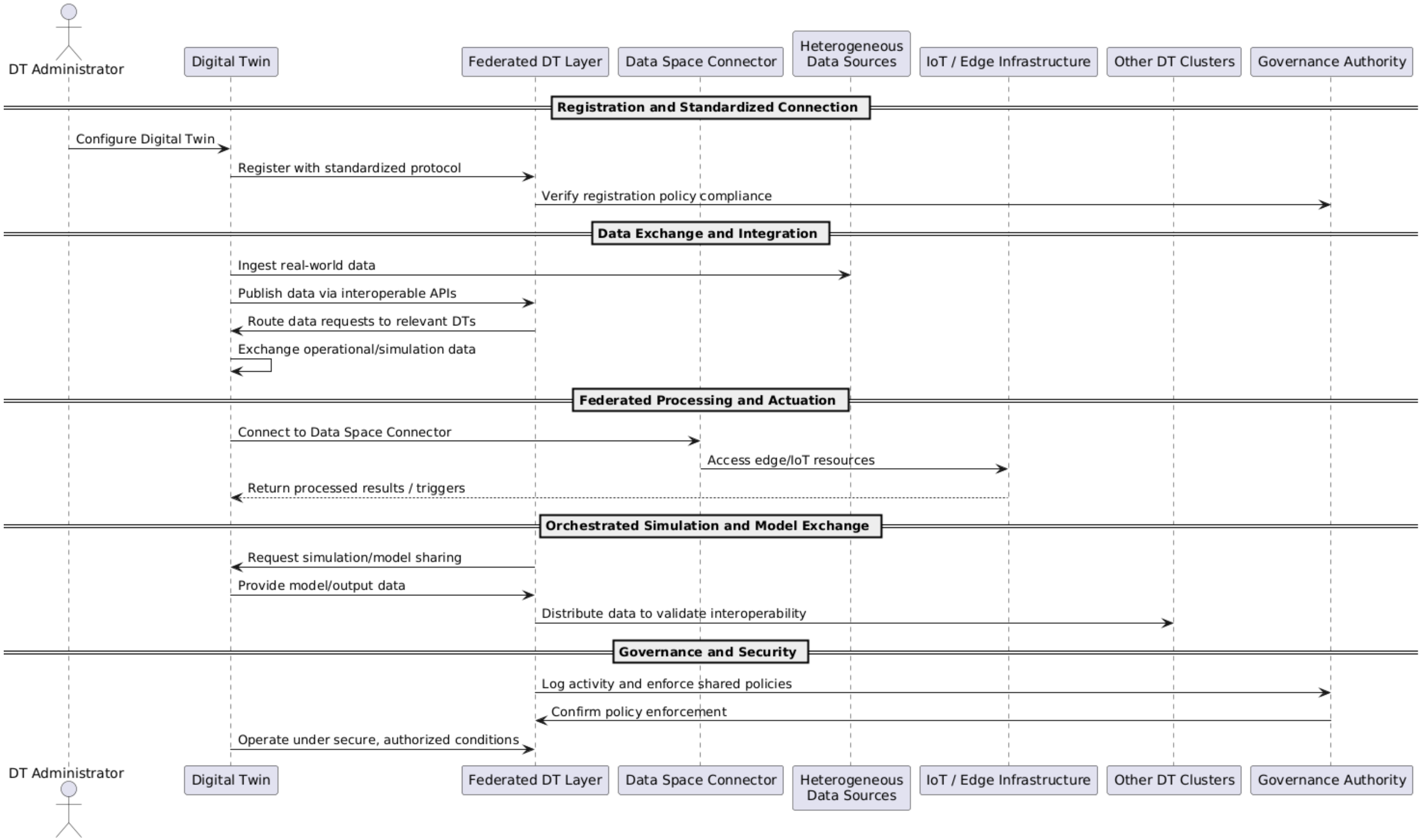
The GSUC_01 is presented in detail as an example in Table 16, while the full list of GSUCs is provided in the annex section of this document.

Each GSUC is also linked to a set of General Functional User Requirements (GFURs), derived according to the methodology outlined in Section 6.1. A summary table mapping GSUCs to their corresponding FURs will be included in Deliverable D3.2, along with the complete list of associated GFURs.

Table 16: General System Use Case 01

GSUC Name	Federated Digital Twin (FDT) ecosystem for Energy System Integration
GSUC ID	GSUC_01
Objectives	• Establish a Digital Twin Federation as an ecosystem of interconnected local Digital Twins forming a cohesive system of systems. • Develop interoperable interfaces to facilitate seamless bidirectional data flow between physical and virtual entities. • Enable the Digital Twin concept for flexible integration with heterogeneous data sources and infrastructures.

	• Utilize the Data Space Connector for DT to integrate DTs data and models in a seamless and interoperable way, ensuring data control and security. • Lay the foundation for the pan-European Digital Twin ecosystem, supporting an integrated data value chain from the physical layer to grid services. Support orchestration of data and model sharing, data exchange, and real-world data integration across Digital Twin clusters through a Data Space Framework.
Narrative	A fundamental concept introduced by the TwinEU architecture is Digital Twin Federation, a distributed and interconnected system of local Digital Twins that collectively operate as a system. The key part of this federation is the Digital Twin, designed to support the effortless integration of diverse data sources and infrastructures, regardless of their structure and format. By integrating with the Data Space connector, the Digital Twin Federation layer leverages IoT, edge computing, and edge nodes, ensuring effective data acquisition, processing, and utilization. A key enabler of this architecture is the Federated Digital Twin Layer, which plays a pivotal role in: • Integrating heterogeneous network models across national Digital Twin clusters. • Orchestrating data sharing and exchange processes among these clusters. • Enhancing simulation and real-time decision support by incorporating live operational data. This approach creates an integrated data value chain, enabling a resilient, sustainable, and efficient energy system across Europe. The Federated Digital Twin Framework ensures better decision-making, predictive analysis, and operational efficiency, driving innovation and collaboration in the energy ecosystem.
Involved Platforms/ actors	Digital Twin Federation Layer: Middleware Digital Twins Data Space Connector TwinEU System: IoT and Edge Computing Infrastructure Data Orchestration and Interoperability Layer, (e.g. Middleware, GUI for the whole ecosystem); Key Participants: Grid Operators, Policy Makers, Market Participants, and Domain Experts

Sequence Diagrams	

6 Functional Specifications for of pan European DT design

This section provides an overview of the activities carried out within Task T3.2 – Functional specifications of pan-European Digital Twin design. The focus is on the methodology and processes used to identify and structure two main categories of system requirements:

- Functional User Requirements (FURs), which define what the TwinEU system should do in terms of features, behaviour, and user interactions.
- Non-Functional Requirements (non-FURs), which describe how the system should perform, addressing quality attributes such as performance, security, reliability, and maintainability.

The content presented reflects the status of the work at the time of writing and includes a preliminary set of both FURs and non-FURs, derived through an iterative process involving feedback from pilot partners and domain experts. These requirements are based on the use cases defined across the various demonstrators and have been continuously refined through validation activities. Furthermore, the software solutions that are based on the artificial intelligence are used as a support in analysis and formulating the requirements. A representative selection of key requirements is provided in this section to illustrate the approach and structure, while additional draft for N_FURs requirements still under review are included in the Appendix. A summary of the number and types of requirements identified per pilot site is also provided to highlight the scope and coverage of the analysis conducted so far. It should be noted that this section presents a snapshot of the status of Task T3.2. The final, validated and comprehensive set of requirements, including detailed mappings to use cases and demonstrator activities, will be delivered in Deliverable D3.2 "Functional and Technical Specifications".

6.1 Methodology for deriving Functional Requirements

This section outlines the process for extracting specific FURs from UCs for the Pan-European DT design. FURs describe what the system should do. They specify what the system needs to do, behaviour and functionalities, in that way that users' needs are satisfied in the TwinEU system. Input from WP2 is instrumental for deriving FURs, as well-defined Use Cases give the solid bases for work on FURs. They are important for shaping reference architecture and crucial in development processes. Having in mind all these conditions, following steps are defined:

- Evaluation of Use Cases
  - Review demonstration Use Cases
  - Identify the key functionalities
- Requirements Elicitation and Analysis
  - Break down each UC into specific functional requirements that describe the functionalities, features, and behaviours required to fulfil the objectives of the UC scenario. Translate the requirements implied by each UC scenario into actionable and testable functional requirements.
  - Specify Inputs, Outputs, and System Behaviour and Operations
- Documentation
  - Document Functional Requirements
  - Organise Functional Requirements
- Validation and Review

- Prioritize Functional Requirements
- Validate Requirements with Stakeholders, domain experts, pilot partners
- Refine and Iterate

Validation and reviewing processes have been very important in the first iterations of deriving FURs. Dedicated meetings with each pilot site were carried out. Furthermore, data, requests, and responses have been communicated with emails and ad-hoc calls also. Questionnaires, documents, and Excel files with needed information were prepared and exchanged with partners. Detailed responses from the pilot partners were received and analysed. They helped greatly in shaping the FURs. Modifications and adjustments have been made to some FURs, some of them removed, while others were differently prioritized. All requirements (REQs) were defined using the MoSCoW prioritization technique. The acronym MoSCoW means: Must-Have, Should-Have, Could-Have, Won't have. The refinements deriving have included removing ambiguities, gaps, and writing cleaner definitions of the REQs. The defined FURs are aligned with technical constraints as well as business goals, user needs, and project scope. The result of the steps described is a set of functional requirements that will be present here and in the Appendix section. Nevertheless, this is not the final collection of requirements. As not all the UCs are complete and final, and some of the pilot sites will have additional UCs, this process will continue in the next iterations, as described in the methodology. The steps can be resumed by the following image.

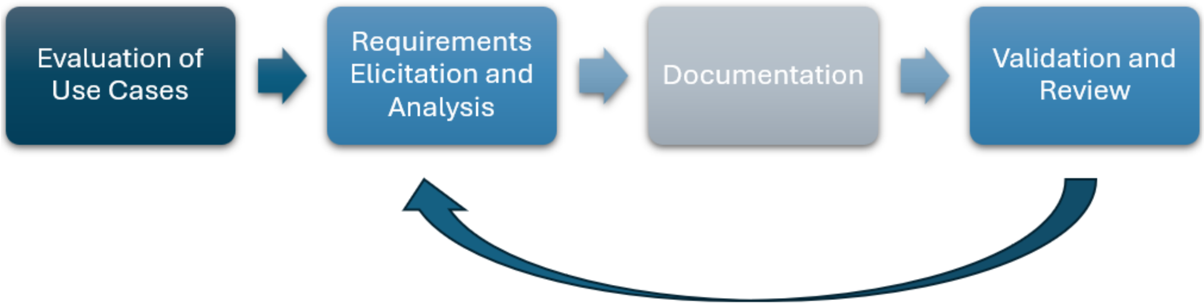


Figure 36: Methodology steps for deriving Functional Requirements

Figure 36 illustrates the adopted iterative process for defining FURs where all use cases are initially well-defined. However, modifications may be required based on input from stakeholders and domain experts or to address clarifications identified during the review of requirements. In case of new UCs or updates, the process restarts from the initial step: "Evaluation of Use Cases."

6.2 Methodology for Non-Functional Requirements

Non-Functional Requirements (non-FURs) describe how systems should work. They define quality attributes of the system. They are aligned with ISO/IEC 25010:2023 standard that provides a framework for evaluating software quality through some key characteristics, including functional suitability, performance, security, and reliability. It ensures systems meet both technical and user needs, guiding the definition of non-functional requirements systematically. The MoSCoW prioritization is used here also. It is very important to which degree the system follows each requirement. Selected quality attributes are clearly defined, bearing in mind that they have an impact on the reference architecture and the whole TwinEU system. These are steps defined so the deriving of non-FURs is straightforward and reliable:

- Evaluation of Standards and Use Cases

  - Understand ISO/IEC 25010:2023 Quality Characteristics: Familiarize with the nine quality characteristics defined in ISO/IEC 25010:2023.
  - Review UCs to understand the business objectives, user needs, and scenarios that will be demonstrated.
- Requirements Elicitation and Analysis
  - Map DEMO UCs to ISO/IEC 25010:2023 Characteristics
  - Translate ISO/IEC 25010:2023 Characteristics into Requirements
  - Specify Measurable Criteria
- Documentation
  - Document Non-Functional Requirements
  - Organize Non-Functional Requirements
- Validation and review
  - Prioritize non-functional requirements
  - Validate with Stakeholders
  - Refine and iterate

The steps can be resumed by the following image.

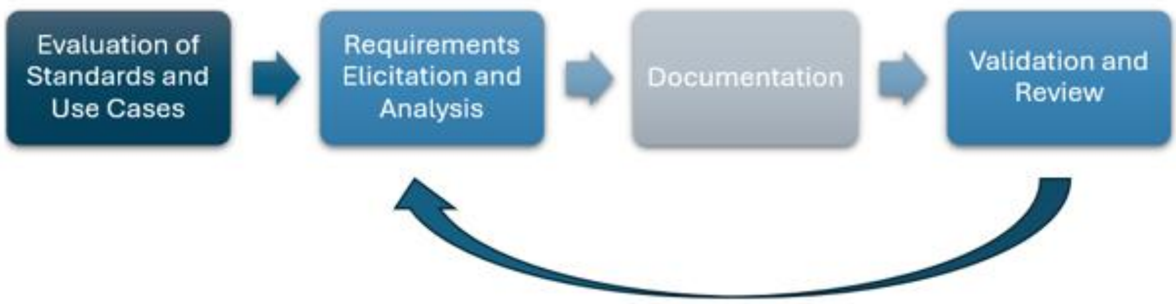


Figure 37: Methodology steps for deriving Non-Functional Requirements

As is the case with FURs, a similar iterative process is described in Figure 37 for non-functional requirements definition. If the standard is revised or significant changes are identified in the pilot's use cases, the iteration will recommence from the initial step: "Evaluation of Standards and Use Cases."

6.3 Analysis of TwinEU Functional Requirements & Specifications

6.3.1 Functional requirements

This section provides a preliminary overview of the FURs identified for each demonstrator, based on the analysis of the related Use Cases. The objective is to offer a clear understanding of how FURs are derived, organised, and associated with different demo/pilot sites.

Using the methodology described in the previous sections, FURs have been defined for each Use Case and validated in collaboration with the pilot partners and Demo leaders. Table 17 presents a high-level summary showing the current number of identified FURs per demonstrator. This offers a snapshot of the progress made so far and helps highlight the distribution of requirements across the various pilot sites. It is important to note that this data reflects a work-in-progress status and may still evolve as validation and refinement activities continue.

Table 17: Summary table with the number of FURs for each DEMO

DEMO FURs summary	Pilot sites	Nº of UCs	Nº of FURs	Total UCs	Total FURs
DEMO5	Dutch-French pilot	2	18	4	34
	East-Mediterranean pilot	1	9		
	Iberian pilot	1	7		
DEMO6	Italian pilot	5	24	15	104
	Slovenian pilot	1	10		
	Hungarian pilot	1	7		
	German pilot	8	62		
DEMO7	East-Mediterranean pilot	3	26	15	148
	Slovenian pilot	1	9		
	Hungarian pilot	1	3		
	Bulgarian pilot	10	100		
DEMO8	Dutch-French pilot	1	5	14	104
	Iberian pilot	13	99		
Total		48	380	48	380

To illustrate how the Functional Requirements will be structured in the final documentation (D3.2), Table 18 provides a selection of representative FURs, grouped by demonstrator and identified through specific Requirement IDs. This example demonstrates the format and level of detail that will be adopted in the complete list. The final and consolidated version of this information will be documented in Deliverable D3.2, where all validated Functional Requirements will be formally reported.

Table 18: Sample set of Functional Requirements

Requirement ID	Name	Description	Related Use Case(s)	Note
DT-CYB-03-01	Mitigation Protocol Activation for Local Flexibility Markets	The DT must trigger mitigation protocols for local flexibility markets (short-term and long-term), ensuring that any identified cyber-attacks or abnormal activities are isolated and managed.	Ib04	
DT-O&M-04-02	Legal Compliance	The system must ensure that flexibility solutions adhere to individual legal specifications for both network and market operator requirements.	GE04	

DT-F&OG-01-03	DER Integration and Management	The system must support the integration and management of various DERs, including solar panels, wind turbines, energy storage systems (ESS), and electric vehicles (EVs).	EM-GR-01	
DT-SC&PG-03-04	Remedial actions	The system must suggest a remedial action or set of remedial actions to mitigate transmission system risks. For example, limitation of generation, grid topological actions, definition of controllable devices setpoints.	Ib01	

6.3.2 Non-functional requirements

The Non-Functional Requirements (NFRs) are defined at two levels:

- Demonstrator level
- TwinEU system level

This section aims to establish a common framework that all demonstrators will adhere to, ensuring consistency across pilot implementations. At the same time, it outlines the general quality attributes expected of the TwinEU system as a whole.

6.3.2.1 Non-FURs on the demonstrator level

In the following Table 19 are provided the non-functional requirements on the DEMO level. They are common for all the demonstrators and can be seen as an aspect that shows their key qualities, such as security, efficiency, and suitability.

Table 19: Non-Functional Requirements on DEMO level

Requirement ID	Name	Category	Subcategory	Description
NFR_DEMO_01	Testability and Assessability within Demonstrator Architecture	Maintainability	Testability	The system shall be testable and assessable within the demonstrators' architecture, ensuring that all components and functionalities can be effectively evaluated and verified for performance, reliability, and compliance with specifications.
NFR_DEMO_02	Feedback-Driven Modifiability	Maintainability	Modifiability	The system should be modifiable based on the feedback collected during the evaluation phase of the demonstrations.

NFR_DEMO_03	Precise and Correct Functional Implementation	Functional Suitability	Correctness	The system should ensure the proper and precise implementation of all the envisioned functionalities.
NFR_DEMO_04	Full compliance with GDPR and relevant standards	Security	Confidentiality/Integrity	The system must ensure full compliance with relevant data protection regulations, including GDPR, and industry-specific standards for data management and sharing. Compliance with data protection laws (e.g., GDPR) must be ensured for all personal or operational data processed by the system. GDPR
NFR_DEMO_05	Validation and feedback	Performance Efficiency	Time Behaviour	The system must perform validation and provide feedback within a reasonable time frame to ensure that the process is not delayed.

6.3.2.2 Non-FURs on TwinEU system level

The definition of Non-Functional Requirements (non-FURs) at the TwinEU system level is a key activity that supports the development of the system's reference architecture. These requirements define essential constraints and quality attributes that guide the design of core components and their interactions.

Although the validation of these requirements is nearly complete, some refinements may still be applied. Therefore, the current version should be considered a draft. The final set of Non-Functional Requirements will be formally documented in Deliverable D3.2.

A preliminary list of the identified non-FURs is included as a draft version in the Annex of this document and is already broadly aligned with the reference architecture to ensure coherence in the overall system design.

Table 20: Sample set of Non-Functional Requirements on the TwinEU system level

Requirement ID	Name	Category	Subcategory	Description
NFR_TWINEU_01	Low-Latency Real-Time Data Processing and Communication	Performance Efficiency	Time Behaviour	The TwinEU system must manage real-time data efficiently (e.g. within 5 to 10 seconds). The TwinEU system must process real-time data with minimal latency, ensuring timely responses, enabling real-time or near-real-time

				communication (e.g., under one minute).
NFR_TWINEU_02	Responsive User Interaction and Immediate Feedback	Performance Efficiency	Time Behaviour	The TwinEU system must respond promptly to user inputs and provide immediate feedback, ensuring that users can interact with The TwinEU system efficiently during complex operations.
NFR_TWINEU_03	Uptime and Availability Assurance for Continuous Operations	Reliability	Availability	The TwinEU system must ensure high uptime (minimal downtime) and availability while performing operations, to ensure continuous monitoring and control
NFR_TWINEU_04	User Identification and Authentication	Security	Authenticity	The TwinEU system should uniquely identify all users within the system, ensuring accurate and secure user recognition.

6.4 FUR mapping to UCs Methodology

To ensure a systematic approach in developing FURs within the TwinEU project, a mapping process has been established between the Use Cases defined at each pilot site and the corresponding FURs. This mapping creates a clear and traceable link between the practical needs and scenarios explored in the pilot activities and the formalised functional specifications, which serve as a foundation for the system's technical development and validation. Mapping is conducted in the way in which all identified UCs from pilot sites are analysed at system level, and then, after an elaborate process, FURs are assigned to each of them. These FURs precisely define expectations regarding system behaviour in terms of the needs of end users and stakeholders. In this way, coordination between the TwinEU system development and identified needs in pilot sites' activities is well established. A representative example is Table 21, which illustrates the mapping for the Slovenian pilot site. It shows how specific Use Cases (e.g., SLO-UC-1 and SLO-UC-2) are linked to a set of functional requirements (e.g., DT-O&M-07-SLO01-01 to DT-O&M-07-SLO01-10). This ensures detailed tracking of how system functionalities are covered and implemented in real-world scenarios. The mapping table is structured into three main columns:

- Pilot site under analysis
- Related Use Cases developed
- IDs of the derived Functional Requirements, along with a brief description of each UC

Each Use Case is associated with a tailored set of FURs, defined according to the UC's specific objectives and required functionalities. This structure supports comprehensive monitoring and ensures that all functional aspects essential for real-world applications are addressed effectively. A complete list of mapping tables will be provided in the deliverable D3.2.

Table 21: Slovenian pilot's mapping table/matrix

Pilot	Related Use case(s)	FUR ID
Slovenian pilot	SLO-UC-1 - Dynamic RMS Analysis with Upgraded Transmission System Model	DT-O&M-07-SLO01-01
		DT-O&M-07-SLO01-02
		DT-O&M-07-SLO01-03
		DT-O&M-07-SLO01-04
		DT-O&M-07-SLO01-05
		DT-O&M-07-SLO01-06
		DT-O&M-07-SLO01-07
		DT-O&M-07-SLO01-08
		DT-O&M-07-SLO01-09
		DT-O&M-07-SLO01-10
	SLO-UC-2 - Real-time Dynamic RMS Analysis with Transmission System Model improved with the dynamic parameters of generators and control models of the neighbouring TSOs	DT-F&OG-06-SLO02-01
		DT-F&OG-06-SLO02-02
		DT-F&OG-06-SLO02-03
		DT-F&OG-06-SLO02-04
		DT-F&OG-06-SLO02-05
		DT-F&OG-06-SLO02-06
		DT-F&OG-06-SLO02-07
		DT-F&OG-06-SLO02-08
		DT-F&OG-06-SLO02-09

7 Technical Specifications for Standardised Data Access & Integration

7.1 Introduction

This chapter comprises part of the work done in T3.3 “Technical specification for open interoperable federated DT design” and T2.3 “Key digital technologies boundary conditions and requirements”. Analysis has been performed using the SGAM layers defined in T3.3, refined from the activities reported at M12, Milestone 4, and high-level technical requirements defined from T2.3. The creation and refinement processes of these layers and requirements are further detailed in D3.2 and D2.2 [27].

7.2 Analysis of TwinEU Technical Specifications

This section provides an analysis of a set of high-level technical requirements provided by T2.3, mapping each of them to the corresponding technical specifications defined in the SGAM layers. The objective is to ensure alignment between the technical specifications and the technical requirements, not only by placing the requirements within the corresponding SGAM layers but also by adapting the actors, components, communication protocols, and their interactions based on the requirement definitions.

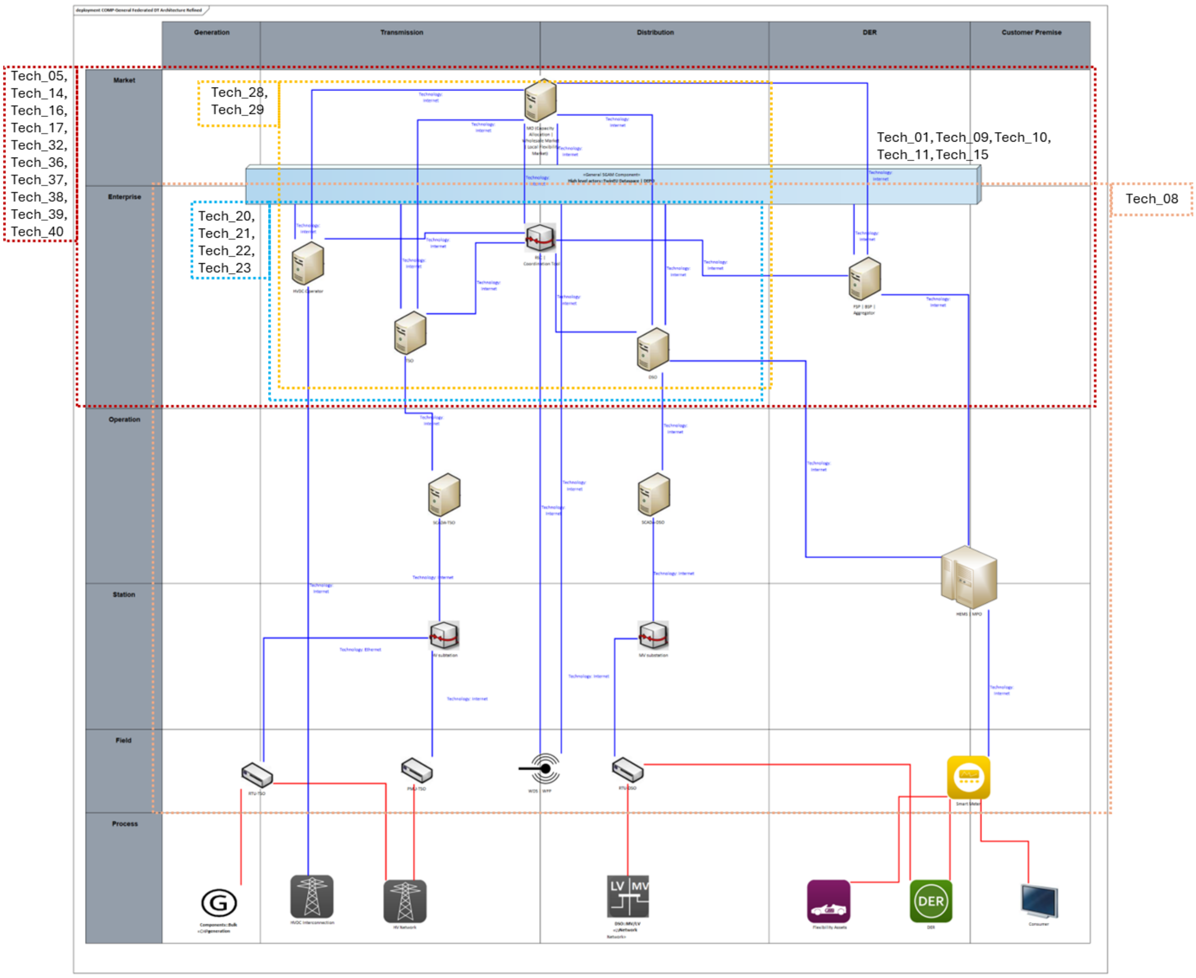


Figure 38: Component Layer

Based on the SGAM model version provided in Milestone 4 at M12, a refinement process has been carried out using the TwinEU actors defined in Section 5.1, the T2.3 high-level technical requirements, and the pan-European scenarios outlined in WP2. As a result, the SGAM layers have been simplified to better support the various actors, communication protocols, and the information exchanged among the components. Additionally, the TwinEU Dataspace has been introduced as a component to facilitate data exchange among Digital Twins.

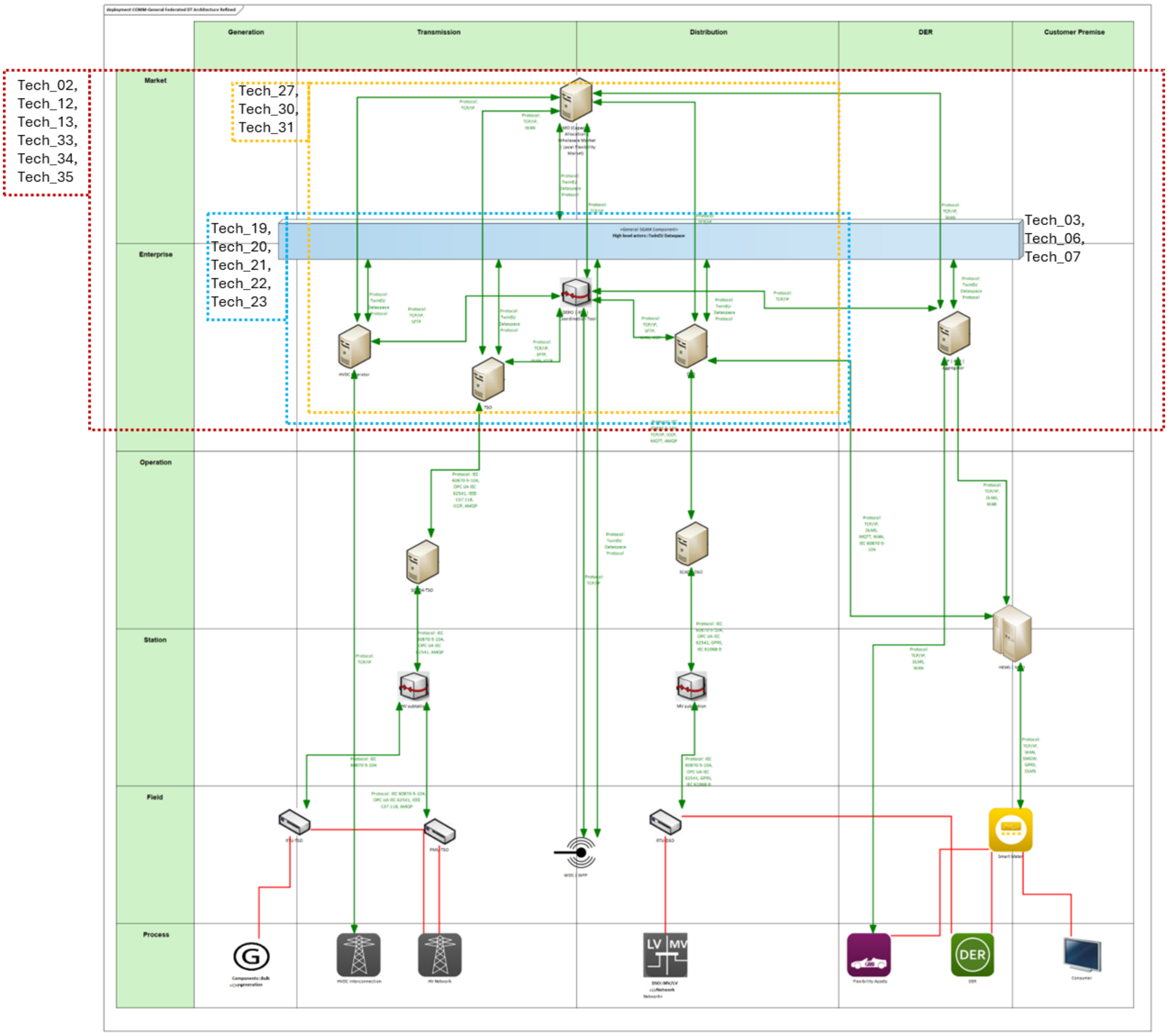


Figure 39: Communication Layer

Regarding the high-level technical requirements, the complete list is available in deliverable D2.2 [27]. The technological limitations defined have been identified and mapped within the SGAM layers, indicating the relevant domains, zones, and technical constraints using highlighted boxes. The mapping process was primarily manual, considering each requirement individually and determining where it best fits depending on the nature of the functionality or constraint. In some cases, a single requirement was mapped across multiple layers due to its relevance.

Starting with the Component Layer (see Figure 38), the mapped requirements refer to specific functionalities, integrations, and intrinsic features of the components and Digital Twins involved. Depending on the domain and zone, various high-level technical requirements affect different Digital Twins. For instance, access control mechanisms, data exchange validation, and data quality checks are features relevant to all defined Digital Twins. In contrast, more specific use cases such as power flow optimization, grid planning, and grid stability are relevant to DTs related to TSO-DSO operations.

Requirements mapped into the Communication Layer and the Canonical Data Model in the Information Layer include protocols, standards, specific features, and security measures applied during communication between different parties or Digital Twins (see Figure 39 and Figure 40). The communication layer focuses on protocol adoption to address challenges during data exchange. Examples include promoting interoperability, standardized data and communication models, and support for decentralized data architectures to ensure secure and reliable communication between entities. Furthermore, data agreements, protocols, and policies are integral to the TwinEU Dataspace framework, impacting not only the Dataspace itself but also the Digital Twins utilizing it.

The Canonical Data Model within the Information Layer provides insights into aspects such as standardization, security, access authorization, and other mechanisms that ensure the reliability of communication processes. This includes data formats and semantic models that promote interoperability, scalability, and data integrity during information exchanges.

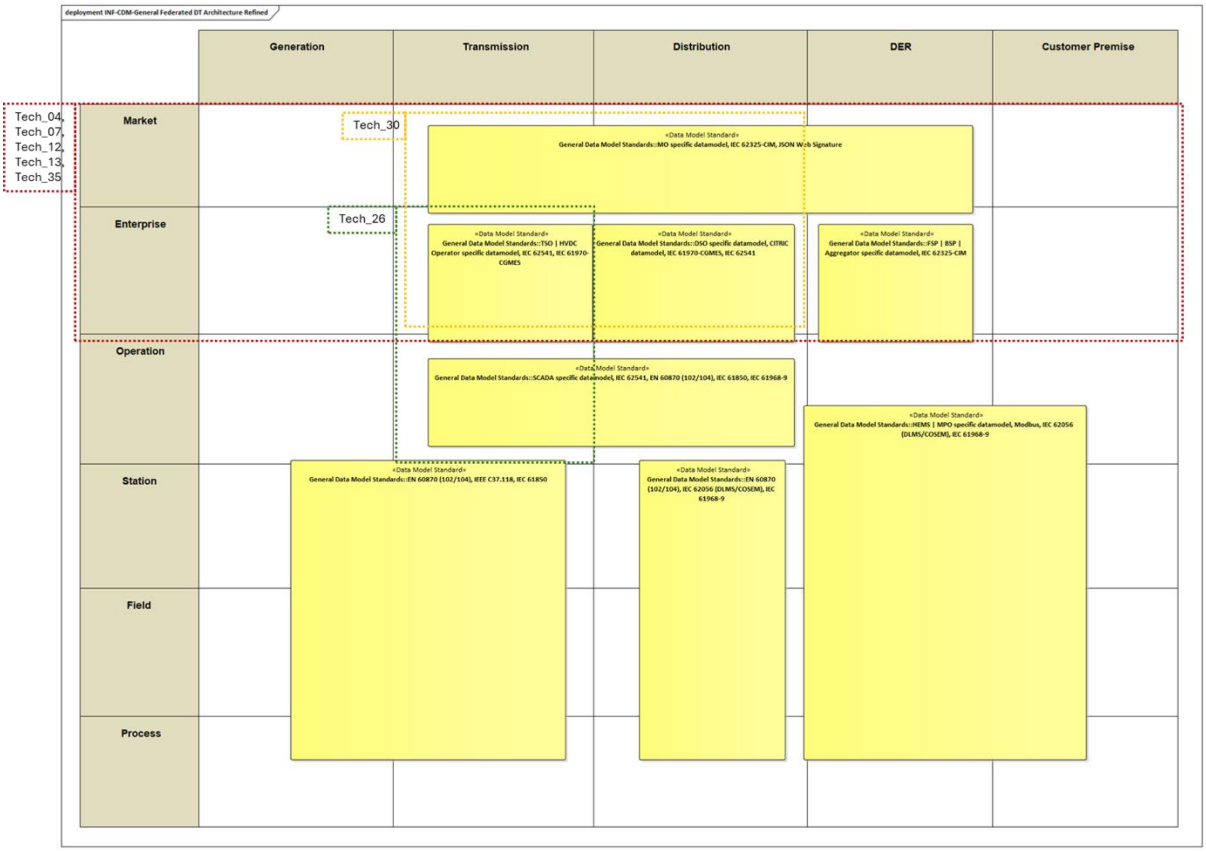


Figure 40: Canonical Data Model

Finally, the Information Layer also includes technical requirements related to applicable data protection laws and regulations, especially the General Data Protection Regulation (GDPR) and relevant national data privacy policies. These regulations are particularly important in relation to data flows, metering information, and real-time data exchange that supports grid observability and the evaluation of system constraints. Compliance with such legal frameworks is essential for ensuring data security and user privacy across Digital Twin interactions.

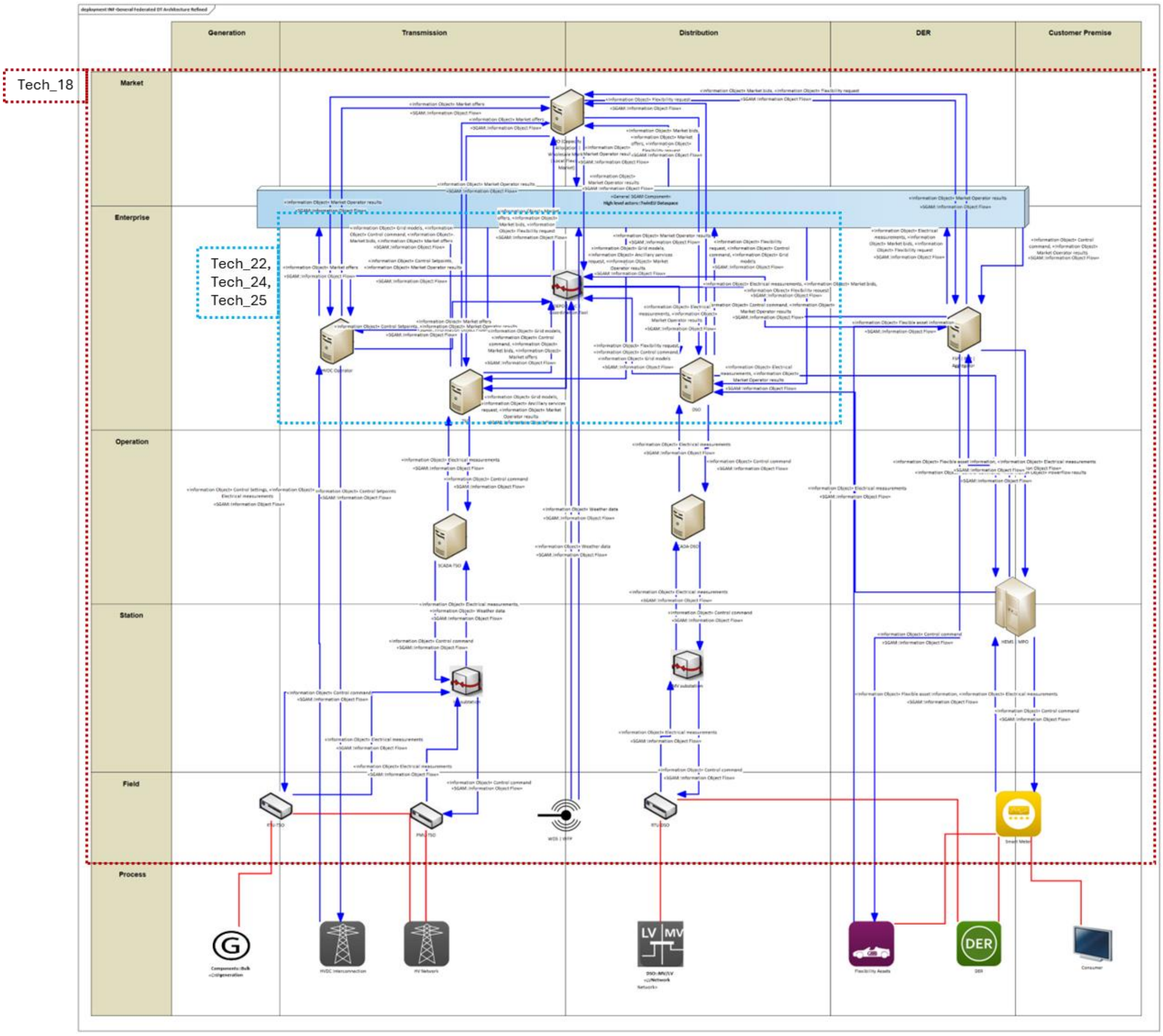


Figure 41: Information Layer

In summary, the mapping of high-level technical requirements provided by T2.3 against the SGAM layers has enabled a structured and coherent alignment between the system's functional needs and its architectural design. Through a refined and actor-oriented interpretation of the SGAM framework, the analysis ensures that the relevant components, communication protocols, and data exchange mechanisms are appropriately addressed. This approach not only highlights the cross-layer relevance of many requirements but also supports the secure and interoperable interaction of Digital Twins within the TwinEU ecosystem. By incorporating data governance principles, compliance with regulatory frameworks such as GDPR, and the integration of the TwinEU Dataspace, the technical foundation is established for a scalable and legally compliant digital energy system.

8 TwinEU Reference Architecture

8.1 TwinEU Objective

The objective of TwinEU is to develop a pan-European federated Digital Twin ecosystem, supported by a robust and modular RA. This RA is designed to enable the seamless integration of renewable energy sources, enhance infrastructure resilience, and facilitate sustainable energy management across Europe. At its core, the TwinEU architecture aligns technical, economic, and societal outcomes with the expected impacts outlined in the project's goals, addressing critical challenges in energy transition and providing a scalable and interoperable framework for diverse stakeholders. The TwinEU RA plays a central role in achieving these objectives by serving as a standardized framework for integrating digital twins across multiple domains. It incorporates a federated approach to enable collaboration between TSOs, DSOs, market operators, aggregators, and other stakeholders. This collaborative structure fosters seamless data and model exchanges, laying the groundwork for interoperable DT ecosystems. The architecture also provides the flexibility to address new multi-system use cases, leveraging advanced modelling and simulation tools to assess scenarios across the European energy grid. The architecture has been designed to align with key European initiatives, including FIWARE, GAIA-X, and the IDSA Reference Model. By integrating open standards like NGSI-LD APIs, the RA ensures compatibility across energy systems and creates a foundation for a future-proof data-sharing ecosystem. This approach allows the modeling of pan-European scenarios while addressing the complexities of grid operation and energy market interconnectivity.

One of the key outcomes enabled by the Reference Architecture is the enhancement of energy system reliability. By supporting advanced scenario modelling and simulation, the architecture facilitates a granular analysis of grid dynamics, enabling stakeholders to evaluate the impact of integrating renewable energy sources on a large scale. For example, the architecture supports interoperability between the Continental Europe Synchronous Area and local energy communities, ensuring that both transmission and distribution systems can operate in harmony. The architecture also promotes economic benefits by enabling the development of new services and business models. By establishing an open and interoperable ecosystem, TwinEU creates opportunities for innovation and entrepreneurship. New services can be deployed quickly within the RA, providing a foundation for data-driven decision-making and fostering a resilient energy economy. The RA's open-source approach further supports widespread adoption, allowing grid operators and market participants to benefit from a scalable and adaptable solution. From a societal perspective, the architecture enhances grid resilience and supports dynamic monitoring, ensuring supply continuity and improved energy system management. TwinEU's RA integrates tools for forecasting, anomaly detection, and infrastructure bottleneck identification, enabling proactive grid planning. The resulting improvements in system flexibility and efficiency contribute to a reliable energy supply, lower operational costs, and reduced environmental impact. TwinEU also enhances data exchange capabilities, creating a higher level of visibility and collaboration among stakeholders. By leveraging advanced data connectors and standardized models, the RA facilitates secure and transparent interactions between prosumers, network operators, and market participants. This approach enables better asset management, faster reaction times during system disruptions, and supports the integration of diverse energy technologies such as green hydrogen electrolysis.

In summary, the TwinEU RA is not only a technical backbone but also a transformative enabler of economic, societal, and environmental benefits. By aligning with European policies and integrating cutting edge technologies, the RA positions TwinEU as a pivotal project in Europe's energy system transformation.

8.2 Vocabulary

In Table 22, we attempt to present all the concepts and terms that the TwinEU system refers to, to create a common vocabulary for all the Actors to avoid any misunderstanding and provide term clarity.

Table 22: TwinEU Reference Architecture Vocabulary

Term	Description
Generic Terminology	
Platform	A sophisticated array of integrated systems, interfaces, and processes working together to offer a range of functions and services.
Reference Architecture	A reference architecture acts as a template design for a system architecture of a particular domain. It can provide a methodology for implementation for all actors involved.
Use Case	A Use Case describes the high-level functions and scope of a developed system.
Business Use Case	It showcases the business processes performed by its business actors for achieving a business goal.
System Use Case	It describes the process for implementing a business use case at the system functionality level, denoting the function or the service provided by the same system.
Requirement	A requirement refers to an individual documented physical or functional necessity that a specific design, product, or process seeks to fulfil.
Functional Requirement	Functionality, behaviour, and input/output information that the system requires.
Non-Functional Requirement	As the "Quality Attributes" of a system they are the conditions under which the solution must remain functional, qualities that the solution must have, or constraints within which it must almost always operate (e.g. reliability, testability, maintainability, availability, performance).
Actor	An actor represents a role carried out by an external entity that engages with the subject (for instance, by exchanging signals and data), whether it is a human user of the system under design (Person), another system, or hardware that utilises the subject's services.
Component	A Component is a modular and replaceable unit that encapsulates specific functionality in alignment with the implementation structure. As a self-contained entity, it is independently deployable, reusable, and replaceable.

	Components execute one or more Application Functions and restrict access to its functionality through a defined set of Application Interfaces.
Device	A Device is a physical IT or OT resource designed for storing or executing system software and artifacts. As a specialised type of Node, a Device includes processing capabilities and is typically used to model hardware systems like mainframes, PCs, or routers. Devices usually form part of a node in conjunction with system software.
Application Programming Interface (API)	It is a specialised software interface which allows connections between components, tools, and platforms. A document or standard that describes how to implement this interface is called an API specification. The term API may refer either to the specification or to the implementation result.
Interoperability	Interoperability involves the standards, protocols, technologies, and mechanisms that enable seamless data exchange between different systems with minimal human intervention. It ensures that diverse systems can communicate and share information in real time.
TwinEU Terminology	
Demo Use Case	Use Case derived directly from the pilots.
Cross-Pilot Use Case	A Use Case that applies to more than one demo to showcase the connectivity amongst demonstrators through the TwinEU Data Space.
TwinEU Use Case	Use Case derived by following two processes; first, we identify and classify data and used services between actors/platforms for all demos. Second, we include SUCs identified in other H2020 projects, based on the work conducted in the context of WP2 that are relevant to TwinEU, to have a complete list of General UCs that will be implemented through the TwinEU digital system.
TwinEU Framework	It is the core design of Reference Architecture. It consists of five main layers: the GUI & Application layer (Marketplace, Digital Twin & Middleware GUI), the Core services layer, the Semantic interoperability layer (as part of the middleware), the Data Integration and Homogenization layer, and the Data Ingestion layer. Core Services, Semantic Interoperability and Integration & Homogenization constitute the TwinEU Middleware.
TwinEU Governance Middleware	It is implemented using a modern approach based on the more innovative standard architecture models and interfaces, namely IDS and FIWARE. It allows the integration and collaboration of the TwinEU participants, facilitating the envisioned data and model sharing operations, ensuring scalability and interoperability, while maintaining data ownership.
OneNet Connector	It is a specific instance of the OneNet Data Space Connector, which will be deployed locally and will allow easy integration and cooperation among the platforms/actors/DTs, maintaining data ownership and preserving access to

	the data sources. Use of the Data Space connector will be dependent upon SUCs and expected to occur if needed in the final technology release.
TwinEU Application Component	One of the main applications of the TwinEU system
TwinEU Data Space Participant	Any kind of actor involved in Data Space. Can be divided into data source, data provider, data consumer and service operator.
Data Source	A more generic source of data that can be integrated into the system, which may include a Data Provider, a single database, an IoT device, a file system, a Digital Twin or similar sources.
Data Provider	A specific participant which can provide data to the system. To submit metadata or exchange data with a Data Consumer, the Data Provider uses software components (connectors) that are compliant with the Reference Architecture.
Data Consumer	A specific participant that receives data from a Data Provider. From a business process perspective, the Data Consumer is the mirror entity of the Data Provider.
Services Operator	A specific participant that makes use of services or tools. The Service Operator registers in the TwinEU Framework in order to have access, deploy, use, integrate with and test the TwinEU digital tools.

8.3 GAP Analysis (relevant initiatives/projects)

The development of the TwinEU open reference architecture requires systematic identification and resolution of key gaps that may impede the integration, interoperability, and efficient operation of DTs within a federated data-space ecosystem. This section provides a comprehensive gap analysis that consolidates insights from the preceding deliverables (D2.1 [26], D2.2 [27]) and the foundational architecture and technical mappings established in this deliverable. The analysis is informed by previous EU-funded initiatives, direct stakeholder feedback, and a review of interoperability, technical, and organizational requirements. The objective is to identify critical gaps that must be addressed to support the realization of a federated, interoperable, and secure DT infrastructure for Europe's energy sector in line with the TwinEU vision.

The gap analysis methodology builds on the knowledge developed in WP2. Specifically, the analysis integrates:

- Challenges and lessons learned from recent EU projects (D2.1) [26]
- Consolidated stakeholder requirements (D2.2) [27]
- Functional and technical boundaries set in WP2 and WP3 tasks,
- Mapping against existing and emerging EU frameworks and architectures.

This enables the identification of both business and operational, as well as technical and implementation related gaps, laying the foundation for actionable recommendations.

8.3.1 Key Gaps Identified

8.3.1.1 Interoperability and Data Exchange

Standards Fragmentation: Despite significant progress, the lack of universal adoption of data models and communication protocols (e.g., CIM/CGMES, SAREF, IEC standards) leads to persistent fragmentation. Existing projects often employ bespoke interfaces, complicating cross-operator and cross-border interoperability.

Missing Adapters and Interfaces: A recurrent gap is the absence of standardized adapters and middleware to bridge legacy systems with new DT platforms, as well as seamless integration of TSO/DSO/customer data flows. This hinders end-to-end data harmonization and operational visibility.

Semantic Interoperability: While syntactic data exchange is often addressed, semantic interoperability remains limited. Common ontologies and shared vocabularies are underdeveloped, hampering automated model, service, and data exchange at scale.

8.3.1.2 Cybersecurity and Data Governance

Inconsistent Cybersecurity Practices: There is a notable disparity in cybersecurity maturity among stakeholders. Encryption, real-time threat monitoring, and zero-trust architectures are not universally enforced, risking critical infrastructure resilience.

Data Sovereignty and Privacy: Adherence to evolving EU legislation (Data Act, NIS2, GDPR) is patchy. Mechanisms for federated identity management, consent-based data sharing, and privacy-preserving analytics are in the early stages, complicating cross-entity data flows.

8.3.1.3 Observability, Monitoring, and Control

Limited Grid Observability (especially at LV level): Real-time monitoring and forecasting at the distribution and prosumer level are constrained by lack of sensorization, non-standardized data acquisition, and insufficient edge/cloud integration.

Incomplete Cyber-Physical Integration: Full IT/OT convergence remains an aspirational objective. Existing deployments often lack dynamic feedback loops between physical assets and digital models, undermining advanced use cases such as automated grid balancing or predictive maintenance.

8.3.1.4 Functional and Technical Gaps in DT Federation

Lack of Federated DT Orchestration Mechanisms: Few reference implementations exist for orchestrating multiple DTs across organizational and national boundaries. Functional and technical specifications for DT federation (identity, access, data brokering, trust) require further development.

Fragmented Validation and KPI Frameworks: Validation processes, KPIs, and benchmarking for DT-enabled services are not harmonized across demonstration activities, limiting cross-project learning and scalability conditions, which are often lacking in current infrastructures. Although WP4 addresses scalability partially through containerization and cloud-based solutions, further optimization and validation are necessary.

8.3.1.5 Stakeholder Engagement and Change Management

Organizational and Cultural Barriers: Resistance to data sharing and DT adoption persists, rooted in legacy practices, risk aversion, and misaligned incentives. Continuous engagement and value demonstration are needed.

Skills and Training Gaps: Deployment and exploitation of federated DTs demand upskilling across the IT, OT, data science, and energy operations domains, which remains insufficiently addressed.

8.3.1.6 Alignment with EU Initiatives and Regulatory Compliance

Incomplete Alignment with Pan-European Data Spaces: While the TwinEU architecture aspires to leverage initiatives like the European Energy Data Space, technical and governance gaps persist, particularly regarding interoperability with other sectoral data spaces and ensuring long-term regulatory compliance, due to dataspace connector compatibility issues.

Regulatory Uncertainty: Fast-evolving EU digital and energy regulations (Data Act, Cyber Resilience Act) may outpace the current design and deployment cycles, necessitating adaptive, future-proof architecture strategies. Proactive engagement with regulators and embedding compliance guidance within the TwinEU architecture are critical to ensure alignment with EU policy (e.g., Digitalisation of Energy Action Plan, Data Act).

8.4 Pan-EU Scenarios

The TwinEU project is advancing the development of a FDT architecture. This reference architecture connects DT technologies that are being developed and demonstrated across eight pilot projects throughout Europe. These pilots implement a range of use cases to test DT models, data exchange mechanisms, and address several critical challenges. To validate the effectiveness and broad applicability of the federated TwinEU architecture, specific DT models and data structures will be shared among partners from different pilot projects. This cross-pilot collaboration, aimed at tackling common challenges through the shared DT framework, forms the basis of what is referred to as the pan-European (panEU) scenario within the TwinEU project. Building on the analysis presented in Deliverable D2.2 "*TwinEU use cases, pan-European scenarios and KPIs*" [27], potential panEU scenario topics have been identified, as shown below:

- **The grid hosting capacity map:** The TwinEU DT technologies developed in the German pilot, that will implement in the demonstration activities the respective use cases described in UC01, UC02, UC03, UC04 and UC08, can provide a significant proposition for a conceptual version of an advanced grid hosting capacity map. This pan-European map is currently being developed as a concept and is not yet fully operational. It aims to provide a harmonised, real-time digital interface for visualizing grid hosting capacity across Europe and appears to echo several of the previously identified challenges for the European power system. This work combines advanced grid data simulations and APIs that enable DSOs to deliver automated feedback on connection requests for both load and generation. In the pan-European context, the automated self-service use case for potential grid connections introduces a new level of interaction between DSOs and their customers. This fully automated process allows connection applicants to instantly receive feedback on potential connection points based on live grid calculations accessible directly via the DSO's website. Additionally, the results of hosting capacity calculations for both loads and generation can be shared as indicative information with end-customers. This supports their decision-making process when implementing new generation units, such as solar PV systems, or large loads like data centres.

- **Co-optimization of the energy and balancing capacity market coupling with dynamic flow-based auction**: The DT technologies developed and demonstrated in the Hungarian pilot (HU03) are highly suitable for addressing the previously mentioned challenges facing the EU energy system. Specifically, use case HU03 focuses on the co-optimization of energy and balancing capacity markets in Hungary through a unified auction platform, enhanced by dynamic, flow-based capacity calculation. This use case introduces an innovative approach to market integration by linking day-ahead and intraday energy markets with balancing services, thereby improving system efficiency and optimizing the use of cross-border transmission capacity. This pan-European (panEU) scenario involving cross-pilot collaboration aligns closely with the objectives outlined in the EU Action Plan for Grids (COM/2023/757), particularly Action 4, which advocates for the smarter utilization of existing grid infrastructure through digital tools and real-time system observability. The application of Dynamic Line Rating (DLR), real-time data integration, and system simulations directly supports this goal, helping to alleviate grid congestion and make more efficient use of network assets. From a digitalization standpoint, the HU03 use case also reflects the priorities set out in the EU Digitalization Action Plan for Energy Markets (COM/2022/552). It contributes to the development of a digital twin for the electricity grid through real-time data exchange, advanced optimization algorithms, and platform interoperability. A key element of this initiative is the establishment of a shared data space that harmonizes diverse data types—such as market bids, transmission capacities, and line ratings—within a unified digital framework. This includes the integration of platforms like ENTSO-E's Transparency Platform and HUPX Labs, further demonstrating the potential for cross-platform collaboration.
- **High accuracy forecasting**: As highlighted in the conclusions of the report *"TSO-DSO Challenges & Opportunities for the Digital EU Electricity System"* [79] by ENTSO-E and the EU DSO Entity, forecasting accuracy is identified as one of the five key barriers to the successful adoption of DT technologies—particularly for enabling seamless data exchange across various platforms and devices. Improving the accuracy of forecasts for demand, generation, and grid capacity (e.g., Dynamic Line Rating – DLR) is essential for enhancing grid utilization and ensuring the security of supply. Better forecasting can also reduce the need for short-term flexibility activation in the balancing timeframe. To achieve greater forecasting precision, the report recommends increased data sharing by BSPs, BRPs, and other relevant stakeholders. It also emphasizes the importance of consolidating the growing number of data sources and developing advanced AI models to process and analyze this data effectively. The TwinEU DT architecture can support the improvement of forecasting accuracy with the technologies that are developed and demonstrated in the pilots. Possible options can be:
    - The DT technologies developed in the Bulgarian pilot, that will implement in the demonstration activities the respective use cases described in UC02, UC03, UC04. The Bulgarian pilot scenarios practically valorise the DT technologies to achieve generation high accuracy forecasts on Wind, Solar and OHL ampacity. These DT models can be connected through the federated TwinEU architecture with data provided by a partner in another pilot cluster to run a panEU scenario in the scope that is described in the above paragraph.
    - The DT technologies developed in the Iberian pilot, that will be implemented in the demonstration activities of the respective use case described in UC01. This concerns the probabilistic grid status forecast and remedial actions identification for the TSO's Control Center Operator, mainly dealing with risky grid status and unbalances in load and demand.
    - Flexibility management and frequency support

- **Flexibility management and frequency support: Flexibility** is a key enabler for the cost-effective large-scale integration of distributed energy technologies into electricity grids. It helps avoid excessive investments in transmission and distribution infrastructure, which could otherwise deter end users from adopting such technologies. This importance of flexibility is also emphasized in the electricity market reform, specifically in Article 19e, which mandates ENTSO-E and the EU DSO Entity to develop a methodology for assessing flexibility needs, available resources, planned investments, and decarbonization targets. Operational reserves will play a crucial role in balancing generation and demand mismatches. Several pilot demonstrations within the TwinEU project illustrate how DT technologies can unlock flexibility:
    - Eastern Mediterranean Pilot (Use Cases EM-GR-02, EM-CY-02): These DT technologies focus on optimizing fast frequency response services through TSO-DSO coordination. By integrating various flexible assets and storage systems, and enabling real-time data exchange across voltage levels, they enhance grid stability. Additionally, the technologies support frequency regulation in low-inertia systems using HVDC interconnections.
    - Iberian Pilot (Use Cases Ib08, Ib09): DT technologies in this pilot aim to identify flexibility needs during both planning and operational phases to mitigate grid congestion and postpone investments in new infrastructure, such as lines or transformers. They also address optimal integration of EV chargers, ensuring voltage quality, phase balancing, and congestion management.
    - Italian Pilot (Use Case IT02): This use case involves developing a digital twin of selected medium-voltage distribution networks, focusing on the integration of DERs like PV systems and EV charging stations. The objective is to assess operational challenges posed by fluctuating load and generation, ensuring secure grid operation in both urban and rural areas. It will also explore how DERs might support transmission-level operations when needed.

These pilots demonstrate how DT technologies can facilitate the effective use of flexibility to support the energy transition while maintaining grid reliability and minimizing infrastructure costs.

- **System security and stability:** The TwinEU project integrates DT technologies and tools designed to enhance operational security and cyber resilience—key priorities for the European power grid. These technologies offer innovative solutions that can improve existing EU practices and be tested as panEU scenarios across multiple pilot projects:
    - Italian Pilot (Use Cases IT01 and IT02): The DT technologies in this pilot enable assessment of the impact of defence systems on the grid, identifying any discrepancies between modelled and actual outcomes in terms of load or power disconnections. They also provide precise evaluation of operational challenges related to fluctuating loads and generation, contributing to secure grid operation in both densely populated urban areas and sparsely populated rural regions.
    - Slovenian Pilot (Use Cases SLO-UC-01 and SLO-UC-02): These DT technologies enhance the dynamic modeling of the grid, improving interoperability and real-time system understanding. By integrating frequency- and voltage-dependent consumption models, they offer a more accurate reflection of real operating conditions. This supports the creation of a dynamic model for the distribution network and facilitates the enhancement of the transmission network's dynamic modeling capabilities.
    - Dutch/French Pilot (Use Cases NL01 and FR01): In this pilot, DT technologies introduce a "game master" function that oversees SCADA modules and enables the simulation of

training scenarios to manage contingencies and the effects of cyberattacks. These real-time simulations help operators understand and respond to cascading failures in interconnected power systems. This capability is essential for developing a highly skilled workforce capable of managing the increasingly digital and complex grids of the clean energy transition era.

Together, these cross-pilot developments demonstrate how digital twins can be leveraged to strengthen both the security and resilience of Europe's evolving energy systems.

8.5 Digital Twin Federation

In this section, the work done within T3.3 will be explained as part of the open reference architecture for MS4. In particular, the collaboration and federation of digital twins will be described using the SGAM framework [80]. This way, technical specifications for open and interoperable DT federated ecosystem can be created, detailing components involved, communication protocols, data models and data exchanged among the different DTs defined during the first year of the project. This work will be further described in D3.2. The information presented in this section represents the initial results generated so far. After this deliverable, the architecture will be refined, and a final version will be generated accordingly.

8.5.1 TwinEU's approach towards DTs Federation and key concepts description

The federation of digital twins can be defined as specific digital twins' collaboration involving interactions between different energy domains or the same domains with multiple digital twins. The methodology proposed in T3.3 has been based on the use cases defined in each pilot, showcasing interconnections among actors such as TSO and DSO, MO and DSO, Aggregator and DSO, etc. These actors are part of the TwinEU actors described in Chapter 5.1. The methodology has been handled with the SGAM framework. This framework allows the creation of five distinct layers. Only the technical-related layers have been selected to create the corresponding technical specifications of the federation of DTs. These layers have allowed the federated ecosystem characterization.

- **Component layer:** This layer is responsible for defining the pieces of hardware and software components involved in the use cases and the physical interconnection between them such as internet, ethernet, PLC, etc.
- **Communication layer:** This layer includes the same components described in the component layer but the interconnection lines between components are the communication protocols that are used to exchange information such as MQTT, TCP/IP, ICCP, SFTP, GPRS, etc.
- **Information layer:** This layer is divided in three sublayers:
  - **Business Context View:** Here the base is the component layer and the connected lines between components are the information objects exchanged such as electrical measurements, grid models, control commands, etc.
  - **Canonical Data Model:** Here, the Data Model Standards are defined, explaining the data exchange format of each interaction.
  - **Standard and Information Object Mapping:** Here a mix of the previous information layers is performed. The Data Model Standards are displayed around the Business Context View layer and connected to the corresponding component that those refer to. Then, Information Objects are displayed and connected with the corresponding Data Model Standard involved.

Once a Use Case is defined using all these layers, there is a clear picture of the technical specifications needed to execute and demonstrate it. Therefore, defining all the Use Cases allows the creation of a general architecture able to generalize not only some key components and DTs involved but also the communication protocols, Data Model Standards and information exchanged among them.

8.5.2 Technical specifications for Open and Interoperable DTs Federation

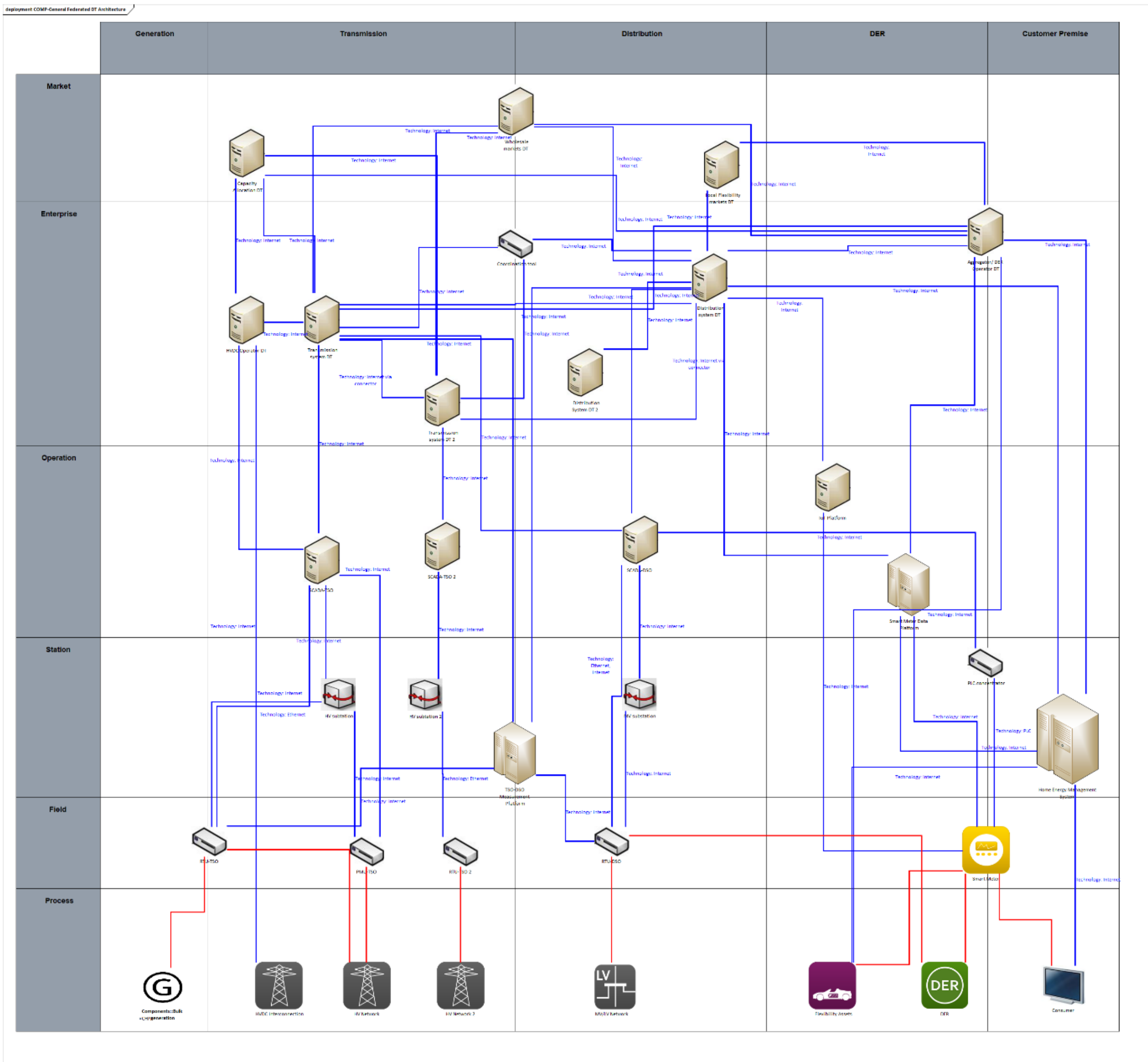


Figure 42: General Component Architecture

Inputs from all the pilots regarding the SGAM layers presented above have been gathered to create a general architecture for the federation of DTs and technical specifications creation. Having this in mind, a generalization work has been performed to outline the key components and interactions, resulting in the following Digital Twins:

- Distribution system DT
- Transmission system DT
- HVDC DT
- Aggregator/DER Operator DT
- Capacity Allocation DT

- Wholesale Market DT
- Local Flexibility Market DT

All these digital twins can be seen along with other intermediate components in Figure 42. Here the basis for the next diagrams is defined including information about physical connections.

The Communication layer follows, see Figure 43. Every interconnection line defines a series of standardized communication protocols among the components defined previously. Further communication mechanisms such as the Dataspace protocol will be defined in D3.2. Once the Data Space concept has been fine-tuned and decided which components make use of it. In this sense, AI/ML algorithms and services, in general, could be encapsulated in this topic.

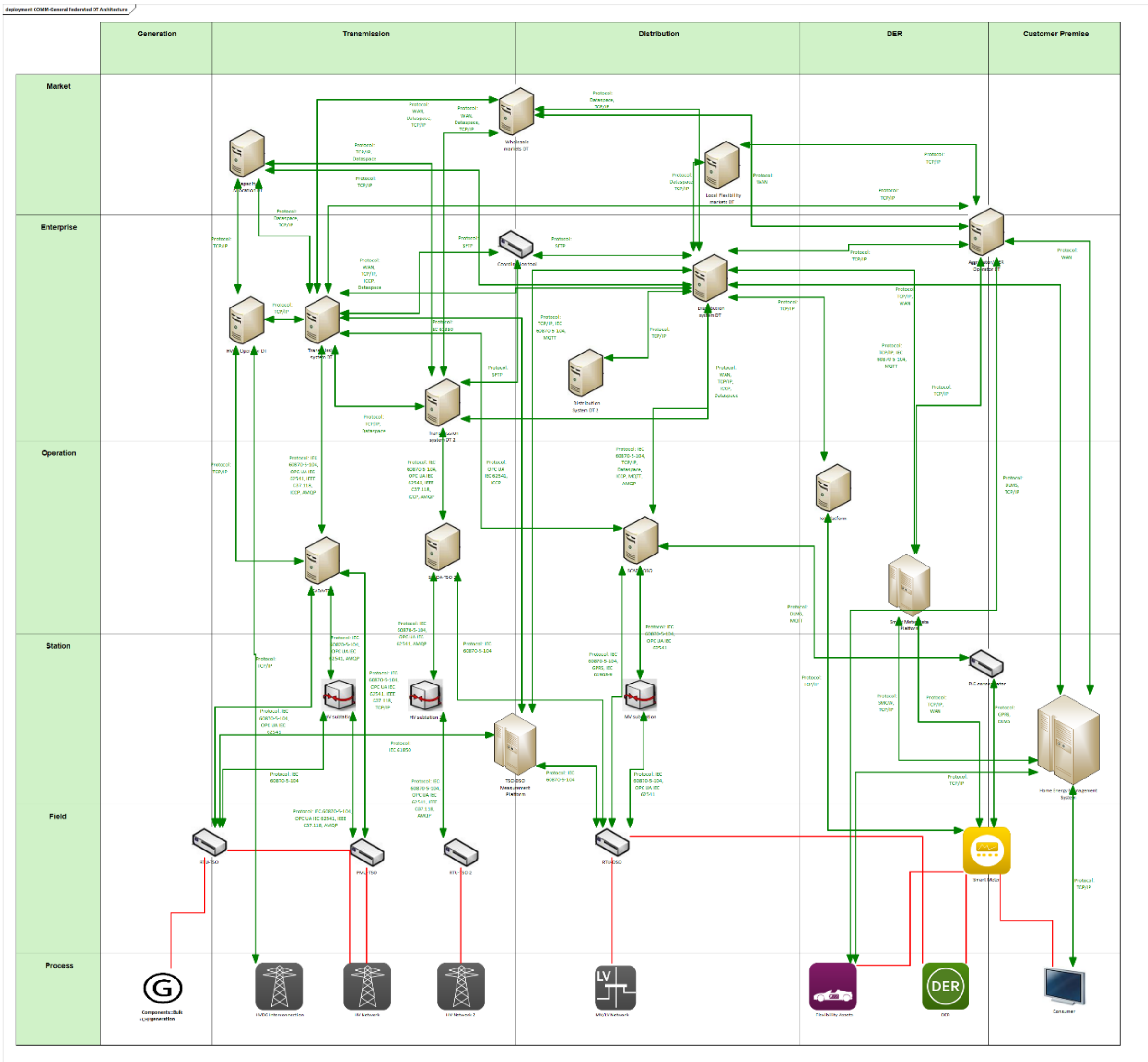


Figure 43: General Communication Architecture

The last one is the Information layer, architecture visualization of data exchange can be seen in Figure 44, main data exchanged among components are electrical measurements, control commands and grid models. This information is susceptible, and Data Spaces are a great example of managing this kind of information with sovereignty and failure proof.

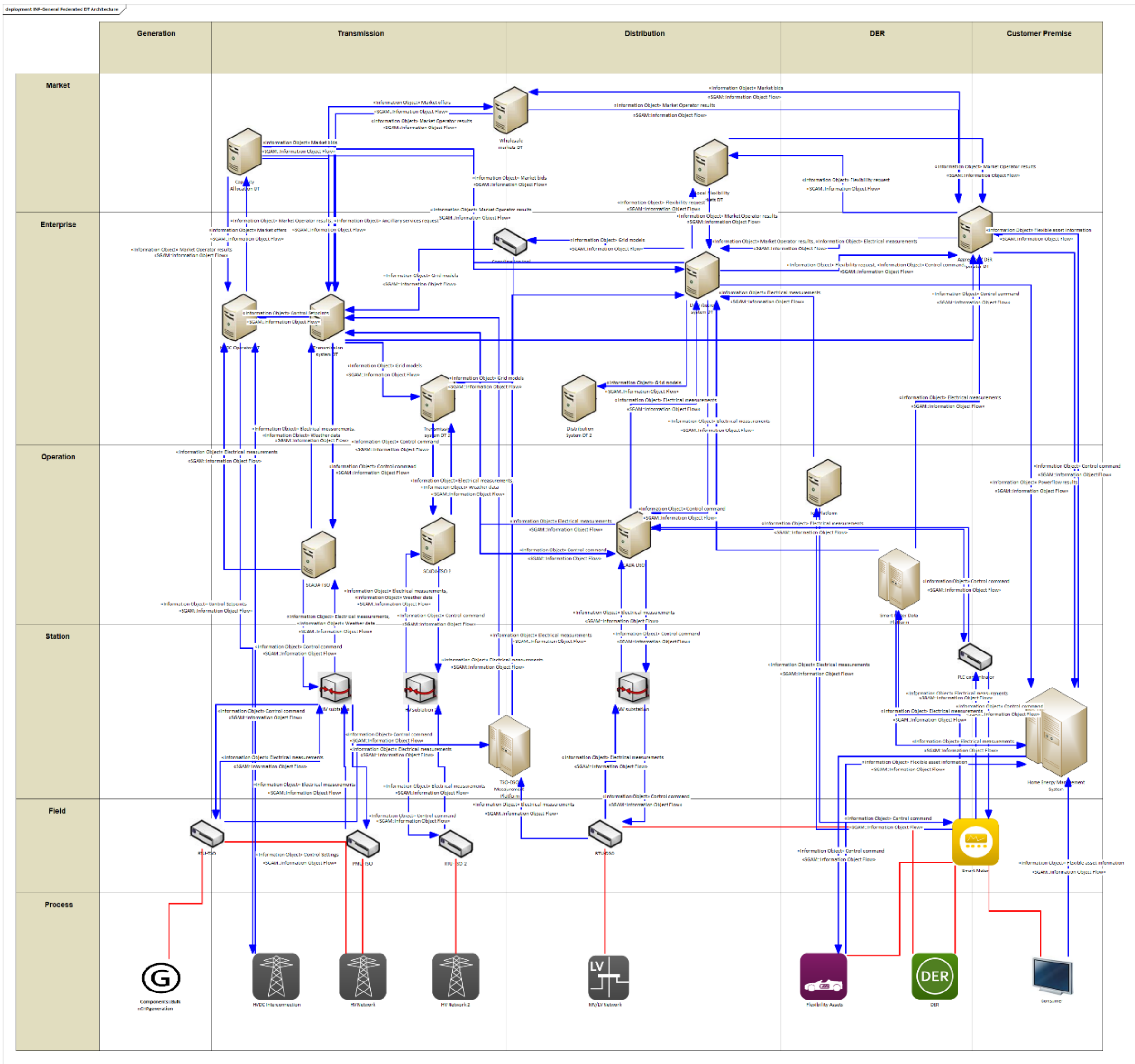


Figure 44: Information Layer

Standardized Data Models can be seen in Canonical Data Model Figure 45, every box gathers many Standardized Data Models considering the components that are inside the corresponding domains and zones from the SGAM framework. There are Data Models not defined yet that will be defined during the project. The mapping between the last two layers is shown in Figure 46.

These layers are the first version of the open and interoperable DT federation for M4, a refinement process will be performed during D3.2 period to include information covered in WP2 such as GAP Analysis, actors involved in TwinEU and the creation of pan EU-scenarios that imply cross-border connections. WP4 will also create a Data Space platform to manage data exchange and services that will affect the architecture in all layers. This iterative process will cover the necessary needs to properly execute and demonstrate the corresponding use cases and define the technical specifications of the federation of Digital Twins.

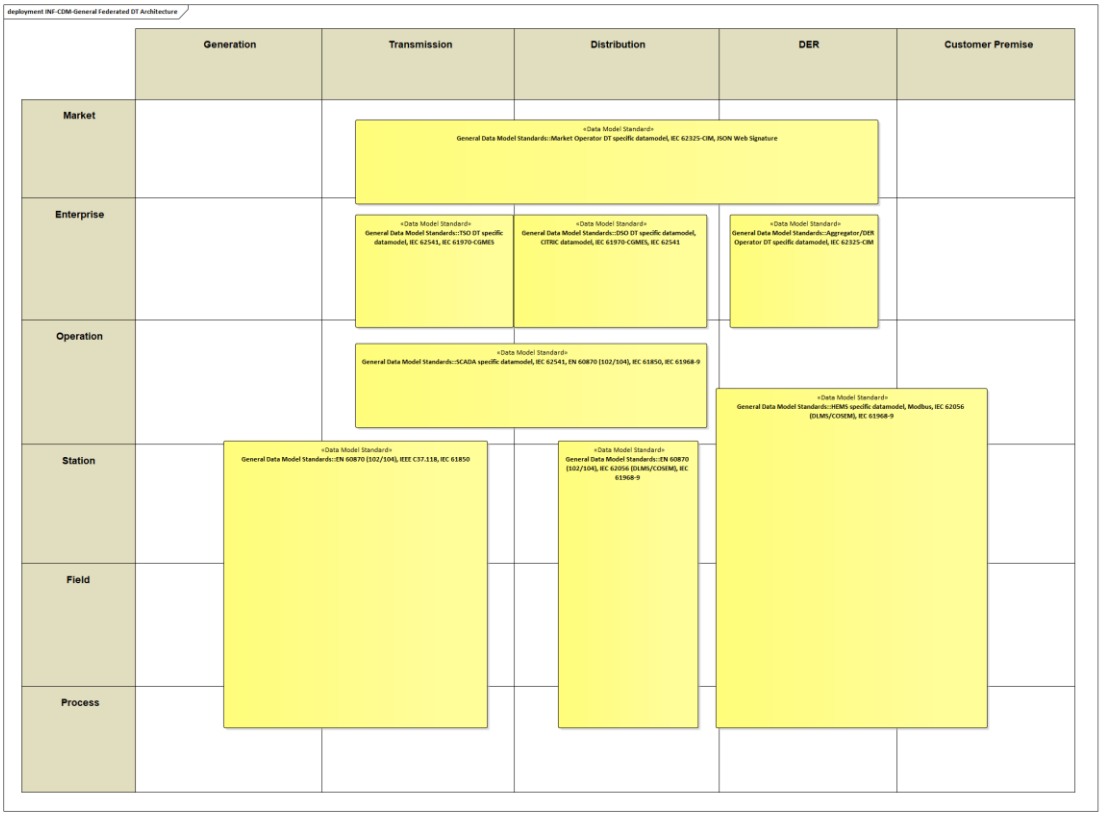


Figure 45: Canonical Data Model

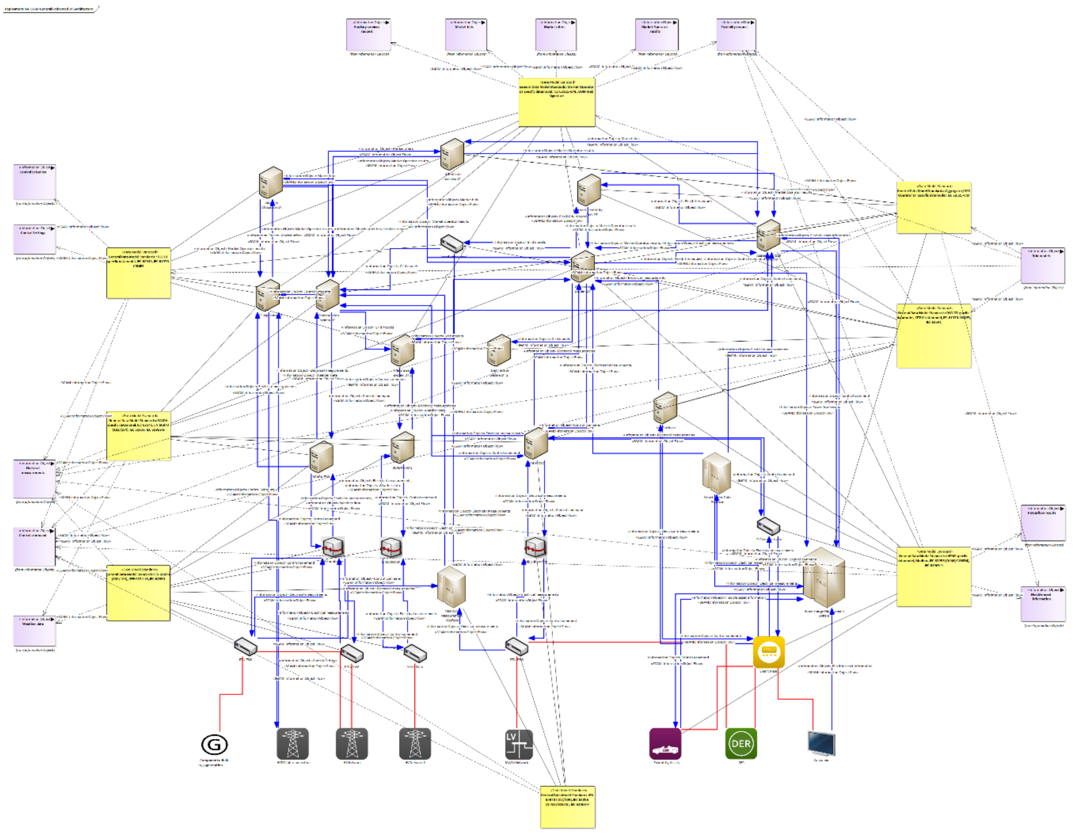


Figure 46: Layer Mapping

8.6 TwinEU Reference Architecture

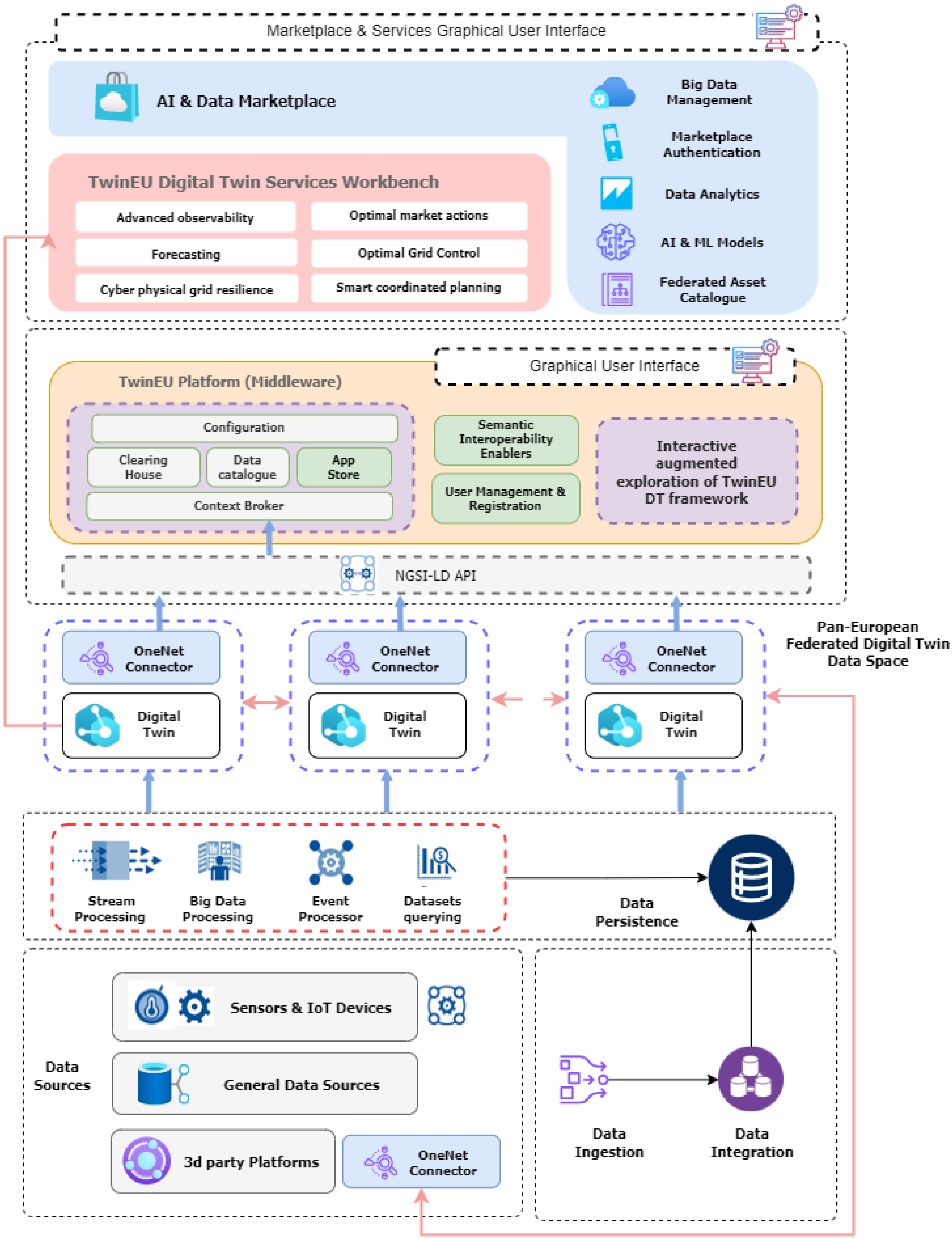


Figure 47: TwinEU RA v.0.1

As outlined in the methodological approach, three initial versions of the architecture were developed during Task T3.1: two draft iterations and one intermediate version. This step-by-step process enabled incremental evolution and refinement of the draft versions, incorporating feedback, comments, and results from technical partners, demonstration partners, and other tasks and work packages (WPs) of the TwinEU project. The first draft, **TwinEU RA v.0.1**, was based on the primary objectives of TwinEU and the overall solution described in the Description of Action (DoA). It includes: the initial concept of the TwinEU Framework; a dedicated data exchange layer to facilitate cross-digital twin integration and cooperation; and a specific layer for AI and marketplace services, aligned with P4 guidelines.

The second draft **TwinEU RA v.0.2** is the second draft version of the architecture. It includes: the first round of feedback from technical partners; the initial results on the analysis on the alignment of reference architectures and technologies that led to the definition of a decentralized approach and the adoption of a Standard Data Architecture (IDS and FIWARE).

The intermediate consolidated version of the TwinEU Reference Architecture (v.0.3) represents the first fully consolidated iteration of the architecture. Building on the draft versions, it incorporates several key elements: a clear depiction of Digital Twin participation within the Data Space, analysis of demonstration and general system use cases, requirements from WP2, and a final round of feedback from technical partners. The analysis of the IDS reference model and FIWARE interfaces also informed the development of a hybrid solution, integrating standard models for implementing the OneNet Decentralized Middleware and the OneNet Connector. The IDS Connector and FIWARE Context Broker were identified as optimal solutions, ensuring high levels of standardization, interoperability, scalability, and reusability within the OneNet framework.

The TwinEU Reference Architecture is structured into three logical layers:

- **Bottom Layer:** This includes data sources, energy stakeholders, TwinEU participants, and integrated data sources.
- **Middle Layer:** This layer forms the TwinEU Data Space ecosystem, enabling the creation of the TwinEU Federation. It includes all the Digital Twins participating in data exchange and model sharing, as well as the OneNet Connector, the first component provided by OneNet.
- **Top Layer:** Defined as the TwinEU Framework, this layer serves as the core of the Reference Architecture. It encompasses all components to be implemented in reference implementation within WP4, along with necessary specifications for data harmonization, ontologies, data modeling, service orchestration, workflow monitoring, analytics, and more.

The final round of partner feedback, combined with the ongoing tool development, fine-tuned the intermediate version of the Reference Architecture (and its subsequent layers) into the final one (v1.0) as depicted below:

- **Digital Twin Layer:** It contains all external DTs managed by energy stakeholders (TSO, DSO, etc.), outside the TwinEU platform
- **Federation Layer:** It includes the developed Dataspace Connector embedded in each Digital Twin and the TwinEU Middleware which provides Data Quality, Data Access Policies, IDM, Semantic Interoperability, Data/Model catalogue
- **Service Workbench:** This layer exposes the TwinEU DT services and AR Exploration module functionality
- **AI & Data Marketplace:** This layer includes all AI/ML Models, Data Analytics and Big Data Management processes supporting Digital Twin development.

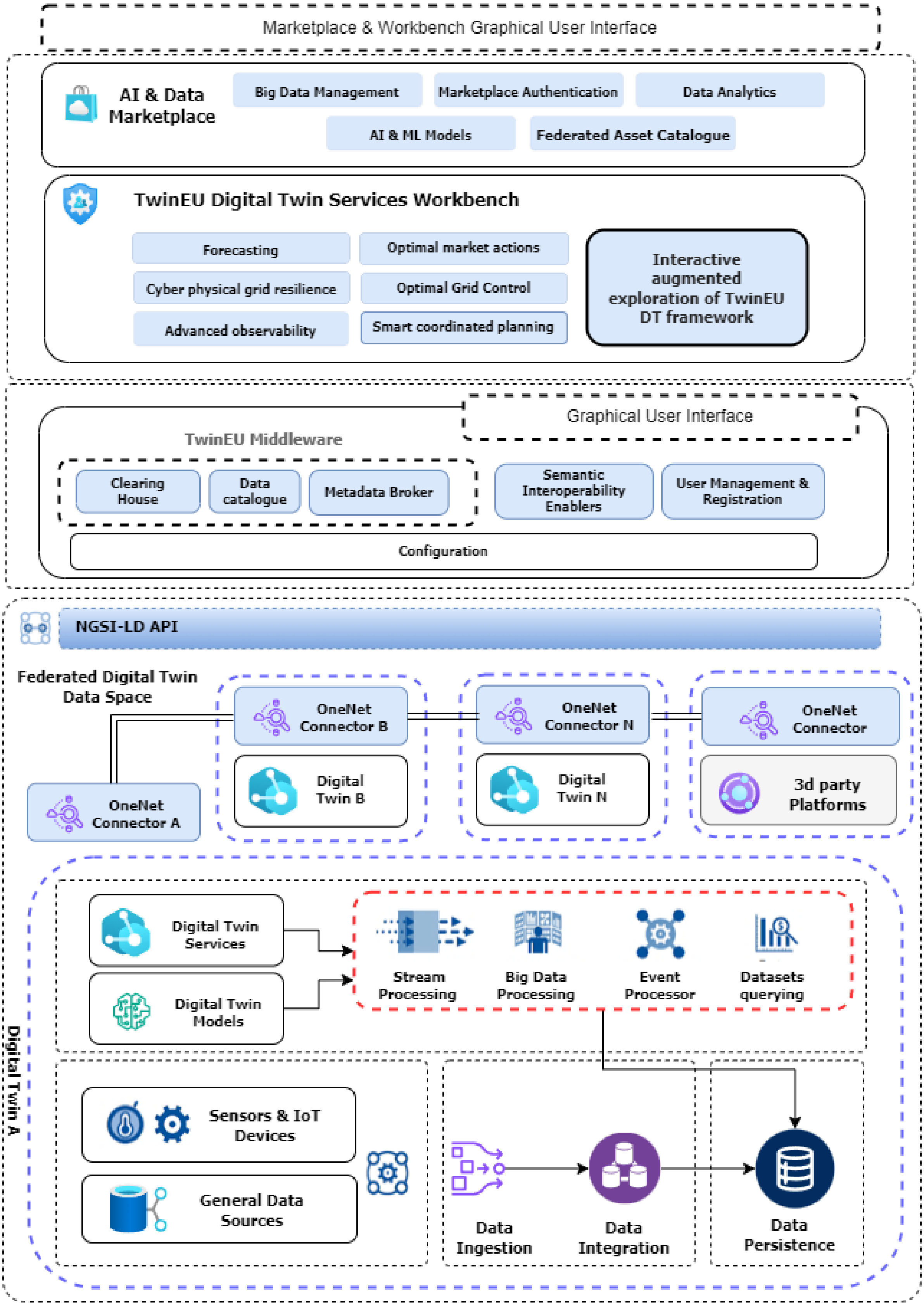


Figure 48: TwinEU RA v.0.2

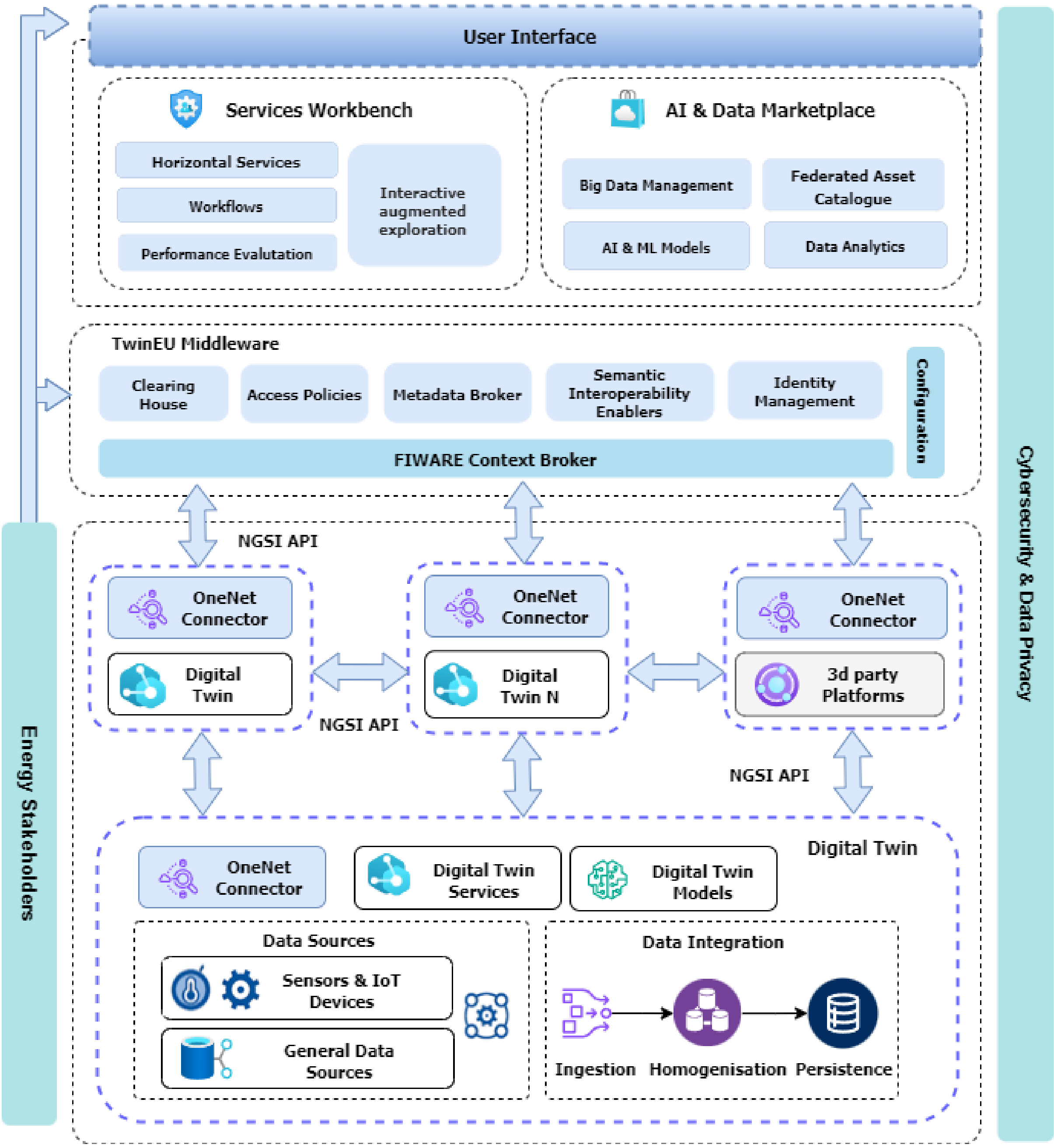


Figure 49: TwinEU RA consolidated intermediate version (v.0.3)

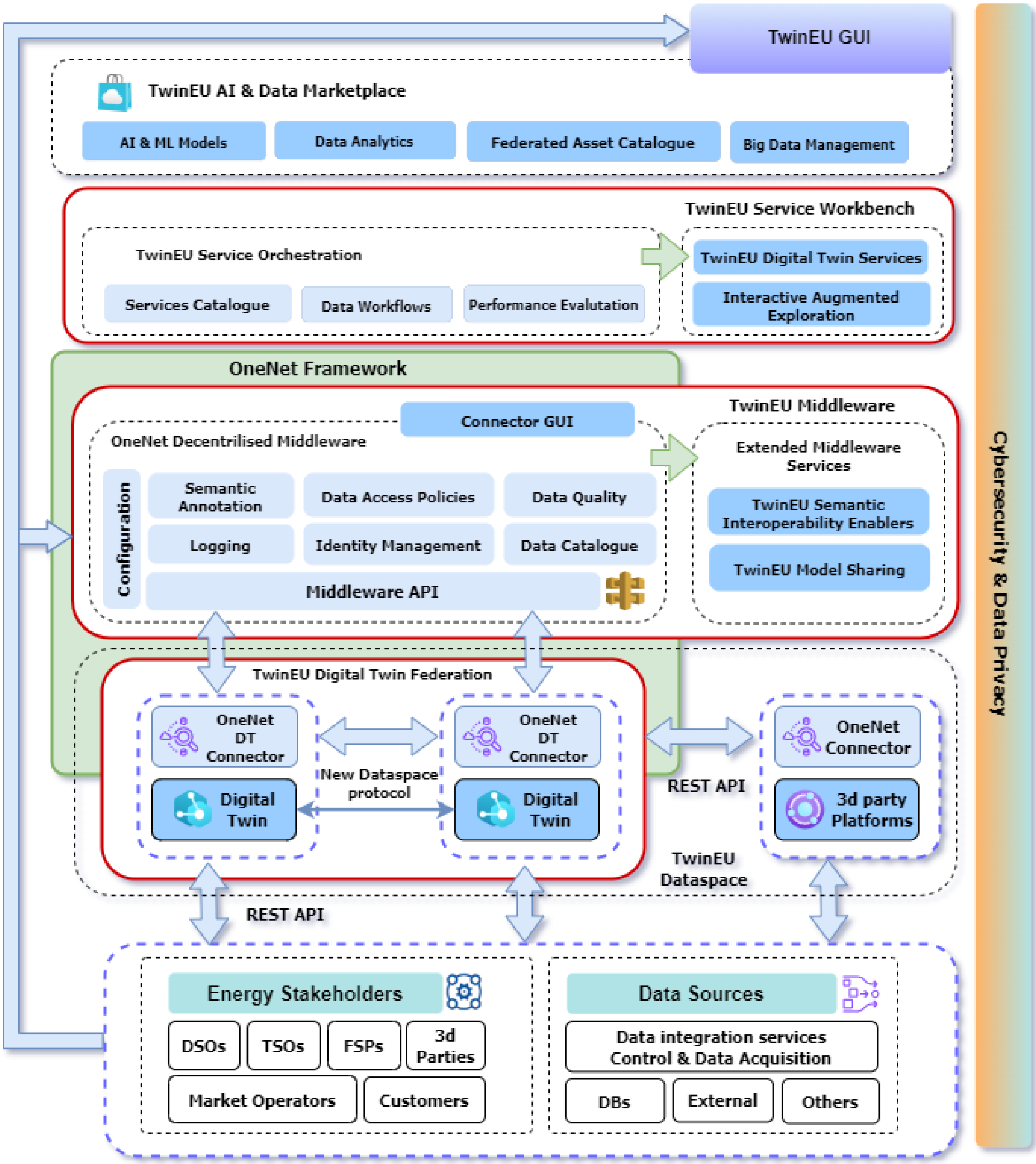


Figure 50: TwinEU Reference Architecture (v1.0)

The Reference Architecture design is based on the below four pillars:

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.

8.7 Design schematic integration with Data Space

8.7.1 Introduction

The development of the TwinEU Open Reference Architecture will support the implementation and integration of a data-space-enabled DT federated infrastructure in WP4. To prepare the integration with data space, this section describes the alignment between the TwinEU Reference Architecture and the core components of a data space. The main objectives of a data space are to generate new value by sharing data efficiently and securely while maintaining control over the conditions of exchange. This aligns with the objectives of TwinEU as there is a federation of digital twins that could find new value by exchanging data. The following building blocks and characteristics are described to clarify the concepts and technologies involved, and finally, a schema depicts how this can be integrated into the TwinEU Reference Architecture. The characteristics of a Data Space are:

- Data Sovereignty: maintaining control over data usage, allowing data owners to define and enforce usage policies. This allows alignment with the legal requirements of each participant.
- Decentralized approach: Rather than relying on centralized data storage, the integration supports a distributed model where data remains with the owner until shared with trusted parties. This sharing is strictly peer to peer from the provider to the allowed consumer.
- Interoperability: Promotes the use of standardized protocols and information models to ensure seamless data exchange across different systems and domains.
- Trust and security: Incorporate mechanisms for establishing trust between participants, such as certification processes and security measures (e.g. onboarding process). The digital identification and the traceability of data of the data transfer is key to provide transparency.

8.7.2 Data Space Functional components

Key core components are necessary for data space operations. As defined in chapter 3.2.1, IDSA provides a System layer from which the core components are Identity Provider, IDS Connector, App Store and Data Apps, Metadata Broker, Clearing House, and Vocabulary Hub.

One of the most important components to provide decentralized integration of data is the **connector**. This is installed in the premises of the TwinEU participants and is connected to the middleware to essentially be able to get services discovery and metadata updated information of the data catalogue, meaning data structures, formats, and policies. In addition, a very important feature of the middleware is logging persistence, which is used to understand the usage and make it possible to record transactions and with this, ensure transparency. The Vocabulary Hub will be composed of metadata conformed to the level of detail of the UCs presented, for this, information about actors, services and data is harmonized and aligned. This process generates the respective catalogues and can be used to feed the semantic enabler with the contextual information of the project. The blueprint for the Common European Energy Data Space (CEEDS) [81] prepared by the Interoperability Network for the Energy Transition (int:net) presents a general data space architecture that can enable new economically feasible business use cases. Figure 51 shows the core components of IDS Reference Architecture Model with the proposed components to realize the CEEDS and the alignment between these components and the TwinEU Reference Architecture. In orange the parts of TwinEU RA are depicted and only components name deviations are explicitly named, while components with similar naming are just marked.

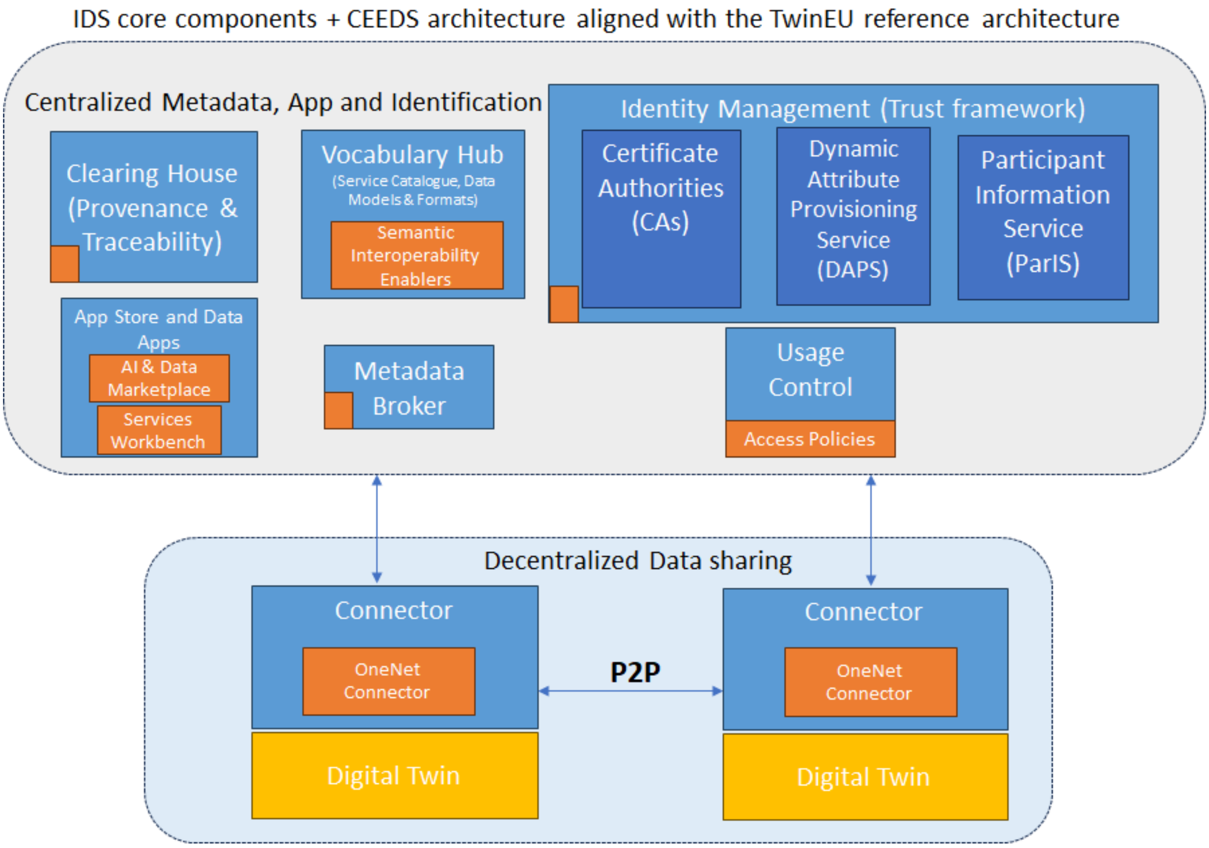


Figure 51: TwinEU Reference Architecture Data Space components aligned with IDS and CEEDS architectures

Figure 51 shows two big blocks, the first one is the centralized part, called "Federated Data Space" by CEEDS, which in general terms oversees the metadata, apps and identification, needed to provide catalogues with descriptions of data, apps and models, and the authentication of users, usage control and traceability of the exchanges. This information needs to be exchanged with the connector.

The second block is the decentralized part of the data space, called "Distributed Data Ecosystems" by CEEDS, where the digital twins can exchange data peer to peer. The DTs do not transmit their data to the central platform, but only need the centralized component to provide governance, descriptions and rules about their data and to get certification that the users they are sharing data with are trusted.

8.7.3 Digital Twin & Data Space integration in the TwinEU context

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 in order 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 architectures 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.

9 Security, Privacy & Legal Compliance

The TwinEU framework forms a federated system of Digital Twins enabling the data and model exchange between different stakeholders in the context of the energy domain. Given the criticality and sensitivity of energy data and energy assets, together with heterogeneous stakeholders with diverse and correlated commercial intents, privacy, security and legal compliance are crucial for the design and deployment of the TwinEU Framework. Additionally, in a context where data-driven services are progressively becoming increasingly valuable and critical to operations and decision-making processes, the TwinEU RA should ensure the protection of its participants' data assets, by integrating unambiguous access and usage policies within the TwinEU ecosystem (TwinEU Data Space).

This dataspace explicitly defines different levels of access, usage policies, and protections tailored to two distinct categories of information: (i) datasets belonging to energy-sector stakeholders (e.g., utilities, market operators) and (ii) personal data of individuals, which falls under GDPR protection. It also supports role-based access, ensuring that only authorised roles can view or act on a given dataset within a defined context.

Regarding the security within TwinEU, the main goal is to form a secure zone around the TwinEU Reference Architecture protecting the TwinEU ecosystem from external factors and protecting individually every TwinEU stakeholder in the TwinEU internal. For this reason, the TwinEU Reference is built based on the IDSA standards that ensure security by design. Each IDSA Connector, which is used for data exchange, implements secure communication protocols, certificate-based mutual authentication, and digital signatures, ensuring that all communications, regardless of origin, are authenticated and authorized before access is granted. Furthermore, the TwinEU Middleware enforces strict, predefined access control policies, monitors connector and user activity, and applies anomaly detection methods to prevent unauthorized behaviours or intrusions. Finally, every implementation and integration steps are followed by extensive structured security audits and penetration testing to evaluate and enhance the system's resilience to address vulnerabilities.

Regarding the Data privacy within TwinEU, the core objective of the system is to ensure user consent and transparency in accordance with the obligations of the GDPR. TwinEU system supports a wide range of usage control policies, allowing data and service providers to specify flexible constraints such as purpose limitation, geographic restrictions, and time-bounded usage. These rules and policies can be defined through the Graphical User Interface of the Middleware and can be dynamically updated. Additionally, every user can easily update, manage, and delete the data and service subscriptions that have been assigned to other users. Finally, the TwinEU ecosystem enables data sovereignty, ensuring that data owners retain full control over how their data and models are shared, used, and processed within the federated ecosystem. To support legal compliance and regulations, the TwinEU system adheres also to European regulatory frameworks including GDPR and Data Governance Act (DGA). The federated data exchange mechanism is supported by legal contracts and trust frameworks defined by the IDSA standard Reference Architecture, which governs the roles, responsibilities, jurisdiction, and liabilities of all participants. Additionally, the Middleware provides legal traceability through secure logging and audit trails that are very important for user accountability. To conclude, security, privacy, legal compliance, and sovereignty are highly significant for the proper functionality of the federated TwinEU ecosystem. More descriptive information and requirements about the cybersecurity, privacy and sovereignty within TwinEU can be found in the Deliverable "D3.2 – Functional, and technical Specifications" in the sections regarding the Task 3.4 "Cybersecurity and data privacy requirements".

10 Lessons Learned & Conclusions

The TwinEU Reference Architecture is aligned with the established components and requirements of the TwinEU project and incorporates several architecture models, one of which is the OneNet framework. Through this framework, we attempt to present the users' entry point into the system and design communication interfaces. Furthermore, we present a streamlined Middleware layer as an aspect of the Reference Architecture harmonized with the Interoperability Specifications which provide depth to both the data interoperability layer and the Sovereignty and Trust layer within RA and align with existing initiatives and concepts, combining the approaches of IDSA, GAIA-X, and AIOTI to serve the TwinEU objectives. The continuous outcome of this RA version will be a 'development view' with a concrete perspective on TwinEU functional specifications mapped to unique components which will be developed according to these specifications. This information builds on the initial WP2 Tasks outcome, as it attempts to substantiate the concepts presented in this document and link them with the project's status.

An important aspect of the TwinEU RA design is the acquired knowledge (lessons learned) which can be used in future similar endeavours to ensure continuous improvement, risk mitigation, and maximized benefits. In more detail these lessons can be summarised as follows:

- The need for Clear Vision and Stakeholder Alignment is paramount as ambiguity in goals leads to fragmented adoption. TwinEU,
    - defined Business Use Cases & strategic objectives early.
    - aligned stakeholders across utilities, regulators, grid operators, tech vendors as much as possible.
    - established a Technical Steering Committee with key representatives.
- It is important to consider incremental adoption as big-bang implementations tend to fail in complex ecosystems. TwinEU,
    - adopted a MVPs development approach: e.g., Minimum Viable Data Space.
    - will use pilot scenarios to validate technology and business model feasibility.
- Interoperability and Standards Adherence is key as lack of standards alignment will result in integration issues. TwinEU RA
    - adopted Gaia-X, IDSA among other standards.
    - leveraged open standards for Digital Twins: e.g., NGSI-LD, DTDL, Asset Administration Shell (AAS).
- Digital Twin Federation design needs to take into consideration a decentralised approach as centralized digital twins could potentially undermine scalability and privacy. So TwinEU designed an RA where:
    - Federated digital twins use a hybrid or fully decentralized approach.
    - semantic web technologies will be used for twin-to-twin communication and harmonization.
- Data Sovereignty and Governance are an important parameter since data misuse fears, stall technological adoption. For this reason, TwinEU decided to
    - Implement IDS connectors to control access rights and data usage policies.
    - Ensure GDPR compliance and sector-specific data regulations.

Key lessons from the whole RA design process can be considered the adoption of a Data Space framework in the energy sector, especially when supporting a Digital Twin Federation, which involves a multidimensional transformation touching on technology, policy, data governance, and organizational culture.

Based on the above key lessons and the TwinEU Reference Architecture design we can create a generic list of **recommendations** which are presented below:

- **Ensure Continuous Stakeholder Engagement & Vision Alignment:** The institutionalization of mechanisms such as periodic stakeholder workshops and a living requirements registry to maintain alignment between evolving business objectives, user needs, and development decisions. As stakeholder needs evolve during implementation, ensuring dynamic alignment helps avoid architectural non-compliance and maintains solution relevance.
- **Advance** the **'Development View' with Traceable Functional Mapping:** Development teams should implement a traceability matrix that directly links functional requirements, business use cases (BUCs), and architectural components. This will enhance transparency, simplify validation, and support agile development by clearly connecting user needs with RA elements.
- **Expand and Formalize Interoperability Specifications:** Technical partners are advised to follow a formal specification handbook that consolidates the use of standards (NGSI-LD, REST, etc.), defines API profiles and semantic models and maps out federated communication protocols. By this approach, especially for the Data Space paradigm, we succeed in having consistent implementation across domains and enable external entities to align with TwinEU standards.
- **Include DevOps and Governance Views in the 4+1 Model: Development teams can extend the proposed** "4+1" model with i) a DevOps View consisting of toolchain and CI/CD strategy and ii) a Governance View with well-defined roles, responsibilities, and data custodianship. This way we achieve operational sustainability and long-term governance beyond system design.

As a final note we can consider that our efforts in the delivery and the design of the TwinEU Reference Architecture are summarized in the outlook below:

Table 23: RA Outlook

Short-Term design
• **Focus**: Finalize the RA methodology, validate in pilot projects, refine interoperability layers.
• **Milestones:**
  o Completion of functional mapping from WP2 BUCs to RA components
  o MVP of the Middleware and OneNet-based interface layers
  o Execution of at least one Data Space PoC demonstrating end-to-end data flow

Medium-Term Design and Components Development
• **Focus:** Operationalization of pilots, federation of Digital Twins, regulatory alignment.
• **Milestones**:
  o Deployment of federated twin environments with measurable KPIs
  o Pan-EU scenarios interoperability tests
  o Demonstration of compliance with Data Space initiatives, and trust frameworks

Long-Term development
• **Focus:** Scalability, reuse, and horizontal replication.
• **Milestones:**
  o Adoption of the TwinEU RA as a standard reference by EU energy initiatives
  o Evolution into a pan-European Energy Data Space model
  o Integration with climate, transport, and smart city Digital Twins
  o Integration with other EU Data Spaces

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Annex A Non-Functional Requirements

In this section, defined draft non-functional requirements for the TwinEU system are presented. Non-FURs are not yet validated, but they are the recommendations to the system, particularly to the reference architecture. Complete and final version of non-FURs will be provided in the deliverable D3.2.

Table A-1: Non-Functional Requirements

Requirement ID	Name	Category	Subcategory	Description
TwinEU_NFR_01	Precise and Correct Functional Implementation	Functional Suitability	Correctness	The TwinEU system should ensure the proper and precise implementation of all the envisioned functionalities.
TwinEU_NFR_02	Accurate Design and Estimation Validation	Functional Suitability	Functional correctness	The TwinEU system must ensure high accuracy in the validation of design elements/estimations to minimize errors and increase the quality of the final design/abnormal market behaviours, minimizing false positives and false negatives.
TwinEU_NFR_03	High-Precision and accurate Data Exchange for Critical Grid Parameters	Functional Suitability/Security	Functional Correctness /Appropriateness	The data exchanged between the DTs must maintain high accuracy and precision, particularly for critical grid parameters such as frequency control, voltage levels, and consumption forecasts/when assessing technical constraints and geographical factors related to, for example, VRES and DER connection points.
TwinEU_NFR_04	Regulatory Compliance for European Grid Operations	Functional Suitability	Functional Correctness	The TwinEU system should adhere to European grid codes such as ENTSO-E's Network Code on Operational Planning & Scheduling (NC OPS), ensuring that planning, forecasting and other operations align with operational standards. The TwinEU system must comply with relevant grid operation standards and regulations, such as ENTSO-E guidelines, to ensure alignment with the operational procedures of European TSOs. The TwinEU system must comply with European energy grid regulations, ensuring that all data exchanges adhere to legal and technical standards for grid operations and energy management.

Requirement ID	Name	Category	Subcategory	Description
TwinEU_NFR_05	Compliance with Local Grid Codes and Standards	Functional Suitability/Security	Functional Correctness /Appropriateness	The TwinEU system should adhere to local grid codes and distribution network standards
TwinEU_NFR_06	Real-Time Predictive Accuracy	Functional Suitability	Functional Correctness	The AI agent must provide real-time grid forecasts and risk assessments within a maximum latency of 1-2 minutes. The AI agent must achieve a forecast accuracy of at least 95% for grid status prediction.
TwinEU_NFR_07	Forecast Accuracy and Validation	Functional Suitability	Functional Correctness	The generated synthetic series/forecasts/simulations outputs must have an accuracy of at least 95% when compared to real-world data.(maybe can be united with the previous requirement)
TwinEU_NFR_08	AI Forecasting Accuracy and Continuous Improvement	Functional Suitability	Functional correctness/Accuracy	The TwinEU system's AI-enhanced forecasting system must achieve an accuracy rate of over 95% in predicting production. Forecast deviations should be minimal, with a feedback loop ensuring continuous improvements.
TwinEU_NFR_09	Continuous Model Refinement and Improvement	Functional Suitability	Functional correctness/Accuracy	The TwinEU system must continuously refine its models to improve accuracy over time using machine learning techniques.
TwinEU_NFR_10	Low-Latency Real-Time Data Processing and Communication	Performance Efficiency	Time Behaviour	The TwinEU system must manage real-time data efficiently (e.g. within 5 or 10 seconds). The TwinEU system must process real-time data with minimal latency, ensuring timely responses, enabling real-time or near-real-time communication (e.g., under one minute).
TwinEU_NFR_11	Timely Data Exchange and Validation	Performance Efficiency	Time Behaviour	The TwinEU system must perform real-time data exchanges and validations/simulations/assessments within predefined time limits (e.g., under one minute for urgent operational adjustments).
TwinEU_NFR_12	Responsive User Interaction and Immediate Feedback	Performance Efficiency	Time Behaviour	The TwinEU system must respond promptly to user inputs and provide immediate feedback, ensuring that users can interact with The TwinEU system efficiently during complex operations.

Requirement ID	Name	Category	Subcategory	Description
TwinEU_NFR_13	High-Capacity Concurrent Data Handling	Performance Efficiency	Capacity	The TwinEU system should be able to handle a large number of concurrent transactions and data points from various grid elements without performance degradation (e.g. up to 10,000). The TwinEU system should be able to handle real-time data from a large number of connections simultaneously, supporting rapid operations.
TwinEU_NFR_14	Efficient Large-Scale Data Processing and Integrity	Performance Efficiency	Resource Utilization	The TwinEU system must handle large datasets efficiently, without performance degradation, and without compromising the accuracy of the exchanged information.
TwinEU_NFR_15	Optimized Resource Utilization for High-Performance Operations	Performance Efficiency	Resource Utilization	The TwinEU system must optimize resource usage to run complex operations without compromising performance, even under high loads.
TwinEU_NFR_16	High-Throughput Data Processing for Grid Analytics	Performance Efficiency	Time Behaviour /Capacity	The TwinEU system should support high throughput to handle the large volumes of information generated by grid models and predictive analytics.
TwinEU_NFR_17	Real-Time, High-Accuracy Simulations	Performance Efficiency	Time Behaviour /Capacity	The TwinEU system must process and simulate scenarios in real-time, ensuring operations without delays that could affect the accuracy of the results. The simulations must have high accuracy, reflecting the actual behaviour of the grid within a small margin of error (e.g., less than 5%).
TwinEU_NFR_18	Precise Forecasting for power prediction	Performance Efficiency /Functional Suitability		The ANN models in the TwinEU system must achieve a high level of accuracy in predicting WPP production, with forecast errors minimized through continuous learning and optimization.
TwinEU_NFR_19	Timely Error Detection and Correction	Performance Efficiency	Time Behaviour	Error detection algorithms the TwinEU system should run within seconds to minutes after receiving new data, allowing for timely corrections.

Requirement ID	Name	Category	Subcategory	Description
TwinEU_NFR_20	Resource Optimization for Operational Cost Efficiency	Performance Efficiency	Resource Utilization	The TwinEU system must efficiently utilize computational and network resources to minimize operational costs, even under high system loads.
TwinEU_NFR_21	High-Frequency Data Handling with Performance Integrity	Performance Efficiency	Time Behaviour /Capacity	The TwinEU system must handle high-frequency data updates without performance degradation, ensuring near real-time response for simulations/operations.
TwinEU_NFR_22	Timely Validation and Feedback Mechanism	Performance Efficiency	Time Behaviour	The TwinEU system must perform validation and provide feedback within a reasonable time frame to ensure that the process is not delayed.
TwinEU_NFR_23	Scalable Grid and Multi-Project Management	Performance Efficiency	Capacity	The TwinEU system should handle large-scale grids and multiple simultaneous maintenance projects across different regions.
TwinEU_NFR_24	Real-Time Dynamic System Assessment	Performance Efficiency	Time Behaviour/Capacity	The TwinEU system must perform real-time assessments of dynamic system behaviour, ensuring fast computation of grid stability, frequency analysis, and ancillary service requirements with minimal delays.
TwinEU_NFR_25	Seamless Integration and Interoperability	Compatibility	Interoperability	The TwinEU system must ensure seamless integration and interoperability with all identified systems (e.g. must be compatible with various TSO and DSO systems, ensuring seamless data exchange and collaboration). The TwinEU system also must be compatible with various digital twin modules and grid systems (grid management systems, planning tools, etc.).
TwinEU_NFR_26	Adaptability to Programming Languages and Data Exchange Protocols	Compatibility	Interoperability	The TwinEU system should be adaptable to different programming languages or data exchange protocols used by the respective DTs.
TwinEU_NFR_27	Support for Standard Communication Protocols and Data Formats	Compatibility	Interoperability	The TwinEU system must support standard communication protocols and data formats for interoperability, for seamless data exchange between all actors in the grid.

Requirement ID	Name	Category	Subcategory	Description
TwinEU_NFR_28	Seamless Integration with Existing DSO /TSO Infrastructure	Compatibility	Co-existence	The TwinEU system must be compatible with existing DSO and/or TSO infrastructure and integrate seamlessly with other grid planning and management systems.
TwinEU_NFR_29	External Data Integration Capability	Compatibility	Interoperability	The TwinEU system must be able to communicate with external databases and models, including those provided by DSOs and/or RES operators.
TwinEU_NFR_30	Intuitive User Interface with Enhanced Visualization and Usability	Interaction Capability	Operability, (User Interface Aesthetics)	The TwinEU system's user interface must be intuitive, providing clear visualization of forecasted grid states/risks/suggested actions. The TwinEU system must provide an appealing, intuitive, coherent and comprehensible interface for viewing, monitoring, configuring or reporting.
TwinEU_NFR_31	Comprehensive Operational Documentation	Interaction Capability	Operability	The TwinEU system should provide a comprehensive documentation for all the envisioned operations.
TwinEU_NFR_32	User Error Prevention Mechanisms	Interaction Capability	User Error Prevention	The TwinEU system must include safeguards to prevent user errors during data input and operations configuration.
TwinEU_NFR_33	Reliability, Robustness and Operational Continuity	Reliability	Fault Tolerance /Availability	The TwinEU system must ensure robustness and high reliability during critical operations (e.g. with a failure rate of less than 0.1%), guaranteeing operational continuity. (percentage can be adapted)
TwinEU_NFR_34	Uptime and Availability Assurance for Continuous Operations	Reliability	Availability	The TwinEU system must ensure high uptime (minimal downtime) and availability while performing operations, to ensure continuous monitoring and control
TwinEU_NFR_35	Fault Tolerance and Resilience Mechanisms	Reliability	Fault Tolerance	The TwinEU system must include mechanisms for fault tolerance to maintain operations during component failures (e.g. implement redundant systems and data sources to safeguard against data loss or system failures). It should include fault-tolerant architecture to ensure that threat detection and protocol activation can proceed even in the event of hardware or software failures.

Requirement ID	Name	Category	Subcategory	Description
TwinEU_NFR_36	Data Backup and Recovery Capability	Reliability	Recoverability	The TwinEU system could have the capability to efficiently restore data that has been directly impacted by an unexpected disruption.
TwinEU_NFR_37	High Reliability Operational Forecasting	Reliability	Availability /Fault Tolerance /Robustness	The TwinEU system must provide highly reliable forecasts/operations with a minimum failure rate of less than 0.1% over continuous 24/7 operation.
TwinEU_NFR_38	Data Integrity and Error Detection	Reliability	Fault Tolerance	The TwinEU system could have strict error detection mechanisms to flag any inconsistencies in the data.
TwinEU_NFR_39	Forecast Availability and System Reliability	Reliability	Fault Tolerance /Availability	The TwinEU system must maintain high reliability, ensuring that forecasts are consistently available and that the model remains operational under varying data loads.
TwinEU_NFR_40	Data Security and Integrity Assurance	Security	Confidentiality, Integrity	The TwinEU system must provide secure processing (secure data handling and security measures for data integrity). The system must ensure the integrity and privacy of data to prevent unauthorized alterations and ensure accurate decision-making, implementing strong cybersecurity measures. All data transfers between digital twin modules must be encrypted.
TwinEU_NFR_41	Secure Data Storage and Access Control	Security	Confidentiality, Integrity	The TwinEU system must provide secure data storage. The TwinEU system must ensure that all data generated, transmitted, and stored is accurate and unaltered, maintaining the integrity of the operation results. It must provide role-based access controls, ensuring that only authorized personnel can manipulate the TwinEU system or access critical data.
TwinEU_NFR_42	User Identification and Authentication	Security	Authenticity	The TwinEU system should uniquely identify all users within the system, ensuring accurate and secure user recognition.
TwinEU_NFR_43	Audit Logging and Reporting	Security	Accountability	The TwinEU system should provide comprehensive logging and reporting features for auditability and regulatory compliance, ensuring that all actions and results can be reviewed and verified.

Requirement ID	Name	Category	Subcategory	Description
				These logs should be easily accessible for audits, ensuring transparency in handling cybersecurity incidents.
TwinEU_NFR_44	Data Security and Protection Measures	Security	Confidentiality/Integrity/Accountability	The TwinEU system must employ robust security measures to protect sensitive grid data, including encryption of data transmissions, secure access controls, and monitoring for cybersecurity threats. All data exchanges between the digital twin, planners, and stakeholders must be securely protected.
TwinEU_NFR_45	Compliance with Industry Standards and Cybersecurity Protocols	Security	Accountability	The TwinEU system should comply with relevant industry standards and protocols, ensuring that it meets regulatory and operational benchmarks. The TwinEU system should comply with industry standards for cybersecurity to protect sensitive grid data and operational commands
TwinEU_NFR_46	Data Source Authentication and Integrity Verification	Security	Authenticity	Masquerade and/or spoofing: The TwinEU system should ensure that data comes from the stated source or goes to authenticated receiver. This is crucial.
TwinEU_NFR_47	Regulatory Compliance and Flexibility Resource Qualification	Security	Maintainability	The TwinEU system should comply to industry standards for flexibility resources and ensure regulatory compliance throughout the qualification process.
TwinEU_NFR_48	Data Privacy and Security Compliance	Security	Confidentiality /Integrity	The TwinEU system should comply that data sharing and interactions within the digital twin adhere to all relevant data regulations and standards, ensuring confidentiality and integrity of exchanged data.
TwinEU_NFR_49	Regulatory Compliance for Renewable Energy and Grid Operations	Security /Safety	Confidentiality /Integrity	The TwinEU system must adhere to national and international regulations regarding renewable energy forecasting and grid operation standards.
TwinEU_NFR_50	Full GDPR compliance	Security	Confidentiality /Integrity	The TwinEU system must ensure full compliance with relevant data protection regulations, including GDPR, and industry-specific standards for data management and sharing. Compliance with data

Requirement ID	Name	Category	Subcategory	Description
				protection laws (e.g., GDPR) must be ensured for all personal or operational data processed by the system. Full GDPR compliance.
TwinEU_NFR_51	Data Anonymization and Confidentiality	Security	Confidentiality/ Privacy	The TwinEU system must ensure the anonymization and confidentiality of the collected sensitive data.
TwinEU_NFR_52	Scalability for Future Expansion and Complex Operations	Maintainability /Modularity or Flexibility /Scalability		The TwinEU system should be scalable to handle increasingly complex operations, including the integration of additional grid sections or equipment. The architecture must support the addition of new grid areas and additional operational scenarios as the system evolves. The TwinEU system must scale to handle multiple geographic locations and different types of renewable resources as required by the expanding power grid.
TwinEU_NFR_53	Seamless Upgrade Support	Maintainability	Modularity /Adaptability	The TwinEU system should support future upgrades without major disruptions to the existing architecture.
TwinEU_NFR_54	Dynamic Load Scalability	Maintainability /Modularity or Flexibility/ Scalability		The TwinEU system must be scalable to handle increasing data loads.
TwinEU_NFR_55	Modular Maintainability and Upgradability	Maintainability	Modularity	The TwinEU system could allow for easy updates and maintenance with minimal downtime, using a modular design approach. The TwinEU system could be designed for easy maintenance, allowing for updates, bug fixes, and improvements without significant downtime.
TwinEU_NFR_56	Testability and Assessability within Demonstrator Architecture	Maintainability	Testability	The TwinEU system shall be testable and assessable within the demonstrators' architecture, ensuring that all components and functionalities can be effectively evaluated and verified for performance, reliability, and compliance with specifications.
TwinEU_NFR_57	Feedback-Driven Modifiability	Maintainability	Modifiability	The TwinEU system should be modifiable based on the feedback collected during the evaluation phase of the demonstrations.

Requirement ID	Name	Category	Subcategory	Description
TwinEU_NFR_58	Code Clarity and Documentation	Maintainability	Analysability /Modularity	Code should be well documented and understandable.
TwinEU_NFR_59	Automated Testing and Validation	Maintainability	Analysability /Modifiability/	The TwinEU system must support automated testing and validation of new functionalities to ensure stability when updates are deployed. The TwinEU system could include automated testing and validation tools to ensure that any updates to the existing models or communication protocols do not introduce errors.
TwinEU_NFR_60	Automated Functionality Testing and Stability Assurance	Performance Efficiency/Flexibility	Scalability (Flexibility) Capacity (Performance Efficiency)	The TwinEU system must support automated testing and validation of new functionalities to ensure stability when updates are deployed. The TwinEU system could include automated testing and validation tools to ensure that any updates to the existing models or communication protocols do not introduce errors.
TwinEU_NFR_61	AI Adaptability for Dynamic Grid Integration	Flexibility	Adaptability	The AI model must be flexible enough to support new weather stations, lines, or regions added to the grid over time.
TwinEU_NFR_62	Data Integration, Scalability and Adaptability	Flexibility	Scalability	It must be capable of adapting to new datasets or sources of data.
TwinEU_NFR_63	Platform and Environment Independence	Flexibility	Adaptability	The TwinEU system must be platform and environment agnostic.
TwinEU_NFR_64	Deployment Flexibility	Flexibility	Installability	The TwinEU system must be deployable in any environment (e.g., using Kubernetes, Docker or similar approach).
TwinEU_NFR_65	Grid Configuration Adaptability	Flexibility	Adaptability	The TwinEU system must be adaptable to different grid configurations and capable of integrating with various monitoring and/or control devices/new types of energy sources. It should support the inclusion of new renewable resources as technology advances (e.g., tidal energy).

Requirement ID	Name	Category	Subcategory	Description
TwinEU_NFR_66	Regulatory and Technological Adaptability	Flexibility	Adaptability	The TwinEU system must be adaptable to evolving grid conditions and regulatory changes, allowing for updates to flexibility requirements as new technologies (e.g., vehicle-to-grid systems) are introduced.
TwinEU_NFR_67	Geographic and Regulatory Flexibility	Flexibility	Adaptability /Modularity	The TwinEU system must be designed for deployment across different geographic regions and be adaptable to varying regulatory and market environments across the EU.
TwinEU_NFR_68	Overload Detection and Prevention	Safety	Operational constraint	The TwinEU system could include mechanisms to detect and prevent overloads that could lead to unsafe conditions and potential hazards.
TwinEU_NFR_69	Safety Warning and Prevention	Safety	Hazard warning	The TwinEU system should provide timely warnings to prevent actions that could compromise safety.
TwinEU_NFR_70	Critical Failure Mitigation	Safety	Fail safe	The TwinEU system must shut down non-essential functions when critical failures are detected, ensuring that essential operations can continue without compromising safety.
TwinEU_NFR_71	Real-Time Safety Monitoring and Alert	Safety	Risk identification	The TwinEU system could continuously monitor safety-critical data points (e.g., temperature, pressure, voltage) and flag any deviations from predefined safe ranges to alert operators of potential risks.

Annex B General System Use Cases

In this Section, General System Use Cases (GSUCs) are presented. GSUC_01 is shown in the Section 5.5. Use Cases are presented in a uniform manner, following the standards and methodology described in the previous Horizon 2020 project OneNet.

Table B-1: GSUC_02

Name GSUC	AI-Driven Big Data ad IoT Data Orchestration and Marketplace for Cross-Platform Digital Twin Services
GSUC ID	GSUC_02 (Adapted from the EU H2020 project OneNet and expanded)
Objectives	• Enable AI, Big Data and IoT data orchestration for cross-platform services • Tracking the performance of the cross-platform services • Develop a Big Data / AI marketplace to enhance interoperability and service discoverability. • Facilitate data-driven AI solutions, including demand/generation forecasting, behavioural analytics, elasticity profiling, and predictive modelling. • Integrate service, data, and model discoverability to support the orchestration of federated Digital Twin data spaces. • Extend the IDSA-compliant Federated Catalogue into a Services Workbench, acting as a mediator for open services utilization. • Support containerized service integration (e.g., via Kubernetes) for scalable and efficient deployment. • Provide advanced analytics, data visualization, and AI model deployment capabilities within the marketplace.
Narrative	This General TwinEU SUC describes the TwinEU Orchestration Workbench for enabling AI, Big Data and IoT cross-platform services. The TwinEU Orchestration Workbench aims to allow the necessary scalability support for the near real time IoT sensing, gathering and big data management of consumer and/or network data at the grid. The TwinEU Orchestration Workbench allows to integrate data coming from the OneNet middleware and implement a data pipeline orchestration. It also should include: Job Scheduling; App/Service registry and discovery; Error/Retries management; SLAs tracking, alerting and notification. The TwinEU Orchestration Workbench will be expanded to include a Big Data / AI marketplace for service, data, and model interoperability. This marketplace will serve as a central hub where AI-driven services, data assets, and analytics tools can be discovered, integrated, and utilized across the TwinEU ecosystem. It will address key data-driven challenges, such as demand/generation forecasting, behavioural analytics, and elasticity profiling, by facilitating real-time and batch data processing. To achieve scalability and seamless integration, the IDSA-compliant Federated Catalogue will evolve into a Services Workbench, providing containerized service orchestration via Kubernetes. This workbench will enable plug-and-play service integration, allowing users to deploy and manage AI-powered services efficiently. Additionally, it will feature built-in

	analytics and data visualization capabilities, enhancing decision-making for grid operators, policymakers, and energy market participants. By establishing this marketplace-driven approach, the TwinEU ecosystem will create a decentralized, interoperable, and scalable environment that fosters collaboration, innovation, and optimized resource utilization across the European energy sector.
Steps	• The Service Provider register its service in the TwinEU Workbench. • The Service Provider create a workflow, using TwinEU Middleware Data for running a service. • The TwinEU Workbench monitors the execution of the job, manages the errors and needed retries as well as tracking the performance. • The Service Provider access to a log result for all the activities of the job. • Design and implement the Big Data / AI marketplace, ensuring interoperability and service discoverability. • Develop data ingestion and curation mechanisms for batch and real-time data processing. • Integrate AI-driven solutions for predictive analytics, behavioural modeling, and elasticity profiling. • Enhance the IDSA-compliant Federated Catalogue into a fully operational Services Workbench. • Enable containerized deployment of services using Kubernetes and other orchestration technologies. • Provide built-in analytics, AI model deployment, and visualization tools within the marketplace. • Ensure secure and trusted access control for data providers, consumers, and AI service developers. • Validate marketplace functionality through real-world grid operation scenarios and Digital Twin integration use cases.
Involved Platforms/ actors	Third-Party Actors Service Provider TwinEU System Orchestration Workbench Federated Catalogue for AI & Data Services Containerized Deployment Environment (e.g., Kubernetes) TwinEU Middleware TwinEU Workbench TwinEU AI/Big Data Marketplace: AI Model Repository Service and Data Asset Registry Advanced Data Visualization & Analytics Tools Key Participants: Grid Operators, Market Operators, AI Service Providers, Digital Twin Developers, Energy Researchers

Sequence Diagrams

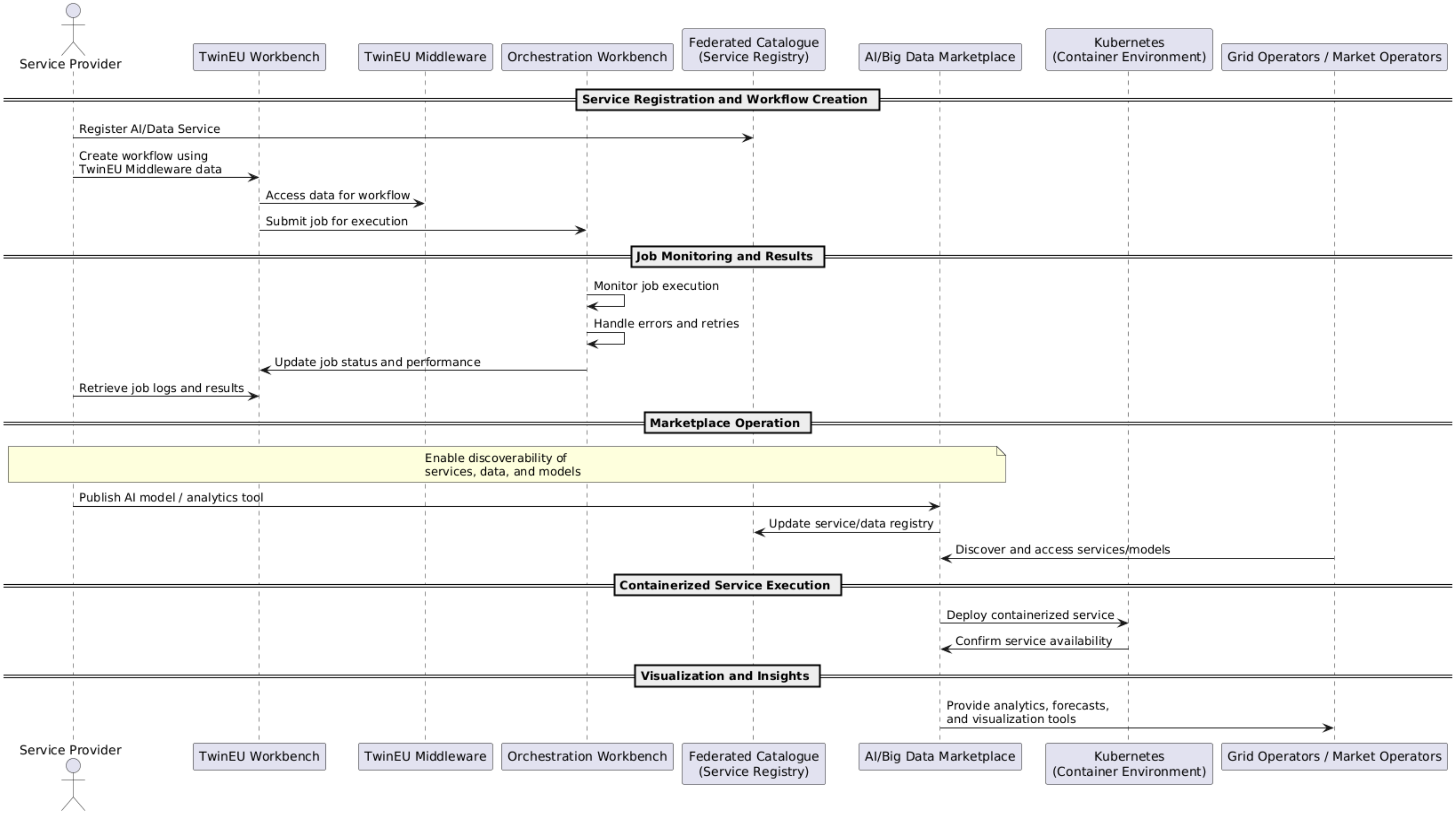


Table B-2: GSUC_03

<table>
<tr><th>Name GSUC</th><th>Integration of IoT devices and other data sources to TwinEU</th></tr>
<tr><td>GSUC ID</td><td>GSUC_03</td></tr>
<tr><td>Objectives</td><td>Integrate diverse IOT devices and data sources using standardized protocols and mechanisms
Enable a data-model agnostic near real-time data collection based on standardized mechanisms and model
Support seamless integration and interaction between IoT devices and external data sources to TwinEU participants</td></tr>
<tr><td>Narrative</td><td>Platforms and applications in the Smart Energy domain must exchange near real-time data in a standardized, interoperable, and unambiguous manner. The definition of standardized mechanisms, data’s format and meaning is crucial for the IoT integration and in particular for near real-time data.

This General System Use Case describes how the TwinEU System provides a data-model agnostic connector, enabling standardized data exchange using standardized protocols and mechanisms and leveraging on stream processing platform (e. g. Kafka).

The integration operations allow applications to create high stream data exchange, maintaining all the characteristics and principles of the data space. IoT devices and other data sources are integrated through standard registration and interaction protocols, ensuring secure and scalable data provision and consumption within TwinEU.</td></tr>
<tr><td>Steps</td><td>Scenario 1 – Identification:
Data sources and consumers are identified using TwinEU identity management mechanisms.
Scenario 2 – Data Provision and Consumption:
Data Streaming Provision: Data Providers can create, modify, and delete data sources with near real-time data provisioning
Data Streaming Consumption: Data Consumers can retrieve or query streaming data</td></tr>
<tr><td>Involved Platforms/ actors</td><td>TwinEU Participant
Data Provider
Data Consumer
Data Source (IoT Device + other devices). In this particular Use Case, the Data Source represents the integration of IoT devices or other kind of near real-time data sources.
TwinEU System
Identity Provider
Middleware and Connector
Data Source Registry (Federated Catalogue)</td></tr>
</table>

Sequence Diagrams

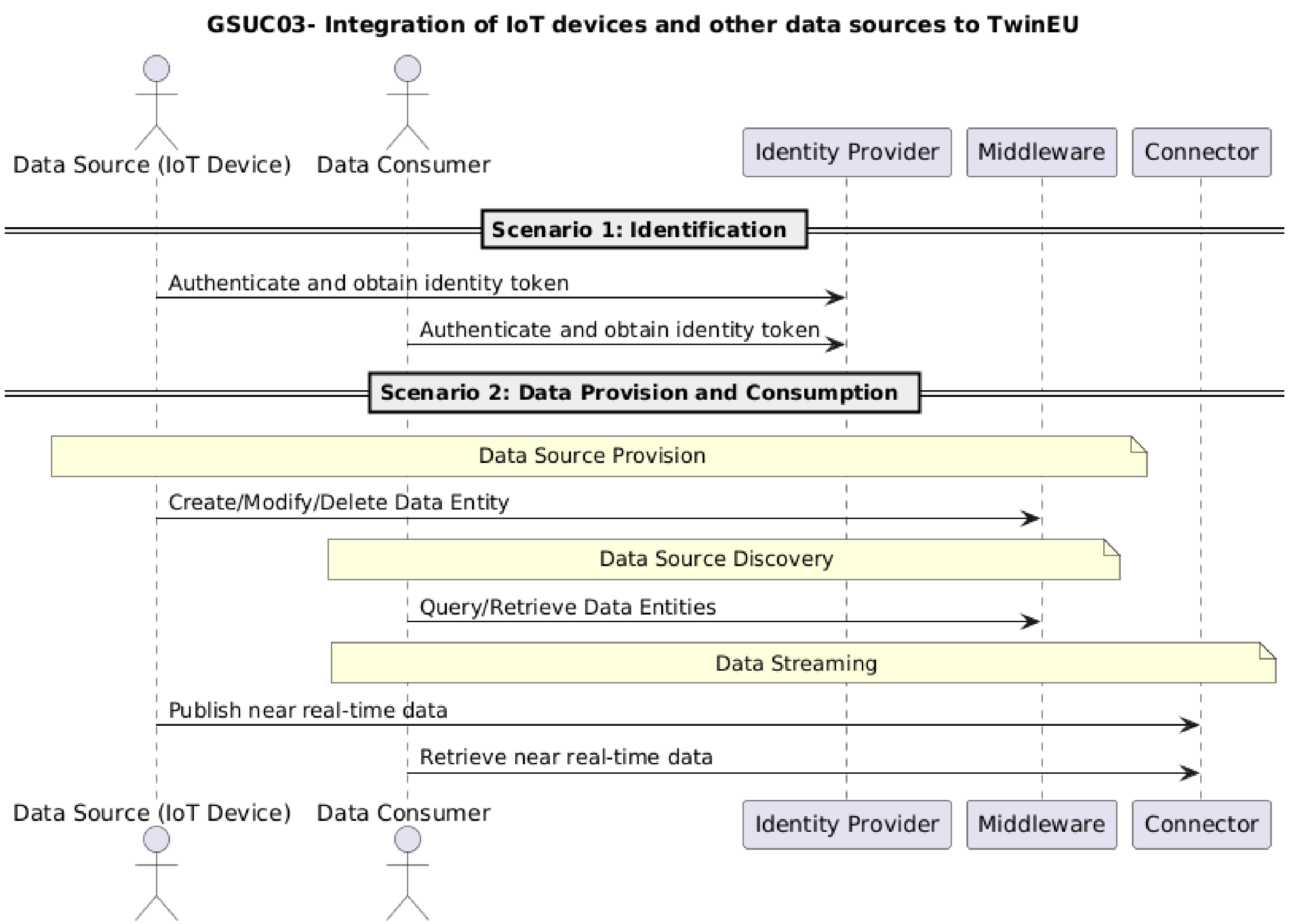


Table B-3: GSUC_04

Name GSUC	Regulatory Compliance Exchange and Reporting
GSUC ID	GSUC_04
Objectives	• Ensure Compliance with Regulatory Standards • CIM standard is defined in communication and information layers of SGAM communication model • Perform Compliance Validation and Reporting of regulatory compliance of all TwinEU components • Monitor and Audit Regulatory Changes on all levels of TwinEU system (not automated tool, manual processes) • Enable secure and transparent data exchange
Narrative	All exchanges and data used in the TwinEU system should be compliant with appropriate standards, directives, laws, and codes, with special attention to the integration of CIM (Common Information Model) standard in SGAM communication model. It is important to enable the regulatory compliance on all levels of TwinEU system
Steps	• Define and update regulatory requirements • Ensure compliance validation processes • Make that data exchanges are secure and transparent and aligned with standards Notify system operators automatically when compliance is endangered. • Enable continuous monitoring and auditing of regulatory changes
Involved Platforms/ actors	Regulatory Authorities, Grid Operators, Market Operators, Data Space participants

Sequence Diagrams

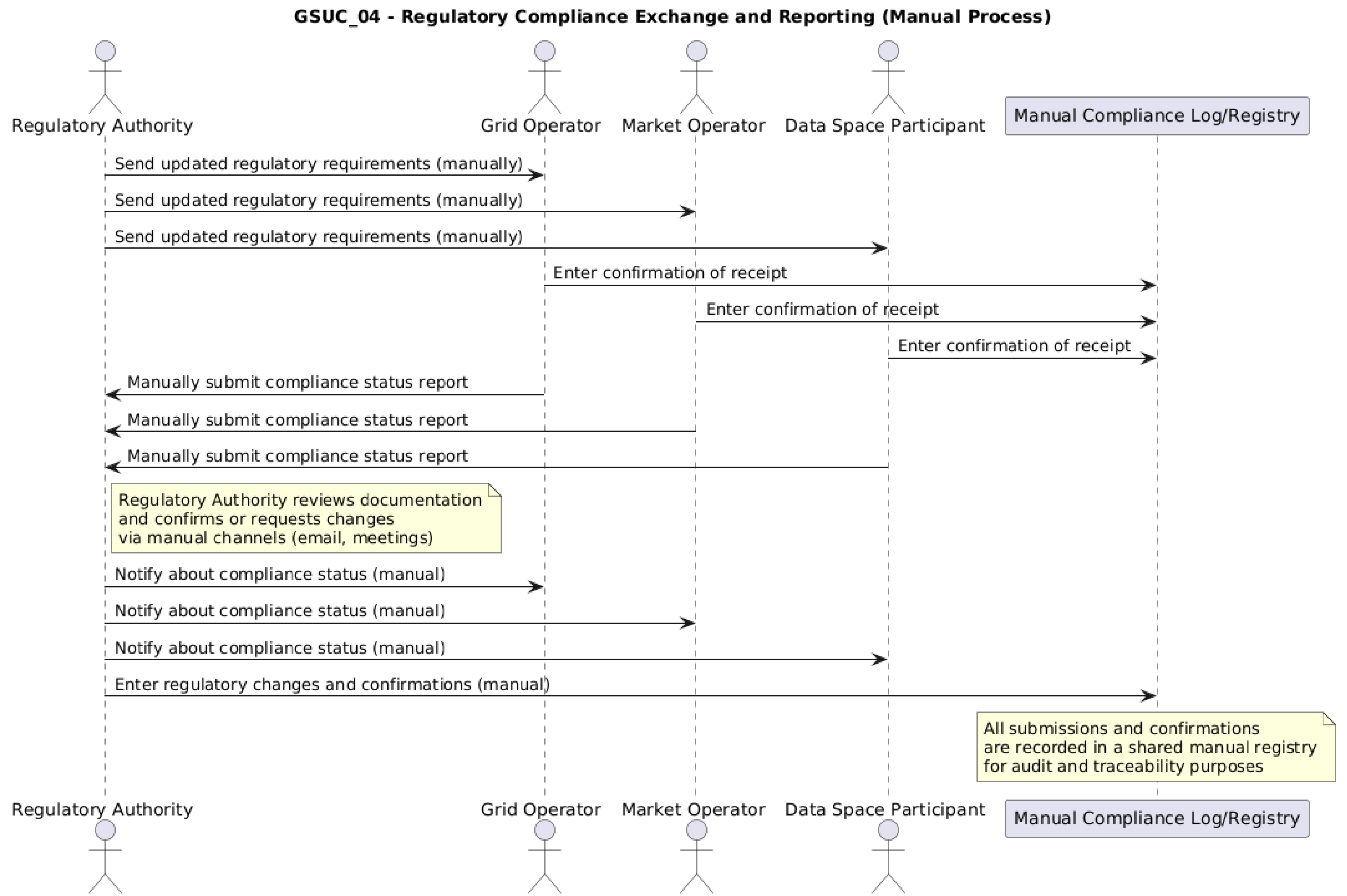


Table B-4: GSUC_05

Name GSUC	Resilient Energy Infrastructure Planning including Dynamic Renewable Energy Integration and Digital Twin-Driven Grid Resilience and Anomaly Detection
GSUC ID	GSUC_05
Objectives	• Perform grid resilience assessment through real-time and scenario-based simulation. • Simulate dynamic integration of Renewable Energy Sources (RES) and Distributed Energy Resources (DER). • Simulate Abnormal Conditions and Disruptions • Detect abnormal operating conditions and infrastructure anomalies using Digital Twin-driven analytics. • Identify critical bottlenecks and stress points across the transmission and distribution grids. • Enable predictive modelling of pan-European interconnected market behaviours and grid responses. • Provide actionable stability and risk analysis reports to grid operators and policy enforcement systems.
Narrative	The TwinEU System enables real-time and predictive simulation of the energy grid under dynamic RES/DER integration scenarios. The system uses parameterized simulation inputs provided by Transmission System Operators (TSOs) and Distribution System Operators (DSOs), including expected RES penetration profiles, load forecasts, and contingency events. The Digital Twin simulation tools within TwinEU process these parameters to: • Continuously evaluate grid resilience across multiple temporal and spatial scales. • Detect infrastructure stress indicators and anomalies using event-driven monitoring. • Predict grid behaviour under abnormal conditions such as extreme weather, cyber incidents, or sudden load fluctuations. • Model complex, cross-border energy flows in the context of interconnected European markets.
Steps	• Parameter codes for integration of RES and DER are issued by grid operators • TwinEU simulation tools are employed to analyse the grid behaviour under different circumstances • Identify infrastructure bottlenecks and anomaly detection • Recommendations for energy grid stability and overall resilience of energy infrastructure • Modelling Pan-European scenarios of energy smart grid
Involved Platforms/ actors	Grid Operators, TSOs, DSOs, Policy Makers, Domain experts

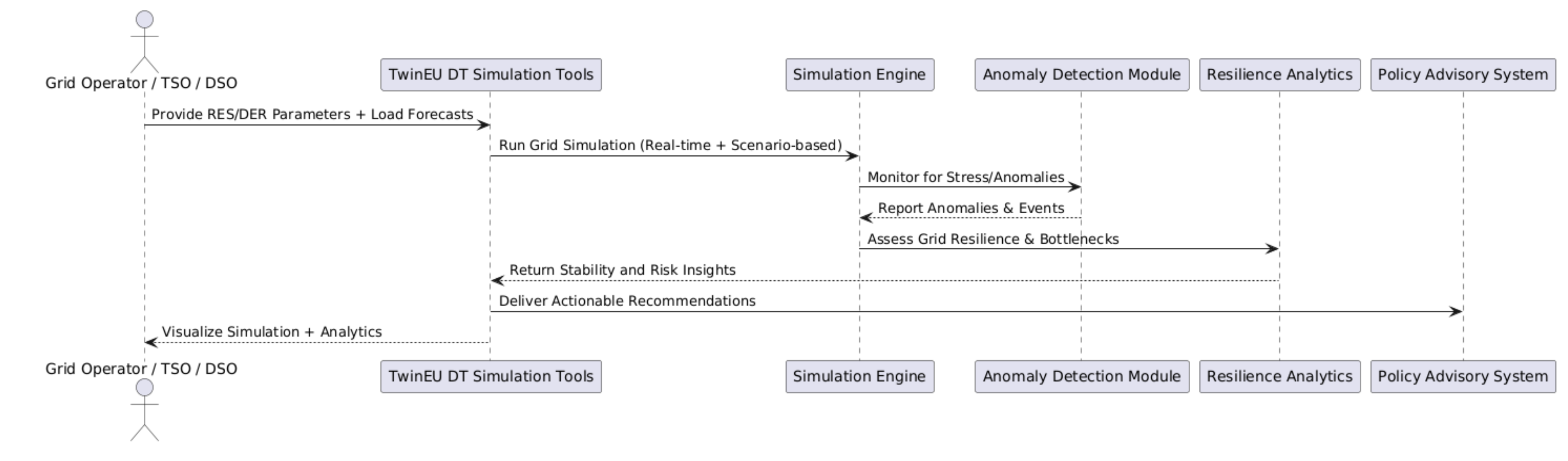
Sequence Diagrams	

Table B-5: GSUC_06

Name GSUC	TwinEU XR Framework for DTs visualization and validation
GSUC ID	GSUC_06
Objectives	Implement the TwinEU XR framework to support high-quality real-time immersive DT visualization experiences. Enable multiuser XR environments for enhanced collaboration and decision-making. Facilitate interactive data visualization using Virtual Reality (VR) approach. Enhance data accessibility and usability through advanced visualization and validation services. Integrate Unity3D-based immersive workbench as a plugin, providing an intuitive and simplified workflow.
Narrative	To improve resilient energy infrastructure planning and dynamic renewable energy integration, TwinEU will introduce a real-time immersive DT framework capable of supporting multiuser XR environments. This framework will provide interactive, data-driven simulations, allowing grid operators, policymakers, and domain experts to visualize complex energy scenarios more intuitively. The TwinEU immersive environment will be integrated as a Unity3D plugin, offering a user-friendly interface and a set of building blocks to simplify the creation of multiuser XR experiences. This will enable stakeholders to interact with real-time energy data, analyze grid stability, and optimize energy distribution using advanced Virtual Reality (VR) visualization techniques. By leveraging scalable and adaptable architecture, the framework will mainly support a DT design validation scenario, integrating immersive XR-based visualization and including anomaly detection, risk assessment, and proactive grid management, fostering a more resilient, efficient, and interactive energy ecosystem.
Steps	• Develop the TwinEU DT immersive framework, integrating high-quality real-time DT visualization. • Implement a Unity3D-based immersive workbench as a plugin, streamlining user interaction with DT data. • Design a set of building blocks to facilitate fast and user-friendly XR experience creation. • Integrate VR capabilities for advanced visualization of energy infrastructure and grid performance. • Ensure framework scalability and adaptability, allowing applications to support different use cases and simulation scales. • Develop interactive services to provide data visualization, anomaly detection, and grid simulation insights.
Involved Platforms/ actors	TwinEU DT Framework: Unity3D Plugin Immersive Digital collaborative platform Advanced DTS Visualization (VR)

	Design Validation interface TwinEU System: Data Space Framework Data Orchestration and Validation Tools Grid Operators, TSOs, DSOs, Policymakers, Market Participants, and VR Experts

Sequence Diagrams