TwinEU

Functional and Technical Specifications

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List of Abbreviations and Acronyms

Acronym	Meaning
ACER	Agency for the Cooperation of Energy Regulators
aFRR	Automatic Frequency Restoration Reserve
AI	Artificial Intelligence
AMI	Advanced Metering Infrastructure
AMQP	Advanced Message Queuing Protocol
API	Application Programming Interface
ARE	Automated requirements engineering
BCP	Business Continuity Plan
BSP	Balancing Service Provider
BUC	Business Use Case
CBME	Cross-Border Market Exchange
CGMES	Common Grid Model Exchange Standard
CIS	Center for Internet Security
CIM	Common Information Model
CMS	Cybersecurity Management System
COSEM	Companion Specification for Energy Metering
CSF	Cybersecurity Framework
DDoS	Distributed Denial of Service
DEPO	Data Exchange Platform Operator
DER	Distributed Energy Resource
DGA	Data Governance Act
DLR	Dynamic Line Rating
DLMS	Device Language Message Specification
DoS	Denial of Service
DPSIM	Real-Time Dynamic Power System Simulator
DSP	Dataspace Protocol
DSO	Distribution System Operator
DT	Digital Twin
eIDAS	Electronic Identification, Authentication and Trust Services
EE-ISAC	European Energy Information Sharing & Analysis Centre
EMS	Energy Management System
ENTSO-E	European Network of Transmission System Operators for Electricity
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
FCR	Frequency Containment Reserve
FDT	Federated Digital Twin
FSP	Flexibility Service Provider
FUR	Functional Requirement

GDPR	General Data Protection Regulation
GE	Generic Enabler
GFUR	General Functional Requirement
GPRS	General Packet Radio Service
GSUC	General System Use Cases
HEMS	Home Energy Management System
HPC	High Performance Computing
HV	High Voltage
HVDC	High Voltage Direct Current
IAM	Identity and Access Management
ICCP	Inter-Control Centre Communications Protocol
IDS	Intrusion Detection Systems
IDSA	International Data Space Association
IETF	Internet Engineering Task Force
IoT	Internet of Things
IPS	Intrusion Prevention System
ISAC	Information Sharing and Analysis Centre
ISMS	Information Security Management System
IT	Information Technology
ISO	International Organization for Standardization
JSON	JavaScript Object Notation
JWS	JSON Web Signature
LV	Low Voltage
MDP	Measuring Device Provider
MFA	Multi-Factor Authentication
mFRR	Manual Frequency Restoration Reserve
MPO	Metering Point Operator
ML	Machine Learning
MO	Market Operator
MTTR	Mean Time to Recovery
MV	Medium Voltage
NCCS	Network Code on Cybersecurity
NFUR	Non-Functional Requirement
NIS	Network and Information Systems
NIST	National Institute of Standards and Technology

OHL	Overhead Line
OneNet	One Network for Europe
OPC UA	Open Platform Communication Unified Architecture
OT	Operational Technology
PMU	Phasor Measurement Units
PSS/E	Power System Simulator for Engineering
PV	Photovoltaic
RA	Reference Architecture
RBAC	Role-Based Access Control
RED	Renewable Energy Directive
REMIT	Regulation on Wholesale Energy Market Integrity and Transparency
RES	Renewable Energy Source
REST	Representational State Transfer
RPO	Recovery Point Objectives
RSC	Regional Security Coordinator
RTO	Recovery Time Objectives
RTU	Remote Terminal Unit
SAD	Smart Assistant Developer
SBOM	Software Bill of Materials
SCADA	Supervisory Control and Data Acquisition
SGAM	Smart Grid Architecture Model
SFTP	SSH File Transfer Protocol
SMGW	Smart Meter Gateway
SO	System Operator
SQuaRE	Software Quality Requirements and Evaluation
SUC	System Use Case
TSO	Transmission System Operator
UC	Use Case
UI	User Interface
VR	Virtual Reality
VRES	Variable Renewable Energy Sources
WAN	Wide Area Network
WP	Work Package
WDS	Weather Data Supplier
WFP	Weather Forecast Provider
XR	Extended Reality

Executive Summary

This work focuses on defining the functional, non-functional, regulatory, and technical specifications required to enable the TwinEU Federated Digital Twin (DT) platform. The TwinEU Federated DT platform is designed to enhance the federation and interoperability of the European electricity DT systems through the deployment of interoperable, federated, scalable, and standards-compliant DT solutions.

The objective is to provide a validated and comprehensive set of requirements and specifications that can guide the implementation of the TwinEU DT systems, ensuring interoperability, regulatory compliance, and cybersecurity, while enabling the seamless integration of European, national, and regional digital twins into a coherent energy ecosystem.

The activities followed a rigorous and iterative methodology that combined stakeholder engagement, analysis of system use cases, review of previous European projects, and systematic application of requirements engineering best practices. Inputs were gathered through workshops, validation meetings, and cross-WP collaboration, ensuring that the requirements reflect real operational needs while remaining aligned with European standards and policy frameworks. This process was crucial in consolidating stakeholder priorities, identifying regulatory constraints, and ensuring traceability and validation of requirements across all stages.

As a result, the work delivered a comprehensive set of functional and non-functional requirements, a well-structured technical specification based on the SGAM framework, and clear guidelines for regulatory compliance, cybersecurity, and data privacy. Together, these outcomes form the technical backbone for the implementation of the TwinEU Federated DT platform.

Therefore, the main outcomes can be summarised as follows:

- A consolidated set of Functional Requirements and Non-Functional Requirements, validated across system use cases and demonstrator scenarios;
- Definition of technical specifications structured along the SGAM Framework layers (Component, Communication, and Information);
- Identification of regulatory and compliance requirements essential to enable cross-border federation of DT energy systems, integration with European Data Spaces, and system-wide interoperability, while ensuring full legal alignment;
- Provision of technical guidelines and recommended best practices addressing cybersecurity, data protection, and privacy compliance, ensuring the secure and reliable operation of the TwinEU Federated DT platform.

1 Introduction

The transition towards a sustainable, resilient, and cybersecure European energy system requires advanced digital tools capable of integrating diverse infrastructures, actors, and data sources. Digital Twin technology plays a key role in this transformation, as it enables accurate modelling, prediction, and optimisation of energy system operations across different geographical and organisational levels.

Within this context, the concept of a federated pan-European Digital Twin emerges as a fundamental innovation. By interconnecting locally implemented DTs into a coordinated and interoperable framework, it allows secure and standardised data exchange, enhances cross-border system observability, and supports the large-scale integration of renewable energy sources. Beyond infrastructure management, it also strengthens market efficiency and transparency through advanced simulation and decision-support capabilities.

The purpose of the work presented here is to establish the functional and technical foundations necessary to make this federated DT platform operational. This involves not only identifying the functional and non-functional requirements that the system must fulfil, but also consolidating the technical specifications and regulatory guidelines that will ensure its alignment with European standards and policies.

The outcome of this effort lays the groundwork for subsequent implementation and validation activities, providing a clear technical and methodological roadmap that connects system-level requirements with TwinEU demonstrator specific needs.

1.1 Objectives

D3.2 - Functional and Technical Specifications defines the specific functional and technical outputs required to support the implementation of both the TwinEU Federated DT platform and the DEMO-level DT systems, providing a clear link between the high-level system requirements and the detailed technical implementations to be carried out in the subsequent phases of the project, specifically within WP4 and WP5 to WP8.

The specific objectives of the work carried out are to:

- Consolidate a validated set of Functional Requirements (FURs) and Non-Functional Requirements (NFURs), covering both the TwinEU Federated DT platform and demonstrator-specific DT services.
- Provide detailed Technical Specifications, structured according to the Smart Grid Architecture Model (SGAM), covering the component, communication, and information layers necessary to build a scalable, secure, and interoperable platform.
- Identify relevant regulatory and compliance requirements, providing the design constraints and legal boundaries that ensure conformity with European and national regulations, including cybersecurity, data protection, and energy market standards.
- Serve as a unified technical reference for subsequent project work packages, in particular WP4, focused on the development of the TwinEU Federated DT platform, and WP5 to WP8, which involve the validation of Demonstrator-level DT services.
- The document is intended for a wide audience, including system developers, project partners, regulatory stakeholders, and technical experts involved in the design and implementation of the TwinEU Federated DT system.

1.2 Involved WP3 Tasks

This deliverable has been developed within WP3 – *Open Architecture and Design for pan-European Federated Data Space-enabled Digital Twin*, which defines the architectural, functional, technical, and regulatory framework for the TwinEU Federated DT platform.

In particular, this deliverable reports the results of the following tasks:

- Task 3.2 – Functional Specifications of pan-European DT Design: definition of functional requirements for both the TwinEU Federated DT platform and the demonstrator-level DT systems, based on use cases, stakeholder needs, and regulatory constraints.
- Task 3.3 – Technical Specifications of Open Interoperable Federated DT Design: definition of technical specifications using the SGAM framework, ensuring interoperability, scalability, and alignment with smart grid and data space standards.
- Task 3.4 – Cybersecurity and Data Privacy Requirements: identification of cybersecurity and data protection requirements for the TwinEU Federated DT platform, ensuring compliance with European and international legal frameworks.

1.3 Link with other WPs/Tasks

The activities and outcomes of *WP3 – Open Architecture and Design for pan-European Federated Data Space-enabled Digital Twin* are closely interconnected with other work packages within the TwinEU project, following a structured, bidirectional flow of information and validation.

WP2 – *Digital Twins EU-level cross-stakeholder use cases capitalization and preparation* has provided the foundational inputs for WP3, including:

- Business Use Cases (BUCs), representing the operational scenarios and system needs reported in D2.2 [19].
- The Gap Analysis, identifying technical, regulatory, and interoperability gaps in the current energy system reported in D2.1 [18].
- The High-Level Technical Specifications, defining initial architectural expectations and system boundaries reported in D2.2.

Based on these inputs, WP3 has produced:

- General Functional and Non-Functional Requirements, ensuring technical consistency and alignment with project objectives;
- Detailed Technical Specifications, addressing the architecture, interoperability, and system integration aspects;
- Cybersecurity and Data Privacy Requirements, ensuring compliance with European legal frameworks and standards.

These results from WP3 have been transferred to WP4 – *Data-space DT Federated Infrastructure Development and Integration*, serving as the technical basis for platform development. In return, WP3 has received continuous feedback and validation from WP4, allowing for refinement and adjustment of requirements based on practical implementation insights.

Additionally, WP3 has delivered:

- Demonstrator-specific Functional and Non-Functional Requirements.
- Technical Specifications for the deployment of DT services

- Cybersecurity and Privacy Guidelines.

These results have been transferred to WP5 to WP8, supporting the definition and development of DEMO DT services across different project demonstrators. Likewise, the demonstrator partners have provided feedback and validation on the requirements and technical specifications, ensuring that they are aligned with real-world needs and implementation constraints.

This iterative, multi-directional exchange has been essential to guarantee that all functional and technical specifications produced within WP3 are validated, applicable, and consistent with both the system-level vision and demonstrator-specific requirements of the TwinEU project.

1.4 Outline of the deliverable

This deliverable is structured to provide a comprehensive yet modular overview of the Functional and Technical Specifications for the TwinEU Federated DT system.

Each section is designed to be self-contained, allowing readers to focus on specific topics of interest based on their role or area of responsibility within the project. The following overview summarises the content and purpose of each main section:

- **Section 1 "Introduction"**: Outlines the project context, TwinEU objectives, the role of the Federated Digital Twin platform, and the importance of this deliverable within the project's technical framework.
- **Section 2 "Functional Specifications of Pan-European DT Design"**: presents the functional requirements for the TwinEU Federated DT system, including lessons learned from relevant European projects, stakeholder needs, use cases, and a systematic methodology for requirements definition.
- **Section 3 "Technical Specification of Open Interoperable Federated DT Design"**: describes the technical architecture and specifications necessary to enable an interoperable, scalable, and secure Federated DT platform, following the SGAM framework.
- **Section 4 "Conclusions"**: summarises the main findings, recommendations, and next steps for the technical development and deployment of the TwinEU system.
- **Annex section**: provides detailed supporting materials, including comprehensive lists of use cases, functional requirements, non-functional requirements, and architectural definitions that support the main document content.

2 Functional specifications of pan European DT design

2.1 General description

The functional specifications of the pan-European DT design include requirements for the federated system of DTs, successful communication among DTs, integration of data in real-time or near real-time, prediction and optimization, implementation of data space framework, AI-driven data processing and analytics, and support for RES deployment. Furthermore, the TwinEU Federated DT system abides by all EU, national, and regional standards, regulations, network codes, and laws that apply to the project's scope.

The most important categories of requirements for defining and describing the TwinEU Federated DT system are functional (FURs), non-functional (NFURs), and regulatory requirements. The pan-European DT platform is guided by these requirements, which are also aligned with the TwinEU reference architecture.

Furthermore, the functional specifications for a pan-European DT aim to build a strong and resilient system. The implementation of the TwinEU DT framework is led by effective methods shaped by functional and non-functional requirements and specifications. Consequently, the pan-European scenarios development is enabled by connections between local DTs, a very intuitive user interface, a set of comprehensive services for all system operations, data source interaction and storage, as well as management, monitoring, and documentation.

Moreover, the key functional specifications for the pan-European DT design include specifications of data integration, exchange and storage, interoperability between the systems, monitoring, compliance with European Standards and Regulations, and scenarios simulation.

At its core, a set of detailed functional requirements is derived based on the use cases (UCs) and the needs of stakeholders, domain experts, and demonstrators defined in WP2. The defined FURs are in the range from business to systematic. Sets of non-functional requirements are determined in a way that one set describes the whole TwinEU Federated DT system, while the other set is meant for the DEMOnstrator level. In this way, all the parts of the TwinEU project are well-defined and represented in detail. Finally, the regulatory environment is formed by the applicable EU and national regulations and laws, as well as internal policies and procedures.

2.2 Results and achievements of other major Horizon projects

The definition of the TwinEU functional specifications was also based on an in-depth analysis of the most relevant European projects in the energy field, which were identified within WP2. Among these, the European projects OneNet [7] and Enershare [23] provided essential contributions, especially in terms of functional (FUR) and non-functional (NFUR) requirements, already consolidated and validated at European level. The insights and results gathered from these projects provided a solid basis for the definition of the functional specifications of the TwinEU Federated DT platform.

A particularly valuable outcome of the OneNet project was the definition of General System Use Cases (GSUCs), which describe representative operational scenarios for the European energy system. Many of these GSUCs have been revised, adapted and integrated into the TwinEU project to align with its specific objectives and to better meet the needs of the market and the European energy network. In parallel, some general functional requirements defined in OneNet were also updated and incorporated into the TwinEU architectural framework. Particular attention was given to aspects such as federation, semantic interoperability and integration with data spaces. These elements are fundamental to support a distributed, collaborative and scalable architecture, which is at the core of the TwinEU project vision.

The analysis of the FURs and NFURs of OneNet and Enershare helped to identify common challenges and essential functionalities for the design of the TwinEU federated DT platform. The adaptation and integration of these pre-existing requirements not only accelerated the specification process but also reduced the risks and increased the reliability of the reference architecture.

The inclusion of the knowledge and solutions from the previous Horizon projects, particularly OneNet and Enershare, represents a significant step in shaping the functional specifications in TwinEU project. These projects have already addressed numerous technical and organisational challenges and serve as foundation for further innovations throughout TwinEU project. Relying on the previously validated and tested results facilitates the effective resolution of challenges in modelling requirements and GSUCs of pan-European DT design. Additionally, this method of including notable achievements of other European project in the energy domain, ensures that TwinEU project is built on past successes while avoiding previous drawbacks.

2.3 Results and findings from Stakeholders Business Use Cases

This section presents a consolidated overview of the demonstrator needs, stakeholder groups, and business use cases that inform the design of the TwinEU Federated DT system. The content and findings are primarily based on the work reported in Deliverable 2.2 "*TwinEU Use Cases, Pan-European Scenarios and KPIs*" [19], and Deliverable 3.1 "*TwinEU Open Reference Architecture*" [20]. These relevant inputs provide a critical foundation for deriving functional specifications that are grounded in the real operational contexts and business challenges faced by the stakeholders involved in TwinEU.

2.3.1 Demonstrators' needs

The demonstrators involved in the TwinEU project exhibit diverse requirements driven by distinct national energy frameworks, digitalization levels, and operational challenges. Key identified needs across the eight demonstration pilots include:

- **Advanced Grid Monitoring and Control:** Essential for real-time visualization and monitoring of transmission and distribution networks using SCADA systems, sensors, and smart meters, notably emphasized by Germany, Hungary, and Bulgaria.
- **Forecasting and Optimization:** Deployment of advanced AI-driven forecasting tools for renewable energy generation (wind and solar), grid conditions, and dynamic line rating (ampacity) to improve grid operations and optimize resource allocation, prominently featured in Bulgaria and Iberia.
- **Congestion Management and Flexibility:** Implementing proactive and reactive congestion management solutions and optimally leveraging distributed flexibility resources to mitigate grid constraints, especially prioritized by Germany, Eastern- Mediterranean, and Bulgaria.
- **Market Innovation and Integration:** Enhancing market functionalities through co-optimization techniques, capacity allocation, local flexibility markets, and integrating novel market products, strongly highlighted in the Hungarian and Iberian pilots.
- **Cybersecurity and Resilience:** Developing robust mechanisms for cyberattack detection, prevention, and resilience evaluation, particularly crucial in the Dutch/French pilot, with broader implications for operational security across other demonstrators.

- **Cross-border Coordination and Interoperability:** Facilitating data exchange, regulatory alignment, and operational harmonization to enable a federated, pan-European energy system, critical to Iberian and Eastern-Mediterranean pilots.
- **Asset Management and Maintenance**: Utilizing digital twins for proactive maintenance planning, infrastructure validation, and simulation-based system security and defense strategies, a focal point for the Italian and Slovenian pilots.

Addressing these varied and practical demonstrator needs ensures that the TwinEU DT system effectively supports both immediate operational optimization and long-term strategic planning.

2.3.2 Users' overview

The successful implementation of the Pan-European Digital Twin (DT) system within the TwinEU framework depends upon a complex ecosystem of diverse stakeholders, each contributing distinct requirements and operational insights. This section, informed by section 5.1 “TwinEU Actors” from Deliverable 3.1 TwinEU Open Reference Architecture, delineates these stakeholder groups and highlights their relevance to specific demonstration pilots, thereby informing targeted functional specification development.

Main Actor Groups and Their Roles:

- **Transmission System Operators (TSOs):** Responsible for operating and developing transmission networks, ensuring grid stability and facilitating interconnections with distribution networks and cross-border entities (Bulgarian, Eastern Mediterranean Greek, Hungarian, Iberian, Italian, Slovenian, Dutch).
- **Distribution System Operators (DSOs):** Manage local distribution networks, integrate distributed energy resources (DERs), and play a key role in market facilitation and congestion management (Bulgarian, German, Eastern Mediterranean Cyprus, Eastern Mediterranean Greek, Iberian, Italian, Slovenian).
- **Market Operators (MOs):** Coordinate energy and flexibility markets, matching supply and demand, and integrating congestion management services (Eastern Mediterranean Cyprus, Eastern Mediterranean Greek, German, Hungarian, Iberian).
- **Flexibility Service Providers (FSPs)/Balancing Service Providers (BSPs):** Aggregate distributed resources to offer flexibility and balancing services for congestion management and frequency response (Eastern Mediterranean Cyprus, Eastern Mediterranean Greek, German, Iberian).
- **Distributed Energy Resources (DERs):** Include renewable generation, storage, and demand response assets at distribution level, actively contributing to grid services (Eastern Mediterranean Greek, Italian).
- **Asset Owners/Customers:** Users or owners of physical/digital assets, utilizing DTs for monitoring and management (German).
- **Home Energy Management System (HEMS) Providers:** Optimize residential energy usage and support grid balancing needs (German).
- **Data Exchange Platform Operators (DEPOs):** Ensure secure data exchange and interoperability across stakeholder platforms (German, Slovenian).
- **Digital Twin (DT) Operators:** Conduct reliability analysis and contingency assessments to ensure system resilience (Iberian).
- **High-Voltage Direct Current (HVDC) Operators:** Manage high-voltage DC interconnections, facilitating secure interregional power transfers (Eastern Mediterranean Cyprus).

- **Metering Point Operators (MPOs):** Maintain smart meters and provide accurate operational data (German).
- **Measuring Device Providers (MDPs):** Install and maintain monitoring equipment for real-time grid data collection (German).
- **Weather Data Suppliers (WDS)/Weather Forecast Providers (WFPs):** Provide critical data for accurate forecasting and operational optimization (German, Belgian).
- **Regional Security Coordinators (RSCs):** Coordinate cross-border grid reliability and operational alignment among TSOs (Eastern Mediterranean Cyprus).
- **Regulatory Authorities:** Oversee market operations, compliance monitoring, and system security regulation (Eastern Mediterranean Greek).
- **Academic Institutes:** Facilitate DT model development and validation, enhancing operational capabilities and research dissemination (Dutch, Hungarian).
- **Research Centres:** Engage in advanced R&D and support innovative DT applications (Iberian).
- **Information Technology (IT) and Software Providers:** Supply DT systems with integration tools, debugging, and advanced functionalities (Belgian, Hungarian, Iberian).
- **Smart Assistant Developers (SADs), Trainees, Trainers:** Develop and utilize DT-based training modules for improved operational performance (French).
- **End Users/Prosumers:** Residential, commercial, and industrial participants interacting with DT-enabled market and grid interfaces (All pilots, notably German, Italian, Iberian).

2.3.3 Overview of TwinEU Business Use Cases

The TwinEU project has identified a comprehensive set of Business Use Cases (BUCs) that form the backbone of its DT system design. These BUCs, systematically documented using the IEC 62559-2 template, address business priorities across all demonstration sites and ensure alignment with project goals. This overview draws on Section 5.4 of Deliverable 2.2: TwinEU Use Cases, Pan-European Scenarios and KPIs, and Section 5 of Deliverable 3.1: TwinEU Open Reference Architecture.

Scope and Domains:

The BUCs span several strategic business domains:

- **Data Exchange and Enhanced Forecasting:** Secure, interoperable data sharing between DTs and advanced AI-driven forecasting for renewables and grid status (Bulgarian, Iberian, German, and Slovenian pilots).
- **Cybersecurity and System Stability:** Real-time cyberattack detection, impact analysis, and stability assessments to strengthen operational resilience (Dutch-French, German, and Slovenian pilots).
- **HVDC and Renewable Integration:** Advanced forecasting, HVDC operational management, and resilience in cross-border and island grids (Eastern Mediterranean, Italian, Slovenian pilots).
- **Flexibility and Congestion Management:** Aggregation and activation of distributed flexibility resources for congestion management, balancing, and market participation (German, Iberian, Hungarian, Bulgarian, and Slovenian pilots).
- **Integration of Distributed Energy Resources (DERs):** Network planning, simulation-based validation, and local market mechanisms for high DER integration (Italian, Slovenian, French, and German pilots).

BUC Hierarchy and Business Alignment:

The BUCs are organized hierarchically, from high-level, pan-European scenarios down to specialized and individual pilot cases, to ensure both broad systemic impact and local relevance. Each use case is mapped to specific business goals, regulatory drivers, and KPIs, guaranteeing that the DT system's functionalities directly serve the operational and commercial needs of all stakeholders.

Representative Examples:

- The **Bulgarian pilot** demonstrates AI-enhanced renewable forecasting and secure TSO/DSO data exchange.
- The **Dutch-French pilot** features DT-based cyberattack detection, resilience, and stability assessment for critical infrastructure.
- The **Eastern Mediterranean pilot** advances HVDC and renewables integration with forecasting and cross-border system support.
- The **German, Iberian, Hungarian,** and **Slovenian pilots** focus on dynamic congestion management, flexibility activation, local market integration, and advanced DER orchestration.
- The **Italian** and **Slovenian pilots** validate new DER integration strategies through simulation, digital twin-based planning, and only for Slovenian pilot cross-border grid security assessments.

In summary, the TwinEU BUCs serve as a blueprint for aligning technical development with real business processes and stakeholder expectations. Their breadth and hierarchical organization guarantee that the DT system addresses critical operational challenges, supports market innovation, and fulfils regulatory requirements across the diverse European energy landscape.

2.4 Methodological approach

The methodology presented in this section outlines the processes and techniques used to develop the Functional Requirements (FURs), Non-Functional Requirements (NFURs), and regulatory requirements for the TwinEU Pan-European DT design. This methodology provides guidelines on how the tasks and services should be performed. To develop tailored solutions for the TwinEU project, it is necessary to consider characteristics of the specific domain and the systems that include these NFURs, FURs, and regulatory requirements. All of these factors influence the selection of development options for the TwinEU system [2], so the process of their recognition and definition is described in detail in this documentation. It can be pointed out that a well-structured methodology for defining all requirements leads to a project that aligns business objectives, meets business and user needs, employs efficient methods, and adheres to legal standards.

Requirements (REQs) present key aspects of any software system. From the early stages of the development process, REQs are used to define the goals that need to be accomplished in the system [5]. The methodology of identifying functional and non-functional requirements, as well as the regulatory requirements, provides the core systematic framework for ensuring correct and efficient development and implementation of the project's services. REQs need to be clearly defined to ensure the success of the TwinEU project as they guarantee that the system's performance, objectives, and conditions are met. The structure of each methodology (for FURs, NFURs, and regulatory REQs) is illustrated and well-represented. The generalized approach for requirements elicitation and derivation is shown in the Figure 1. It can be concluded that while the procedures in these methodologies are general, they contain distinctive steps specific to each methodology and the desired outcomes are achieved by specifying well-defined steps to gather, derive, and analyse all the requirements.

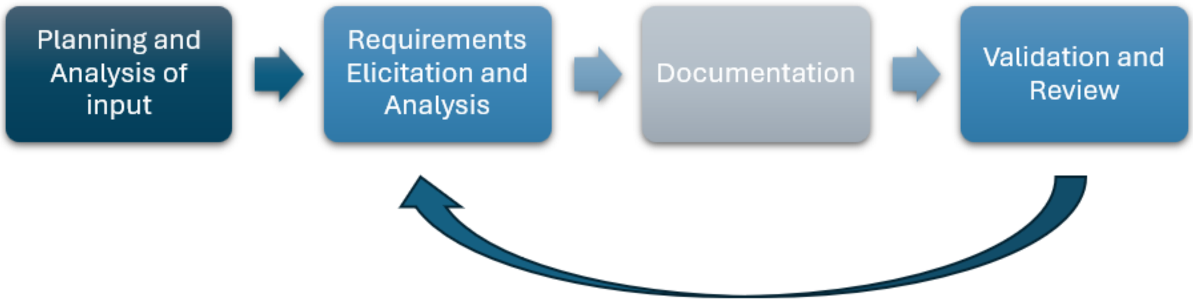


Figure 1 - Generalized methodological approach for deriving requirements

One of the critical domains for REQs methodology is requirements engineering (RE). RE is the field of deriving and documenting requirements. It considers system's objectives, functions, and constraints. RE is crucial for the quality of the project's software. The RE discipline defines organised, analytical, and recursive processes for requirement's completeness, consistency, and relevance [5]. The methodology for deriving REQs explained here is built to reduce the cost and time of creating the TwinEU system, as well as to improve the quality of the software [14].

Another interesting approach is the Automated requirements engineering (ARE), which holds great potential. There are various tools and techniques that can automate specific steps in the methodology for deriving requirements, optimizing processes and minimizing the time and effort required. ARE is an evolving field, with tools that are beginning to be widely adopted [5]. In the TwinEU project, some of these automated and semi-automated tools have been used, particularly those related to the Agile methodology (agile-friendly tools like GitHub[1] and Trello[2]) and automated diagram generation, such as PlantUML[3] and Draw.io[4]. Files related to the deriving of requirements are available in the TwinEU GitHub repository [68].

Moreover, there are different tools and techniques that could be used for FURs' and NFURs' elicitation processes [7]. The mechanisms that were recognised by several suites, instruments, and supporting tools for derivation and evaluation have been combined to create a suitable methodology. Some of the existing tools for automation of the requirement management processes have been evaluated and majority of them haven't been mature enough or not fully equipped to work with requirements, such as Gate[5] tool and spaCy[6] library. SpaCy is a powerful open-source Python library for Natural Language Processing (NLP). Users can define rules for extracting requirements, but derived requirements' candidates need to be reviewed, and it seems that not all requirements can be easily obtained from use cases. For most open-source tools, their engagement and endorsement by the broader public is not yet fully done. Nevertheless, the insights and processes provided by these tools are still considered during the derivation of the REQs. The advanced ideas and approaches were taken from these tools in order to create the best TwinEU methodology approach. Consequently, the software solutions that are based on the artificial intelligence are used as a support in analysis and formulating of the requirements.

[1] GitHub: Build and ship software on a single, collaborative platform, https://github.com/.
[2] Capture, organize, and tackle your to-dos from anywhere, https://trello.com/.
[3] PlantUML: a highly versatile tool that facilitates the rapid and straightforward creation of a wide array of diagrams, https://plantuml.com/.
[4] Browser-based diagramming tool that lets you create and share diagrams with anyone, https://app.diagrams.net/.
[5] Open-source software toolkit capable of solving almost any text processing problem, https://gate.ac.uk/.
[6] Industrial-Strength Natural Language Processing in Python, https://spacy.io.

Another concept under consideration is the interdependence between FURs and NFURs, indicating that they should not be regarded as entirely separate elements but rather addressed together. Moreover, reference architecture plays a pivotal role in the implementation of these requirements. The development and implementation of FURs, NFURs, and architectural decisions should thus be approached as components of a unified and integrated process [2].

An additional key aspect explored is requirement management. This essential process in project management involves the collection, analysis, tracking and monitoring of system requirements. The traceability and version control of the documents are also part of requirement management, as well as managing changes in the requirements [17]. Effective requirements management has a main role in project quality and success. Project teams need to have a methodical approach to gathering and tracking requirements. Requirements that are too detailed can increase defects and underutilisation of technology and tools. On the other hand, insufficiently described requirements may lead to conflicts and not using important functions. [17] All challenges in requirement management are important to be recognised. Some of them are requirement elicitation and management, rapid changes in requirements and refinements. If software and infrastructure are complex, these challenges are even bigger and good management practices are crucial to overcome all the issues. [17] The success of any project depends on the well-defined requirements that do not keep changing during the whole project lifecycle, especially in finishing stages. To prevent the project failure and create the system that users, stakeholders, and other actors expect, the REQs must be correctly defined. Furthermore, errors in the requirements phase certainly produce problems in the system design, architecture, and implementation [5].

Elicitation as the main step in defining the requirements, identifies REQs and deliberates with stakeholders, by decomposing the system, conducting the analysis with stakeholders and users, and defining main capabilities and operations. The decomposition process and operationalization process lead the refinement of requirements to achieve more detailed requirements [2].

One of the key components of the methodology presented in this document is the MoSCoW prioritization method. This technique represents four categories: must-have, should-have, could-have, and won’t-have. Must-have initiatives represent the core, mandatory needs of the project. Should-have category requirements are also essential, but the project’s system can function without them as they are not vital functionalities. Could-have initiatives are not necessary for the project. They have a smaller impact on the project than should-have category of requirements. The “will-not-have” category requirements do not have to be included in a given release, and they are not a priority.

The methodology outlined in this section and its subsections is aligned with the well-known processes, where elicitation, negotiation, analysis, documentation, validation and management as a whole are the key aspects of requirement engineering. Interview, Observation, Analysis, Focus Groups, Brainstorming, Prototype of the system, JAD Session (Joint application design), Prioritization of Requirements are main gathering activities that are connected to interaction with stakeholders and users, as well as definition of the system needs [4]. In the TwinEU project, detailed methods for requirements elicitation (REQs) have been followed, ensuring a structured and iterative approach involving users, stakeholders, architects, and developers. These parties, which are part of WP2, WP3 and WP4, collaborated in creating User Stories, Use Cases, and defining all requirements from the early stages of the project. This process has aligned the project's scope with high-quality planning, improving overall performance. The chosen methodology led to the definition of complete, concise, accurate, and verifiable specifications, minimizing common risks such as miscommunication with stakeholders or changes to requirements very late in the project.

2.4.1 Methodology for deriving Functional Requirements

URs, as it is well-established in the literature, represent what the system should do to meet the user's needs. In other words, they define what the system is required to accomplished and what its functionalities are. FURs express the desired behaviour of system. This behaviour is composed of services, tasks, and functions that the system should execute [5]. FURs are typically derived from System Use Cases (SUCs) and are essential for ensuring that the system's design aligns with user scenarios and objectives, thereby enhancing the DT system's relevance, usability, and operability.

In the context of the TwinEU project, FURs are systematically derived from SUCs to ensure that the system supports the objectives of the users and stakeholders. A structured, iterative approach is employed to guarantee that these requirements are comprehensive, clear, and achievable. This process includes detailed analysis of business processes, stakeholder involvement, and precise documentation of the system's expected behaviours.

The following subsections outline the methodological approach used in WP3 to derive FURs, focusing particularly on two types of FURs: General Functional Requirements (GFURs) and DEMO functional requirements (DEMO FURs).

All FURs have been reported in this deliverable according to the following format to ensure clear understanding and ease use in the subsequent phase of the TwinEU project: Requirement ID, Name, Description, Related Use Case(s), and Note, as it is shown in Table 1.

Table 1 - FURs documentation format

Requirement ID	Name	Description	Related Use Case(s)	Note
DT-O&M-06-GE-04	Detection of Congestion Points	The system must detect and highlight potential congestion points within the grid.	Ge03	Demonstration of digital twinning for grid management, operation and monitoring, German pilot
DT-SC&PG-03&04-IB-63	Flexibility Service Provider (FSP) Prequalification for Neighbouring System Operators (SOs)	The system must facilitate the prequalification of Flexibility Service Providers (FSPs) to provide flexibility to neighbouring System Operators (SOs) where they have no direct connection.	Ib14	Demonstrations of digital twinning for smart coordinated planning of the grid, Iberian pilot

2.4.1.1 Methodology for defining General Functional Requirements based on General SUCs

GFURs are derived from high-level specifications of the core interconnections and tasks in the TwinEU DT Federated platform. These specifications, reported in Section 2.5.3 defined as General System Use Cases (GSUCs), are essential for achieving the project's objectives, business processes and goals. These GSUCs represent key elements for defining GFURs, guiding the system's design and ensuring alignment with user needs and project requirements.

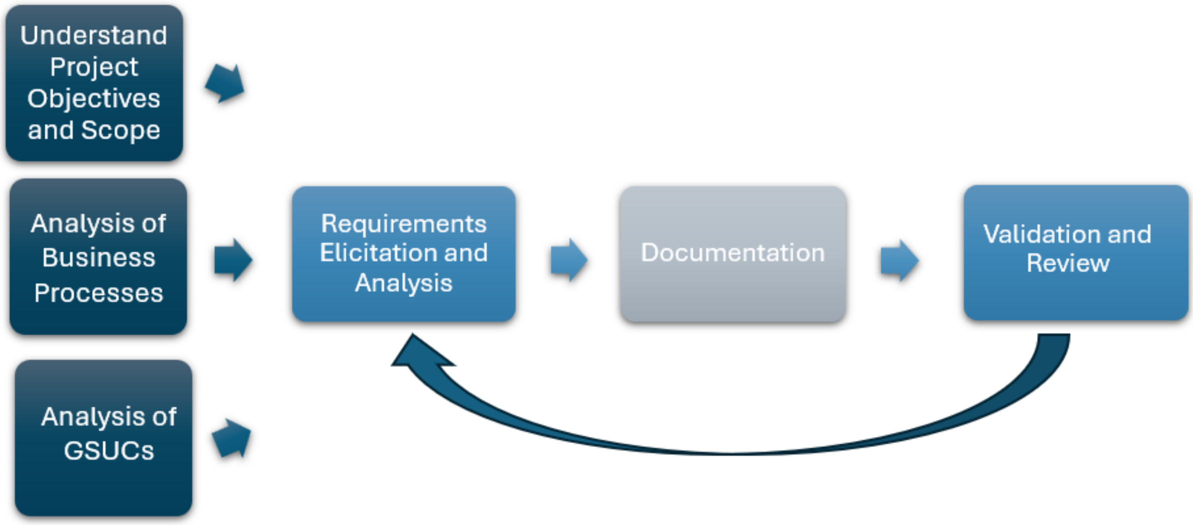


Figure 2 - Methodology steps for deriving General Functional Requirements

The methodology for defining GFURs from GSUCs for the Pan-European Digital Twin (DT) design describes in detail the process of examining, decomposing and assessing GSUCs as well as the whole TwinEU Federated DT system. As illustrated in Figure 2 the methodology consists of several key steps, which can be outlined as follows:

- Planning
    - Understand Project Objectives and Scope – Examine and analyse all the documentation about the project and review project objectives, business vision, and strategic goals.
    - Analyse Business Processes and General System Use Cases – Identify main inputs, outputs, aspects, procedures, and actions to better understand business processes that shape GSUCs
- Requirements Elicitation and Analysis
    - Identify Stakeholders and User Requirements – Recognise the key stakeholders and conduct exploration sessions with stakeholders, users and developers to better understand their needs and requirements.
    - Decompose the system into functional areas, modules, or components based on its architecture, domain areas, or user roles.
    - Identify the main functional areas or modules that represent the main capabilities, operations, and features of the TwinEU Federated DT system, such as data management, user management, reporting, analysis, and integration.
    - Conduct Functional Decomposition: Break down high-level functions into detailed sub-functions.
    - Perform System Use Cases Decomposition into key parts.
    - Map GSUCs components to functionalities to define functional requirements, having in mind the derived system modules.
    - Prioritize functional requirements based on their importance to achieving project goals, meeting stakeholder needs, and delivering value to end-users. Use techniques such as MoSCoW or value vs. effort analysis to prioritize requirements effectively.

- Documentation and Specification
  - Document functional requirements in a structured format, such as use case diagrams or textual descriptions, to precisely describe the desired system behaviours and functionalities.
  - Organize functional requirements into categories or modules based on the system's architecture, domain areas, or user roles for clarity and manageability. Group related requirements together to facilitate understanding, analysis, and traceability throughout the project lifecycle.
- Validation, Verification, Review
  - Validate and verify functional requirements with stakeholders, architects, developers, and domain experts to ensure they accurately reflect stakeholder needs and are feasible to implement. Furthermore, gathered requirements should fulfil the project’s objectives by reviewing all the relevant documentation [5].
  - Refine and iterate by deriving the REQs in cyclic processes, filter and clear the definitions, and consult with all involved actors. The new iteration can be also invoked by newly developed insights or modified business and user needs.

Requirement management takes care of all modifications, tracks changes in requirements and makes sure that those changes have been made to meet stakeholder’s needs.

2.4.1.2 Methodology for defining Demo Functional Requirements based on Demo SUCs

The methodology for defining DEMO FURs built upon Demonstrator System Use Cases (DEMO SUCs) is the process that enables deriving concrete, distinct and well-defined requirements from the description of these main system functionalities and objectives. This procedure is essential for the successful development and implementation of the TwinEU DEMO DT systems. Together with GFURs it secures that all functionalities, needs and goals of the system are correctly realized, followed, tested, and used.

Analysis and understanding of SUCs is key for the methodology process. Understanding the needs and aims of the users and stakeholders is the bases for starting to develop precise and straightforward requirements. For each SUC, users, actions and systems modules that are involved in each use case are identified. Mapping the objectives of SUCs to functional requirements is the main part.

DEMO FURs have been defined through an iterative process able to accommodate any changes in SUCs, the addition of new SUCs, or modification in stakeholder needs. Furthermore, refinement and validation with users and stakeholders can trigger the SUCs correction.

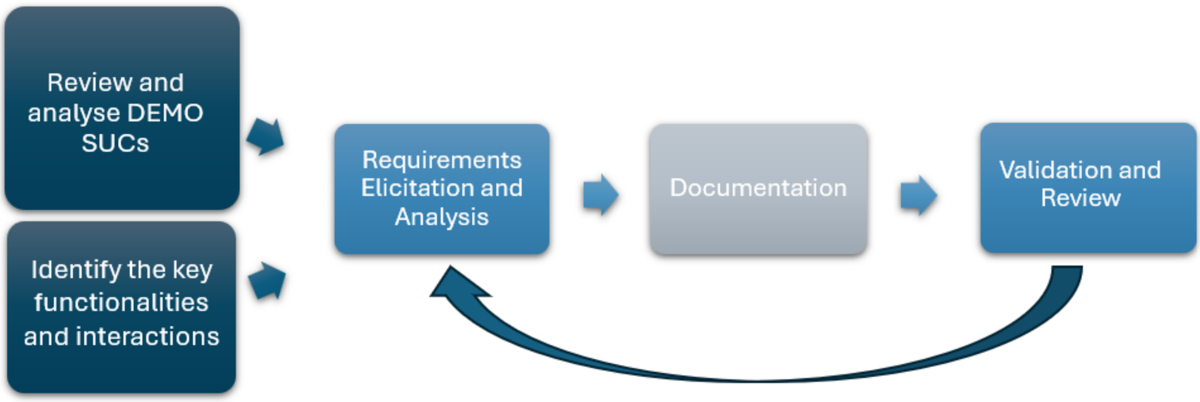


Figure 3 - Methodology for deriving DEMO FURs

As depicted in Figure 3 - Methodology for deriving DEMO FURs, the methodology used for deriving DEMO FURs consists of several key steps and sub-steps, which can be outlined as follows:

- Planning
  - Review Demonstration System Use Cases – Thoroughly examine the DEMO SUCs, their domain(s), scope, objectives and goals, descriptions, Key performance indicators (KPIs), use case conditions etc.
  - Identify the key functionalities and interactions required to support the demonstration scenarios described in the DEMO SUCs. These functionalities represent the fundamental capabilities that the system must exhibit during the demonstrations. – In short, after examining the UCs, deriving what are the main functionalities, behaviours, and aspects that are part of each SUC should be set in place.
- Requirements Elicitation and Analysis
  - Break down each Demonstration SUC into specific functional requirements that describe these functionalities, features, and actions and behaviours required to fulfil the goals of the demonstration scenario. Transfer the requirements indicated by each SUC into functional requirements that can be tested and used.
  - Specify Inputs, Outputs, and System Behaviour
  - Prioritize Functional Requirements – This is also an important step because it helps partners in the TwinEU project can focus on the most important and critical requirements that have the highest effect on the business goals, technical objectives, and user needs.
- Documentation and Specification
  - Document Functional Requirements – All FURs should be well-defined and documented, so that all involved stakeholders and partners that need to work with FURs, have clear understanding of the situation, version, composition, and structure of each DEMO FURs.
  - Organise Functional Requirements – FURs should be organized based on their domain and scope. They should be grouped not only based on the related SUCs but also based on the demonstrator which they belong to.
- Validation, Verification, and Review
  - Validate and Verify Requirements with Stakeholders and User – This phase in the deriving methodology is crucial so that the FURs are aligned with the stakeholders' goals and user needs. They can specify what their objectives are and if they are included into DEMO FURs.

- Refine and Iterate – It is the step that enables better clarification, improvement of the FURs and better fitting to the systems and stakeholder needs by doing refinements and do the definition of DEMO FURs in the iterative processes through the stages of project lifecycle.

Requirement management is present in all stages and is one of the crucial processes in defining requirements.

2.4.2 Methodology for deriving Non-Functional Requirements

The methodology for defining NFURs is a well-defined process aimed for deriving requirements in the most straightforward way, covering all key aspects. The requirements resulting from this procedure describe the TwinEU system's operational qualities, rather than its specific behaviours.

NFURs can be seen as a criterion for validating the project's services. Furthermore, reference architecture is greatly impacted by the NFURs. There are different approaches to NFUR elicitation and validation, and the need for standardized model is in the focus. The standard chosen to be greatly followed is ISO/IEC 25010:2023 [1]. It helps in not just preparation processes, but in the elicitation and categorization processes also.

ISO/IEC 25010:2023 is an international standard that specifies a quality model for systems and software. This standard gives a framework for evaluating and improving the quality of software products. It enables entities to systematically assess their software products in terms of various aspects of quality. The standard makes sure that the system meets both technical and user experience requirements.

ISO/IEC 25010:2023 is widely used to enhance system performance, security, reliability, scalability, maintainability, and usability, making it an essential tool for developing high-quality software solutions. This standard gives hierarchy of nine characteristics and their sub-characteristics that describe in detail quality properties of the software products. NFURs are derived based on the following categories and sub-categories [1], as shown in Figure 4:

- Functional suitability: Capability of a product to provide functions that meet stated and implied needs of intended users when it is used under specified conditions.
  - Functional completeness: Capability of a product to provide a set of functions that covers all the specified tasks and intended users' objectives.
  - Functional correctness: Capability of a product to provide accurate results when used by intended users.
  - Functional appropriateness: Capability of a product to provide functions that facilitate the accomplishment of specified tasks and objectives.
- Performance efficiency: Capability of a product to perform its functions within specified time and throughput parameters and be efficient in the use of resources under specified conditions. It is in regard with CPU, memory, storage, network devices, other software products and configurations, energy etc.
  - Time behaviour: Capability of a product to perform its specified function under specified conditions so that the response time and throughput rates meet the requirements
  - Resource utilization: Capability of a product to use no more than the specified amount of resources to perform its function under specified conditions

  - Capacity: Capability of a product to meet requirements for the maximum limits of a product parameter. It refers to the number of items that can be stored, concurrent users, the communication bandwidth, the throughput of transactions, and the size of a database.
- Compatibility: Capability of a product to exchange information with other products, and/or to perform its required functions while sharing the same common environment and resources.
  - Co-existence: Capability of a product to perform its required functions efficiently while sharing a common environment and resources with other products, without detrimental impact on any other product.
  - Interoperability: Capability of a product to exchange information with other products and mutually use the information that has been exchanged.
- Interaction capability: Capability of a product to be interacted with by specified users to exchange information between a user and a system via the user interface to complete the intended task.
  - Appropriateness recognizability: Capability of a product to be recognized by users as appropriate for their needs. The information can be provided through demonstrations, tutorials, documentation, home page.
  - Learnability: Capability of a product to have specified users learn to use specified product functions within a specified amount of time.
  - Operability: Capability of a product to have functions and attributes that make it easy to operate and control.
  - User error protection: Capability of a product to prevent operation errors.
  - User engagement: Capability of a product to present functions and information in an inviting and motivating manner encouraging continued interaction.
  - Inclusivity: Capability of a product to be utilised by people of various backgrounds.
  - User assistance: Capability of a product to be used by people with the widest range of characteristics and capabilities to achieve specified goals in a specified context of use.
  - Self-descriptiveness: Capability of a product to present appropriate information, where needed by the user, to make its capabilities and use immediately obvious to the user without excessive interactions with a product or other resources.
- Reliability: Capability of a product to perform specified functions under specified conditions for a specified period of time without interruptions and failures.
  - Faultlessness: Capability of a product to perform specified functions without fault under normal operation.
  - Availability: Capability of a product to be operational and accessible when required for use.
  - Fault tolerance: Capability of a product to operate as intended despite the presence of hardware or software faults.
  - Recoverability: Capability of a product in the event of an interruption or a failure to recover the data directly affected and re-establish the desired state of the system.
- Security: Capability of a product to protect information and data so that persons or other products have the degree of data access appropriate to their types and levels of authorization, and to defend against attack patterns by malicious actors.
  - Confidentiality: Capability of a product to ensure that data are accessible only to those authorized to have access.

  - Integrity: Capability of a product to ensure that the state of its system and data are protected from unauthorized modification or deletion either by malicious action or computer error.
  - Non-repudiation: Capability of a product to prove that actions or events have taken place, so that the events or actions cannot be repudiated later.
  - Accountability: Capability of a product to enable actions of an entity to be traced uniquely to the entity.
  - Authenticity: Capability of a product to prove that the identity of a subject or resource is the one claimed.
  - Resistance: Capability of a product to sustain operations while under attack from a malicious actor.
- Maintainability: Capability of a product to be modified by the intended maintainers with effectiveness and efficiency.
  - Modularity: Capability of a product to limit changes to one component from affecting other components.
  - Reusability: Capability of a product to be used as assets in more than one system, or in building other assets.
  - Analysability: Capability of a product to be effectively and efficiently assessed regarding the impact of an intended change to one or more of its parts, to diagnose it for deficiencies or causes of failures, or to identify parts to be modified.
  - Modifiability: Capability of a product to be effectively and efficiently modified without introducing defects or degrading existing product quality.
  - Testability: Capability of a product to enable an objective and feasible test to be designed and performed to determine whether a requirement is met.
- Flexibility: Capability of a product to be adapted to changes in its requirements, contexts of use, or system environment.
  - Adaptability: Capability of a product to be effectively and efficiently adapted for or transferred to different hardware, software or other operational or usage environments.
  - Scalability: Capability of a product to handle growing or shrinking workloads or to adapt its capacity to handle variability.
  - Installability: Capability of a product to be effectively and efficiently installed successfully and/or uninstalled in a specified environment.
  - Replaceability: Capability of a product to replace another specified product for the same purpose in the same environment.
- Safety: Capability of a product under defined conditions to avoid a state in which human life, health, property, or the environment is endangered.
  - Operational constraint: Capability of a product to constrain its operation to within safe parameters or states when encountering operational hazard.
  - Risk identification: Capability of a product to identify a course of events or operations that can expose life, property or environment to unacceptable risk.
  - Fail safe: Capability of a product to automatically place itself in a safe operating mode, or to revert to a safe condition in the event of a failure.
  - Hazard warning: Capability of a product to provide warnings of unacceptable risks to operations or internal controls so that they can react in sufficient time to sustain safe operations.

- Safe integration: Capability of a product to maintain safety during and after integration with one or more components.

Figure 4 - ISO/IEC 25010:2023 Quality model characteristics

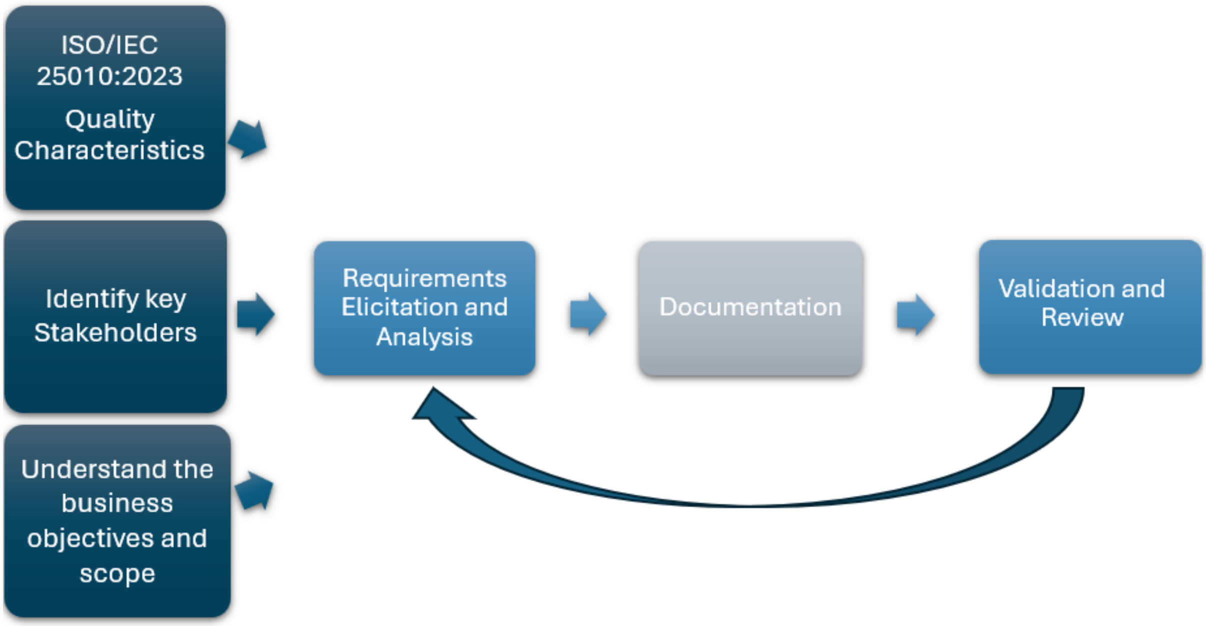


Figure 5 - Methodology steps for deriving Non-Functional Requirements

Figure 5 illustrates the approach used for deriving NFURs, which are described as follows:

- Planning

- Understand ISO/IEC 25010:2023 Quality Characteristics: Familiarize with the nine quality characteristics defined in ISO/IEC 25010.
- Identify key Stakeholders and conduct meetings – Identify all key participants: system architects, developers, domain experts, legal teams, end users, business analysts, compliance officers etc.
- Understand the business objectives, scope, KPIs, user needs, and scenarios that will be considered.

- Requirements Elicitation and Analysis
  - Map DEMO SUCs to ISO/IEC 25010 Characteristics: Analyse each DEMO SUC and identify which ISO/IEC 25010 quality characteristics are relevant to the scenario
  - Translate ISO/IEC 25010 Characteristics into Requirements: For each relevant quality characteristic, translate the general concept into specific non-functional requirements that address the needs of the DEMO SUCs. Use the ISO/IEC 25010:2023 standard as a reference to ensure that the derived requirements align with established best practices and terminology.
  - Specify Measurable Criteria: Define measures, benchmarks, and acceptance standard for each non-functional requirement to enable objective evaluation and validation during the demonstrations. Ensure that the criteria are specific, measurable, achievable, relevant, and time-bound (SMART).
  - Prioritize non-functional requirements – Priority can be critical, high, medium, or low. If necessary, the priority can be emphasised in the definition of REQ.
- Documentation and Specification
  - Document Non-Functional Requirements – The standardized format is used: Unique Requirement ID, Name, Category, Subcategory, Description. In the Description section is written what the requirement ensures and if the NFUR relies on other requirements.
  - Organize Non-Functional Requirements
- Validation, Verification, and Review
  - Validate and Verify with Stakeholders – Review of the documented NFUR is done together with stakeholders, architects, domain experts, and developers
  - Refine and iterate – This step is crucial to ensure that the NFURs stay relevant and aligned with system needs that can be changed/evolving. Measurement criteria can be refined, priorities should be adjusted if conditions are changed, and REQs should be refined if system services are modified.

Effective requirement management improves the project's distinctness and ensures that the final TwinEU system meets all the goals.

NFURs are documented in this deliverable in the following format:

Table 2 - NFUR documentation format

Requirement ID	Name	Category	Subcategory	Description
DEMO_NFUR_01	Efficient Large-Scale Data Processing and Integrity	Performance Efficiency	Resource Utilization	The system must handle large datasets (large volumes of data) efficiently, without performance degradation. The system must be able to

				handle large volumes of data without compromising the accuracy of the exchanged information.
DEMO_NFUR_02	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.

2.4.3 Methodology for defining Regulatory Requirements

Regulatory requirements refer to legal or industry regulations, directives and standards that the system must comply with. This process represents another important aspect considered in the definition of the TwinEU system requirements, aiming at aligning the project with compliance criteria of regulations, directives and standards, with main reference to the Energy domain.

In particular, the process included a phase of identification and analysis of the relevant standards, regulations, and directives, both at the European national and regional levels, for the design of the Pan-European Federated DT (WP2 input), along with a series of interviews and questionnaires distributed to the stakeholders. In the questionnaire "Regulatory Requirements and Cybersecurity and Data Protection Questionnaire" is used structured format that clearly divides each part of the questionnaire according to thematic sections and numbered questions. Three logical sections used are: "General Information", "Analysis of Regulatory and Cybersecurity Environment in the chosen project", and "Regulatory and Cybersecurity Requirements Identification in TwinEU project". Questions are easy to follow and reference. Open-ended questions enable high-quality answers. The concept of questionnaire encourages participants to be as much involved in data gathering as possible.

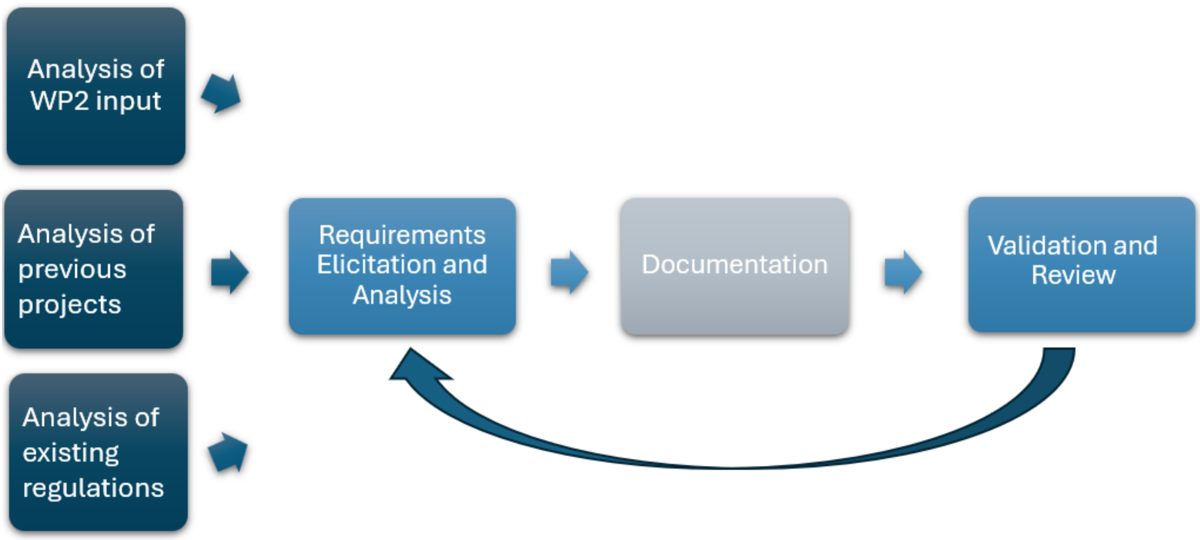


Figure 6 - Methodology for deriving Regulatory Requirements

As shown in Figure 6, the methodology is composed of several essential steps, which can be summarized as follows:

- Planning
  - Analysis of the WP2 input – WP2 input helps in finding all the requirements that are related to the TwinEU project. National and regional regulations and laws that the pilots mush adhere to, and the whole regulatory environment of the stakeholders and pilots should be analysed and considered for defining regulatory requirement on the TwinEU system level.
  - Analysis of the previous projects – Analysis of steps taken by other Smart Grid projects. The projects have been chosen by their effect on energy system optimization and innovations in smart grid. Fields such as digital twins, cybersecurity, and interoperability should be covered by these projects. Furthermore, it is preferable that the scope of the project is spanning across several European countries.
  - Analysis of the existing regulations and directives – All the regulations, directives, codes, and laws that are connected to energy market and energy infrastructure, data protection, sustainability, data privacy etc. should be closely analysed.
- Requirements Elicitation and Analysis
  - Definition of the list of regulatory requirements required – After analysis in the first step, go through all the potential requirements and select appropriate ones that shape the TwinEU system. The list should include all requirements relevant to the TwinEU projects ecosystem.
  - Define internal compliance policies and procedures – Internal policies and procedures are mandatory to enable compliance with all the regulations, directive, standards, codes, and laws. TwinEU internal compliance processes should be carefully specified, aligned with the regulatory requirements previously generated.
  - Analysis of each needed regulatory requirement identified – Evaluation and breakdown of all REQs that are considered and included into the regulatory environment for the TwinEU project. Examination of the effect of selected regulatory REQs on the TwinEU Federated DT platform should be done.
  - Prioritize Regulatory requirements
- Documentation and Specification
  - Document Regulatory Requirements – This step includes maintaining traceability for these REQs.
  - Organize Regulatory Requirements – They can be grouped based on the sector/area of interest.
- Validation, Verification, and Review
  - Validate with domain experts and internal and external legal teams, to ensure local and EU regulations alignment.
  - Refine and iterate – Follow all modifications and new versions of national and EU laws, codes, directives and standards. Make sure that internal policies and procedures are up-to-date.

Continuous management of the requirements during all iterations is necessary.

2.5 Definition of TwinEU Requirements and Specification

2.5.1 TwinEU open reference architecture

This section reports the final version of the TwinEU Open Reference Architecture, as defined and consolidated in Deliverable 3.1 [20].

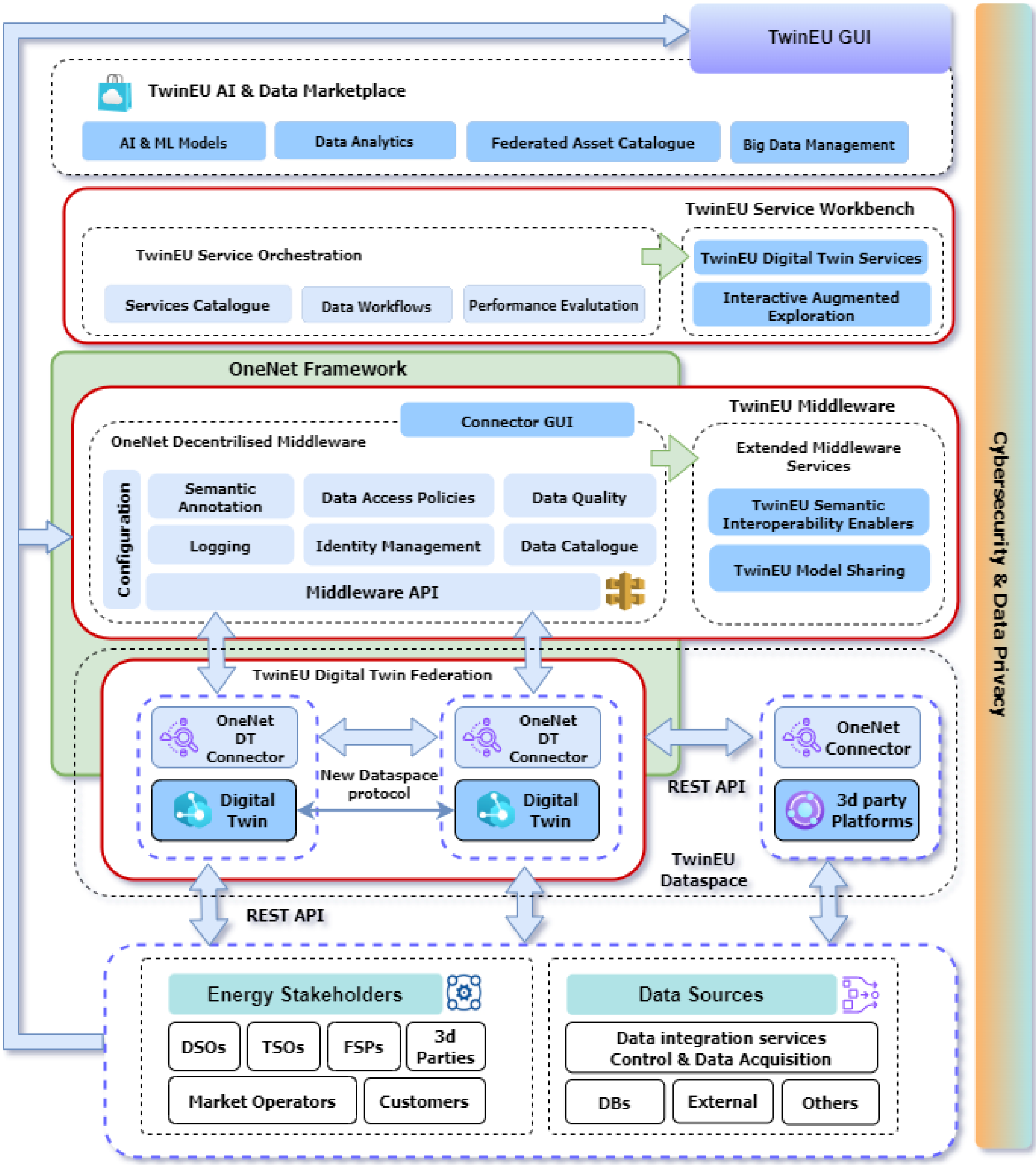


Figure 7 - TwinEU Reference Architecture (v1.0)

The development of the TwinEU Open Reference Architecture was part of an iterative and parallel process, carried out in close coordination with the definition of functional requirements, non-functional requirements, regulatory requirements, as well as the identification of cybersecurity, data privacy, and technical specifications.

It is important to underline that these activities followed a bidirectional approach, where the architectural design evolved alongside the progressive definition of requirements and specifications.

In this process, the evolving system architecture provided guidance and constraints for finalising requirements, while the requirements themselves informed architectural choices, ensuring consistency and technical feasibility.

Figure 7 shows the final version of the TwinEU Open Reference Architecture, which represents a coherent and integrated framework aligned with European standards and designed to enable federation, data space integration, interoperability, DT model exchange, and scalability. The architecture is aligned with the System Use Cases, the functional, non-functional, and regulatory requirements, as well as the technical specifications, including those related to cybersecurity and data privacy, ensuring consistency across the entire system design and implementation process.

2.5.2 TwinEU Demo Use Cases analysis results

This section provides a detailed examination of the demonstrator Use Cases (UCs) specific to the TwinEU project. Identifies key Demonstrator UCs that represent various practical scenarios and interactions within the DT ecosystem.

The area of application for each set of UCs is determined by the Work Packages they are aggregated into, having demo UCs for:

- **Cyber-physical grid resilience** (WP5, participating pilots: Dutch-French, Iberian and Eastern-Mediterranean).
- **Grid management, operation and monitoring** (WP6, participating pilots: Italian, German, Slovenian and Hungarian).
- **Forecasting and optimal grid and market actions** (WP7, participating pilots: Eastern-Mediterranean, Hungarian, Bulgarian and Slovenian).
- **Smart coordinated planning of the grid** (WP8, participating pilots: Iberian and Dutch-French).

2.5.2.1 Cyber-physical grid resilience DEMO UCs

The Use Cases (UCs) demonstrating the use of digital twins for cyber-physical grid resilience aim at:

- developing scenarios for impact analysis of cyber-attacks;
- developing metrics to quantify the ability of power grid to withstand disruptive events at both cyber-physical layers;
- demonstrating methods to safeguard dynamic stability performance and increase grid operational resilience at TSO-DSO levels;
- propose abnormal market participation detection mechanisms and define protocols to be activated upon these triggers;
- develop training simulator for SOs to response to critical situations.

The defined UCs for addressing the identified objectives and challenges are:

- NL01: DT-enabled real-time cyberattack detection and impact analysis on the operation of integrated power grid
- FR01: Power system training simulator for complex and critical situations
- Ib04: Abnormal market participation detection and protocol activation for mitigating the risk and consequences
- Ib12: Integration of TSO-DSO-MO-Prosumer market coordination

All four UCs contribute to enhancing cyber-physical grid resilience by addressing distinct vulnerabilities across technical, operational, and market layers. In the Dutch Pilot, the deployment of Digital Twin (DT)-enabled real-time cyberattack detection and impact analysis strengthens the grid's capacity to identify, assess, and respond to cyber threats before they affect physical operations. In French Pilot, a power system training simulator prepares operators to handle complex and critical scenarios, enhancing human decision-making and organizational readiness during emergencies. In the Iberian Pilot, the detection of abnormal market participation combined with automated protocol activation mitigates risks arising from compromised or manipulative behaviour in Local Flexibility Markets, while the integration of TSO-DSO-MO-Prosumer coordination ensures secure, synchronized interactions across the system. Together, these initiatives reinforce the resilience of the European electricity system by combining advanced digital tools, real-time response capabilities, secure market frameworks, and skilled operational management.

2.5.2.2 Grid management DEMO UCs

The UCs demonstrating the use of DTs for grid management, operation and monitoring aim at:

- demonstrating the validation of assets and the benefits for the prequalification of flexibility resources and support the simulations of the defence system performances;
- building an end-2-end flexibility solution for all energy system parties, enhance grid planning procedures and allow a Dynamic monitoring of the grid;
- demonstrating advanced static and dynamic security assessment tools using AI;
- developing an ANN-based model as a digital twin of the applied line monitoring sensors.

The defined UCs for addressing the identified objectives and challenges are:

- Ge01: Utilization monitoring on LV-/MV-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 an efficient TSO-DSO data exchange on the interface level.
- Ge08: Visualizing hosting capacities within Connection request and online connection check applications.
- Hu01: Digital twin for power line monitoring
- 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-BUC-1: Dynamic RMS Analysis with Upgraded Transmission System Model
- SLO-BUC-2: Real-time Dynamic RMS Analysis with Transmission System Model improved with the dynamic parameters of generators and control models of the neighbouring TSOs

The set of UCs across the German, Hungarian, Italian, and Slovenian pilots valorise the use of DTs for enhancing grid management, operation, and monitoring through targeted innovations in visibility, control, coordination, and system modelling. In Germany, UCs such as utilization monitoring at LV/MV levels, state estimation under changing topologies, and advanced tools for congestion management improve situational awareness and operational responsiveness. Preventive congestion strategies, household-level flexibility aggregation via HEMS, and regional flexibility aggregation optimize grid usage while reducing stress on infrastructure. Furthermore, the conceptualization of interoperable TSO-DSO data exchange and visualization of hosting capacities enhance coordination and facilitate streamlined grid connection processes. The Hungarian pilot adds value with a digital twin for power line monitoring, enabling continuous condition assessment of infrastructure. The Italian pilot advances system-level resilience and operational planning through digital twin-based analysis of the TSO defence system, evaluation of aggregated DER behaviour during grid events, and scalable DT applications for design validation and data modelling. Lastly, the Slovenian pilot strengthens dynamic grid modelling with RMS analysis and real-time simulations incorporating detailed generator dynamics and inter-TSO control interactions. Collectively, these UCs reinforce grid stability, efficiency, and adaptability in the face of increasing complexity and decentralization.

2.5.2.3 Forecasting and optimal grid and market actions DEMO UCs

The UCs demonstrating the use of digital twins for forecasting and optimal grid and market actions aim at improving the forecasting operations and the related planning and market processes by evaluating the resilience of HVDC interconnection of Greece and Cyprus and the provision of fast response services in Slovenia.

The defined UCs for addressing the identified objectives and challenges are:

- BG01: establishment of the data exchange between the Digital Twins
- BG02: AI-Improved Forecast of Wind Power Plants (WPPs) Production
- BG03: AI-Improved Forecast of Solar Power Plants (SPP) Production
- BG04: AI-Improved Forecast of Overhead Lines (OHL) Ampacity
- BG05: Increase of power flow on cross border transmission lines
- BG06: Determination of optimal locations for RES connection
- BG07: N-1 assessment on the DT level
- BG08: DT-based Maintenance plan of TSO grid
- BG09: Flexibility Requirements to Avoid Congestions
- BG10: Inter-SO Flexibility Exchange
- 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
- EM-CY-01: Congestion management in distribution grids through ancillary services
- EM-CY-02: Frequency support management of HVDC-interconnected systems at a regional level
- Hu02: Enhanced flow-based capacity calculation for market co-optimization using DLR data
- Hu03: Co-optimizing the day-ahead and intraday energy and balancing capacity market
- SLO-BUC-3: Power system analysis tool retrieves operational data from SCADA/EMS

The UCs across the Bulgarian, Eastern Mediterranean, Hungarian, and Slovenian pilots collectively enhance forecasting accuracy and enable more effective, data-driven grid and market actions. In

Bulgaria, the establishment of data exchange between Digital Twins forms the foundation for integrated system forecasting and coordination. AI-driven forecasting for wind and solar generation, as well as overhead line ampacity, improves prediction precision and grid reliability. UCs on N-1 contingency assessment, maintenance planning, and optimal RES siting enable proactive infrastructure planning and risk mitigation. Additionally, identifying flexibility requirements and enabling inter-TSO flexibility exchange support congestion avoidance and cross-border coordination. In the Eastern Mediterranean pilot, both Greece and Cyprus focus on real-time TSO-DSO coordination for congestion and frequency management, ensuring stability in high-RES and HVDC-interconnected systems. Hungary contributes with dynamic line rating-based flow calculations and market co-optimization across energy and balancing markets, improving market efficiency and grid utilization. Finally, Slovenia supports these goals with advanced power system analysis tools that leverage SCADA/EMS data, ensuring that forecasting and operational decisions are based on real-time, high-quality inputs. Together, these UCs strengthen the predictive and adaptive capabilities of the grid, ensuring optimal system performance under evolving conditions.

2.5.2.4 Smart coordinated planning of the grid DEMO UCs

The UCs demonstrating the use of digital twins for the smart coordinated planning of the grid aim at:

- stability of power systems with high penetration of renewable energy sources;
- analysing digital twin applications for control centre support, technical restrictions resolution and operational planning;
- increase cross-border capacity calculations and assess cross-border flexibility and pre-qualification.

The defined UCs for addressing the identified objectives and challenges are:

- NL02: DT-based dynamic stability assessment under active power flow changing events.
- 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
- 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: Long term flexibility in MV
- Ib09: Flex Connections
- Ib10: Probabilistic cross-border capacity allocation
- Ib11: Cross-border assessment of flexibility and pre-qualification
- Ib13: Enhancement of short-circuit models and TSO/DSO information exchange for operational planning
- Ib14: DT-endorsed flexible connection grant through the settlement of a Local Flexibility Market to internally balance the production surplus in congestion-creation hours/scenarios.

The aforementioned UCs contribute to smart coordinated grid planning by leveraging DT and AI technologies to enhance foresight, resilience, and decision-making across multiple layers of the electricity system (transmission and distribution). The Dutch pilot supports dynamic stability assessment under shifting power flow conditions, helping operators anticipate system responses to real-time events. In the Iberian pilot, several DT-based UCs improve both operational and long-term planning: an AI agent forecasts grid status and identifies remedial actions connected to the DT of the Transmission System, while synthetic renewable series generation enables scenario-based planning. Dynamic behaviour assessments and N-1 contingency analysis provide deeper insights into system reliability across interconnected zones. Other UCs focus on facilitating the secure integration of new RES into the MV grid, optimizing maintenance schedules, and assessing long-term flexibility needs. Flexible connections and DT-endorsed connection grants support congestion management by aligning local generation with system needs. Probabilistic approaches to cross-border capacity allocation and flexibility pre-qualification promote more coordinated transnational planning. Additionally, improved short-circuit modelling and enhanced TSO/DSO data exchange strengthen the accuracy and efficiency of operational planning. Altogether, these UCs foster a more adaptive, secure, and optimally utilized power grid.

2.5.3 TwinEU General System UCs

This section provides a comprehensive overview and analysis of the final version of the TwinEU GSUCs. These GSUCs were initially introduced in draft form within Deliverable D3.1 (Section 5.5 System Use Cases Analysis), which presented the preliminary stage of development regarding their identification and conceptualisation. The current version reflects the result of further consolidation, refinement, and validation activities carried out under Task 3.2.

These GSUCs represent the conceptual and technical foundation for the design and implementation of a TwinEU federated DT system for the European energy domain. They describe the key functionalities, interactions, and information flows expected within the TwinEU Federated DT platform, without addressing the detailed technical specifications of individual components. As such, the GSUCs provide a high-level understanding of the system's expected behaviour and serve as the basis for deriving the (GFURs).

The final definition of the GSUCs builds upon a structured methodology, previously outlined in D3.1, which included an in-depth analysis of project objectives, alignment with European energy strategies and reference standards, and active engagement with relevant stakeholders. The definition process involved a series of workshops and technical meetings with representatives from WP2 and WP4, including domain experts, pilot site leads, developers, and technology providers. These interactions were instrumental in validating system-level assumptions, collecting functional requirements, and assessing potential interoperability challenges.

GSUCs are defined according to the following format: ID of GSUC, name of GSUC, objectives, narrative description, steps and workflow, involved platforms/actors, and sequence diagrams. As a result, defined GSUCs present the basis for further development, validation, and integration of functionalities into the reference architecture of the system of DT systems, enabling interoperability, flexibility and resilience of the energy system.

Table 3 presents the complete list of the final GSUCs, including a short description of each use case.

Table 3 - GSUCs summary

GSUCs ID	Name	Description
GSUC _01	Federated Digital Twin (FDT) ecosystem for Energy System Integration	Establishes a system-of-systems approach where interconnected Digital Twins can seamlessly communicate. The federation ensures bidirectional data exchange between all physical and virtual

		entities, enabling integration and interoperability across the energy system.
GSUC _02	AI-Driven Big Data ad IoT Data Orchestration and Marketplace for Cross-Platform Digital Twin Services	Ensures AI-driven data processing, analytics, and automation of cross-platform services. The TwinEU Orchestration Workbench acts as the central system entity, supporting scalable, high-volume data management and facilitating advanced services across the Digital Twin ecosystem.
GSUC _03	Integration of IoT devices and other data sources to TwinEU	Focuses on integrating heterogeneous energy devices and data sources into TwinEU using standardised protocols and mechanisms. Enables efficient real-time data collection, forming the foundation for Digital Twin communication and data exchange. The integration of IoT devices is critical to system operation.
GSUC _04	Regulatory Compliance Exchange and Reporting	Enables all data exchanges and operations within the TwinEU system to comply with relevant regulations, directives, codes, and legal frameworks. Emphasises the integration of the CIM standard within the SGAM communication model to ensure regulatory alignment and interoperability. Contributing to the EU Green Deal targets is necessary.
GSUC _05	Resilient Energy Infrastructure Planning including Dynamic Renewable Energy Integration and Digital Twin-Driven Grid Resilience and Anomaly Detection	Enhances the resilience of the energy grid through TwinEU tools, which provide simulations and analysis for large-scale RES and DER integration. Supports proactive identification of grid bottlenecks and anomalies, modelling energy market scenarios, and optimising infrastructure planning to improve stability.
GSUC _06	TwinEU XR Framework for DTs visualization and validation	Develops a scalable, immersive XR environment for the collaborative visualization and validation of Digital Twins. The TwinEU XR Framework ensures a user-friendly experience, low-latency interaction, and enhanced system understanding for stakeholders through advanced, interactive visual tools.

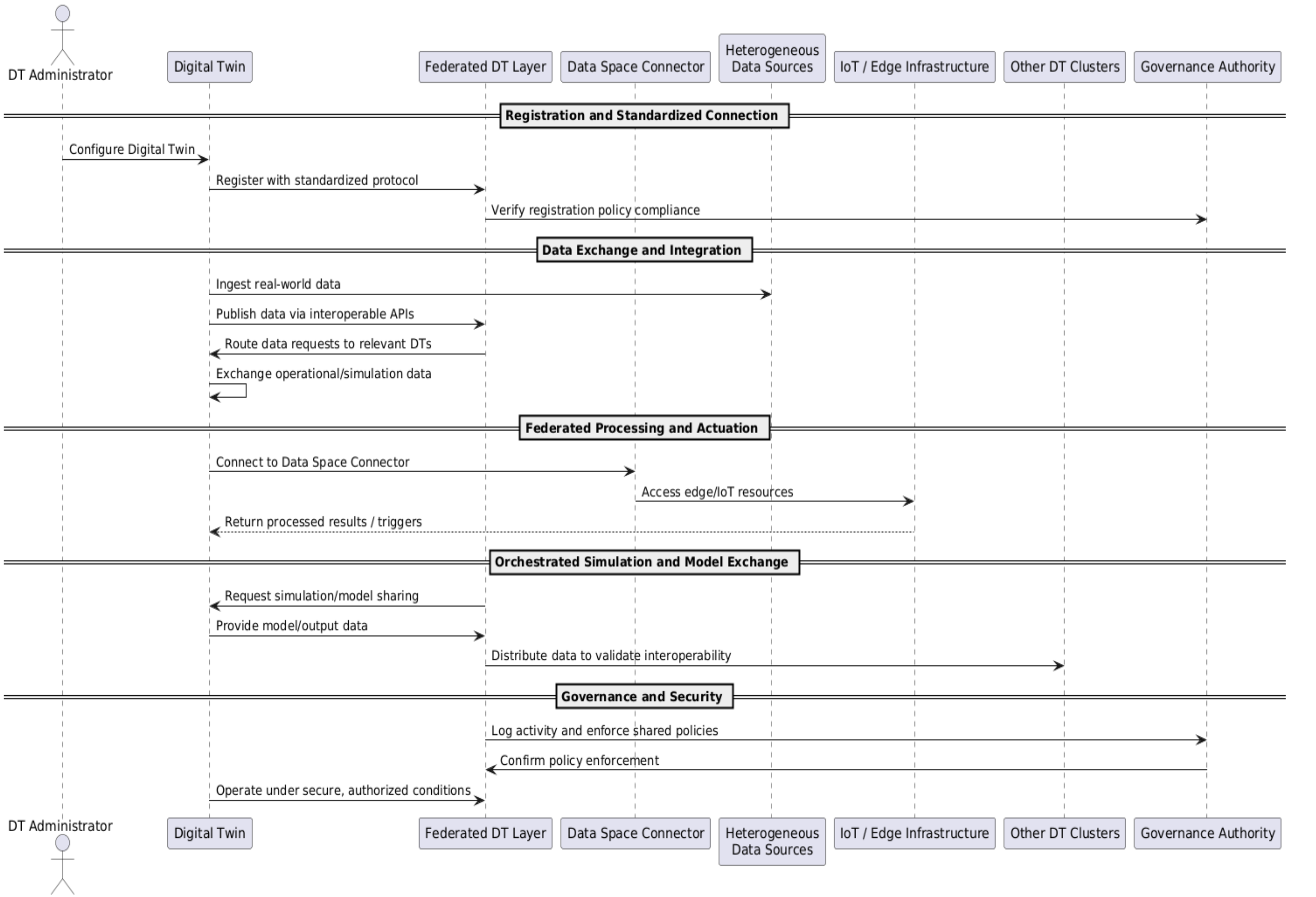
As an example, the detailed specification of GSUC_01 is also provided in the Table 4.

The full, detailed list of GSUCs is available in the Annex A. The Annex A section includes the full scope of GSUCs considered in the TwinEU project. All GSUCs are listed in Annex A for reference, consolidating all identified GSUCs and providing their structured overview.

Table 4 - 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 Diagram



2.5.4 TwinEU Requirement definition: Functional Requirements

This section focuses on defining the functional requirements that are fundamental for the development and implementation of the TwinEU Federated DT system. FURs are well-described and categorized. A detailed overview of the FURs is provided in a systematic and structured manner. This approach ensures that all actors involved in the TwinEU project (including developers, system architects, regulatory bodies, and end users) have a clear understanding of how the system is expected to operate and what key functionalities must be implemented.

The definition of functional requirements is fundamentally based on the TwinEU Use Cases: the GSUCs, as described in Section 2.5.3 of this document, and the DEMO UCs, presented in Section 2.5.2. These use cases provide the conceptual and operational foundation for deriving the complete set of functional requirements for both the TwinEU Federated Digital Twin platform and the demonstrator-specific DT services.

The analysis of the GSUCs led to the identification of GFURs, which describe the essential system functionalities expected from the TwinEU Federated DT system. GFURs cover aspects such as data management, simulations, grid analysis, grid planning, predictions in energy system, along with visualisation services and regulatory procedures. The relevant results from OneNet project are incorporated into the TwinEU GFURs.

The examination of the DEMO UCs enabled the definition of the DEMO FURs, which specify the functionalities needed to address the concrete Use Cases defined by TwinEU Demonstrators. The requirements are tailored to the particular operational scenario, technical constraints, and objectives of each demonstrator.

Functional requirements are defined using the methodology explained in the Section 2.4.1. All steps are followed, input is gathered and analysed, and the resulting FURs have been prepared in iterative processes.

2.5.4.1 Demo Functional Requirements

DEMO FURs have been defined for all DEMOnstrators. Each pilot site's use cases have been analysed, and the FURs are derived based on the methodology described in Section 2.4.1.2. The UCs are grouped based on the DEMO that they belong to. The summary of the result of this process is presented in Table 5.

Table 5 - DEMO Functional Requirements Summary

DEMO FURs summary	Pilot sites	Nº of UCs	Nº of FURs	Total UCs	Total FURs
DEMO5	Dutch-French pilot	**2**	19	4	35
	Eastern-Mediterranean pilot	**1**	9		
	Iberian pilot	**1**	7		
DEMO6	Italian pilot	**5**	37	16	128
	Slovenian pilot	**2**	19		
	Hungarian pilot	**1**	7		
	German pilot	**8**	65		
DEMO7	Eastern-Mediterranean pilot	**3**	26	16	154
	Slovenian pilot	**1**	9		

	Hungarian pilot	**2**	19		
	Bulgarian pilot	**10**	100		
DEMO8	Dutch-French pilot	**1**	5	14	112
	Iberian pilot	**13**	107		
Total	**8**	**50**	**429**	**50**	**429**

To enable a structured way of defining FURs in the TwinEU project, a process of mapping of Use Cases developed by pilots and corresponding FURs is established. For each UC, the relevant FURs are systematically derived and analysed, ensuring a structured approach to requirement definition and validation. This approach ensures a clear traceability between concrete pilot operational needs identified and the formalised set of FURs. An example of this mapping process is provided in Table 6, which illustrates the relationship between the UCs of the Slovenian pilot and their associated FURs. All FURs are reviewed and validated by the related UC. The complete mapping of all UCs and their corresponding functional requirements across the TwinEU demonstrators is provided in the Annex Section C.5.

Table 6 - Slovenian pilot's mapping table/matrix

Pilot	Related Use case(s)	FUR ID
Slovenian pilot	SLO-BUC-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-BUC-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
	SLO-BUC-3 - Power system analysis	DT-O&M-07-SLOBUC03-11
		DT-O&M-07-SLOBUC03-12
		DT-O&M-07-SLOBUC03-13
		DT-O&M-07-SLOBUC03-14
		DT-O&M-07-SLOBUC03-15
		DT-O&M-07-SLOBUC03-16

Finally, this section reports a sample of the DEMO FURs as shown in Table 7, while the full list of DEMO FURs identified is provided in Annex C.

Table 7 - Sample of DEMO Functional Requirements

Requirement ID	Name	Description	Related Use Case(s)	Note
DT-O&M-06-GE-04	Detection of Congestion Points	The system must detect and highlight potential congestion points within the grid.	Ge03	Demonstration of digital twinning for grid management, operation and monitoring, German pilot
DT-SC&PG-03&04-IB-63	Flexibility Service Provider (FSP) Prequalification for Neighbouring System Operators (SOs)	The system must facilitate the prequalification of Flexibility Service Providers (FSPs) to provide flexibility to neighbouring System Operators (SOs) where they have no direct connection.	Ib14	Demonstrations of digital twinning for smart coordinated planning of the grid, Iberian pilot
DT-F&OG-03&04-BG-59	Ampacity Forecast-Driven Decision Support for Infrastructure Optimization	The system could support decision-making of the system operators by indicating areas where the ampacity forecasts could delay or prevent new infrastructure construction. This could help them in optimizing available budget and resources.	Bg05	
DT-O&M-03-IT01-08	Fault Injection for Defense System Response Testing	The system must include a feature to inject faults into the simulated grid (e.g., short circuits, line trips) to assess the defense system's response and effectiveness in mitigating cascading failures.	IT01	
DT-O&M-07-SLO01-02	Dynamic Behaviour Impact Assessment for Network Scenarios	The system must assess the impact of various scenarios on the network's dynamic behaviour.	SLO-BUC-1	
DT-CYB-01-NL01-06	Data Integration	The system should integrate data from various sources, including	NL01	

		TSOs and DSOs, for suitable monitoring and analysis of the grid under cyberattack conditions.		
DT-CYB-04-FR01-01	Simulation Scenario Management for Training Exercises	The system should allow the game master to configure and execute training scenarios that involve events affecting the power and communication networks (e.g., wind variations, cyber-attacks, electrical grid faults).	FR01	
DT-O&M-08-HU01-04	Cost-Effective Operations through Advanced Digital Twin Technology	The system must reduce the dependency on physical monitoring devices by implementing advanced digital twin technology, thereby decreasing maintenance and operational costs.	Hu01	
DT-CYB-02-EM-CY-01-01	DSO Coordination for DER Power Regulation	The system must enable the DSO to coordinate flexible Distributed Energy Resources (DERs) for active and reactive power regulation.	EM-CY-01	
DT-F&OG-01-EM-GR-01-03	Congestion Management through DERs and Demand Response Optimization	The system must facilitate congestion management in both distribution and transmission grids by optimizing the use of DERs and industrial demand response.	EM-GR-01	

2.5.4.2 General Functional Requirements

GFURs are based on the GSUCs that are defined and explained in Section 2.5.3. They are very important, as they are related to the whole TwinEU system. GFURs are a basis of TwinEU for enabling efficient integration, testing, and usability of Digital Twin technologies. A summarised data about the number of GFURs for each GSUC is presented in Table 8.

Table 8 - General Functional Requirements Summary

GFURs summary	**Nº of FURs**
GSUC_01	18
GSUC_02	28
GSUC_03	23

GSUC_04	10
GSUC_05	10
GSUC_06	8

A representative sample of GFURs is shown in Table 9 while the full list of GFURs is available in the Subsection C.6. Table 9 provides a clear understanding of GFURs formulation without overwhelming with the complete set, whereas the complete list of GFURs is provided in Annex C.6 for comprehensive reference.

Table 9 - Sample of General Functional Requirements

Requirement ID	Name	Description	Related Use Case(s)
TwinEU_GFUR_26	Digital Twin Federation Integration	The system must enable the creation of a Digital Twin Federation by integrating local Digital Twins into a system-of-systems.	GSUC_01
TwinEU_GFUR_27	Bidirectional Data Exchange for Physical and Virtual Entities	The system should provide bidirectional data flow between physical and virtual entities.	GSUC_01
TwinEU_GFUR_28	Seamless Interoperability Across Digital Twins	The system should ensure seamless interoperability between different Digital Twins, regardless of their underlying data structures and models.	GSUC_01
TwinEU_GFUR_44	AI & Big Data Marketplace for providers	The system should allow service providers to publish and manage AI models, services, and data assets.	GSUC_02
TwinEU_GFUR_45	AI & Big Data Marketplace for consumers	The system should enable data consumers to access and integrate available AI-driven services via standardized APIs.	GSUC_02
TwinEU_GFUR_46	Predictive Analytics and Data-Driven AI Solutions	The system could offer real-time anomaly detection to identify inconsistencies in energy data and prevent disruptions.	GSUC_02
TwinEU_GFUR_47	Data Streaming Consumption and Querying	The system should allow data consumers to retrieve data entities based on specific queries.	GSUC_03
TwinEU_GFUR_48	Data Streaming Provision	The system shall allow data providers to create, modify, and delete data entities.	GSUC_03

TwinEU_GFUR_49	IoT Indexing and Discovery	The system should enable registration and management of IoT devices as data entities. The system should maintain a catalogue of all registered entities and their associated providers.	GSUC_03
TwinEU_GFUR_51	Validation against regulatory standards, directives, laws, and codes	The system should validate all exchanged data against applicable regulatory standards, directives, laws, and codes.	GSUC_04
TwinEU_GFUR_52	Regulatory Compliance Enforcement	The system should enforce compliance validation before data is accepted or shared within the TwinEU system.	GSUC_04
TwinEU_GFUR_53	Secure and Transparent Data Exchange with CIM in two SGAM Layers	The system must enable secure and transparent data exchange using CIM standard definitions within the Communication and Information layers of SGAM.	GSUC_04
TwinEU_GFUR_61	Grid Resilience Simulation	The system should provide simulation tools to assess the resilience of the energy grid under normal and abnormal conditions.	GSUC_05
TwinEU_GFUR_62	Grid Stability Analysis for RES and DER Integration	The system must detect and analyse grid stability issues caused by the integration of RES and DER.	GSUC_05
TwinEU_GFUR_63	Proactive Grid Planning	The system should support decision-making by grid operators through predictive analytics for grid stability.	GSUC_05
TwinEU_GFUR_71	High-quality Real-time Data Visualization	The system should support high-quality real-time visualization of Digital Twin (DT) data, allowing users to possibly view and analyse live grid performance.	GSUC_06
TwinEU_GFUR_72	Multiuser XR Collaboration	The system should allow multiple users to interact and collaborate within the same Extended Reality (XR) environment in real time.	GSUC_06

TwinEU_GFUR_73	Unity3D-Based Plugin Integration	The system must integrate a Unity3D-based plugin to streamline user interaction with DT data and enhance XR visualization capabilities.	GSUC_06

2.5.5 TwinEU Requirement definition: Non-Functional Requirements

This section concentrates on the NFURs' derivation. NFURs are described in the context of development and implementation of the TwinEU system. They have a crucial role in enabling quality, reliability, and compliance with relevant standards. Moreover, these requirements are essential in defining reference architecture. Because of that, they are precisely defined, documented, and validated.

At the core, NFURs represent a set of requirements that specify quality, performance, scalability, safety, and other characteristics of the system, but do not describe concrete functionalities that system should execute. These requirements enable that the TwinEU system fulfils specific standards, regulations, and user needs and expectations in the sense of their efficiency and reliability.

The difference with FURs is that FURs define what the system should do, where NFURs define how the system should work. They are mandatory for long-term success of the project because they have an impact on its usability, sustainability, and ability to adapt to the changes. NFURs are usually referred as quality attributes, as that is the way we are going to write about them in this document. They are also named constraints, goals, extra-functional requirements, and non-behavioural requirements [2].

Design solutions can positively or negatively impact some of NFURs. These can be a basis for discussing if the system follows specific NFURs or not. The system should meet all the defined NFURs, and design decisions should be aligned with all the non-functional requirements. Furthermore, when working with NFURs, an emphasis can be on qualitative or quantitative aspect of these requirements. We choose to give priority to the qualitative approach to the NFURs [2].

NFURs are crucial to the success of the TwinEU project because they describe all system quality attributes [6]. Software requirements and software architecture are fundamental in software development life cycle. Architectural styles are the basic concept of programming architecture. In is important to have a clear understanding of important architectural styles before mapping NFURs into them [6].

The NFURs should be defined early in the projects lifecycle because they help in finding the correct technologies, ensure the needed hardware, and the standards that shape the software development [4]. As the elicitation process is one of the crucial steps for well-defined NFURs, we described the full methodology in the previous section. Another key step is standardized approach to this problem.

NFURs are defined following the methodology presented in the section 2.4.2. The methodology approach presented in the previous EU H2020 OneNet project is updated in the section 2.4.2. As described, one of the most impactful standards for NFURs is ISO/IEC 25010:2023.

ISO/IEC 25010:2023 [1] is a product quality model that is applicable to ICT and software products. It is part of the Software Quality Requirements and Evaluation (SQuaRE) family of International Standards and defines categories and subcategories of the quality model.

In the TwinEU project, NFURs are defined on the DEMOnstration level and on the TwinEU system level. On the DEMO level, common NFURs for all demonstrators are defined. On the other hand, NFURs are defined based on the TwinEU system's objectives and are general for the whole TwinEU ecosystem. The summary of the number of derived NFURs is given in Table 10.

Table 10 - Summary of Non-Functional Requirements

NFURs summary	Nº of NFURs
DEMO	6
TwinEU system	72

The set of DEMO NFURs is presented in Table 11, while the sample of general NFURs is given in Table 12. They are defined and documented in the uniform manner, with categories and subcategories pointed out. ID, Name, and Descriptions are also very important parts of documentation, as they give relevant information and describe each NFUR. Validation is done by all involved parties.

Table 11 - Non-Functional Requirements on the DEMO level

Requirement ID	Name	Category	Subcategory	Description
DEMO_NFUR_01	Efficient Large-Scale Data Processing and Integrity	Performance Efficiency	Resource Utilization	The system must handle large datasets (large volumes of data) efficiently, without performance degradation. The system must be able to handle large volumes of data without compromising the accuracy of the exchanged information.
DEMO_NFUR_02	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.
DEMO_NFUR_03	Feedback-Driven Modifiability	Maintainability	Modifiability	The system should be modifiable based on the feedback collected during the evaluation phase of the demonstrations.
DEMO_NFUR_04	Full GDPR compliance	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. (It is aligned with previous EU H2020 project Enershare)
DEMO_NFUR_05	Validation and Feedback	Performance Efficiency	Time Behaviour	The system validation and provide feedback within a reasonable time frame to ensure that the process is not delayed.
DEMO_NFUR_06	Timely warnings	Safety	Hazard warning	The system should provide timely warnings to prevent actions that could compromise safety.

Table 12 - Sample of Non-Functional Requirements on the TwinEU system level

Requirement ID	Name	Category	Sub-category	Description
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_10	Low-Latency Real-Time Data Processing and Communication	Performance Efficiency	Time Behaviour	The TwinEU system must manage real-time data efficiently. 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_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_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.
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_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_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_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_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.

2.5.6 TwinEU Regulatory Environment definition

This section outlines the regulatory environment with the regulatory requirements that are relevant for the TwinEU project. Here are identified essentials regulations, directives, codes, laws, and standards that are applicable to the Digital Twin system in the context of European Union. Moreover, the analysis of each identified requirement is done.

The TwinEU project extends over a number of the European countries. Because of that, it must work with a complex regulatory environment, influenced by not only the European laws, standards and directives, but also with national and regional regulations and codes. The project aims to create cutting-edge platform that incorporates various energy systems, so it must adhere to strict regulations that include data management, governing, interoperability, monitoring, and sustainability.

Energy and data regulations are different among the countries that are participating in the project, but they are governed by the EU regulations that follows cross-border principles of energy systems and data exchange in Europe. The TwinEU system's utility and trustworthiness must be accomplished, while being compliant with all the major regulations. That is an essential condition.

Compliance guarantees that business processes, operations, and practice are in accordance with an advised and/or agreed set of norms. Compliance requirements may originate from legislature and regulatory bodies and business partner contracts [15]. Obligations of regulatory compliance should be taken very seriously, as they can be challenging and lead to new considerations. On the other hand, well-defined regulatory environment can lead to prosperous and improved results in the project. One of the largest open issues for compliance industry is achieving a balance between control and business objectives [15]. Compliance approach and analysis of the relevant documents and processes started in the early stages of the project.

2.5.6.1 Reviewing Legal and Regulatory Compliance

This subsection provides a comprehensive overview of the regulatory landscape relevant to the TwinEU project. It describes the various legal, regulatory and compliance requirements that affect the design and operation of the TwinEU Federated digital twin system across multiple European countries. Given the cross-border nature of TwinEU, the project must navigate a complex regulatory framework that includes both European Union directives and national or regional laws. Key regulations covered in this section include, but are not limited to, the GDPR, ENTSO-E grid codes, NIS/NIS2 directives, ISO/IEC 27001 standard, and various energy market regulations (e.g. RED II/III, REMIT, Data Act). In addition, the section discusses the challenges of aligning these multi-layered regulatory requirements such as potential conflicts between national laws and high cost of compliance infrastructure. The section addresses the need for consistent interoperability and proposes strategies to ensure that TwinEU remains compliant while fostering innovation. By analysing these legal and regulatory dimensions, this section establishes the basic framework that informs the subsequent technical and operational requirements of the project.

2.5.6.1.1 Essential Regulatory Requirements and Legal Bindings

This subsection identifies key regulatory requirements and legal obligations that are relevant for the implementation of the TwinEU Federated DT system in pan European context and in the context of countries that are part of the projects. European and national laws, regulations, and guidelines that shape energy sector are shown below:

- **Grid Codes:** Compliance with ENTSO-E (European Network of Transmission System Operators for Electricity) grid code [8] – There are connection codes, operational codes, market codes that define this framework that the TwinEU ecosystem should comply with.
- **Common Information Model (CIM)** [8] is included in the ENTSO-E guidelines for standardized data interchange across the electricity market. Alignment with this framework is crucial for interoperability between different modules in the TwinEU system
- **The network code on cybersecurity for EU electricity sector (NCCS)** [24] - Compliment with this regulatory framework for cybersecurity and risk assessment measures. It is part of the ENTSO-E Network Codes and Guidelines also.
- **GDPR (General Data Protection Regulation)** [10] – This legal framework is essential for defining data protection and privacy rules. It is necessary to adhere to its rules.

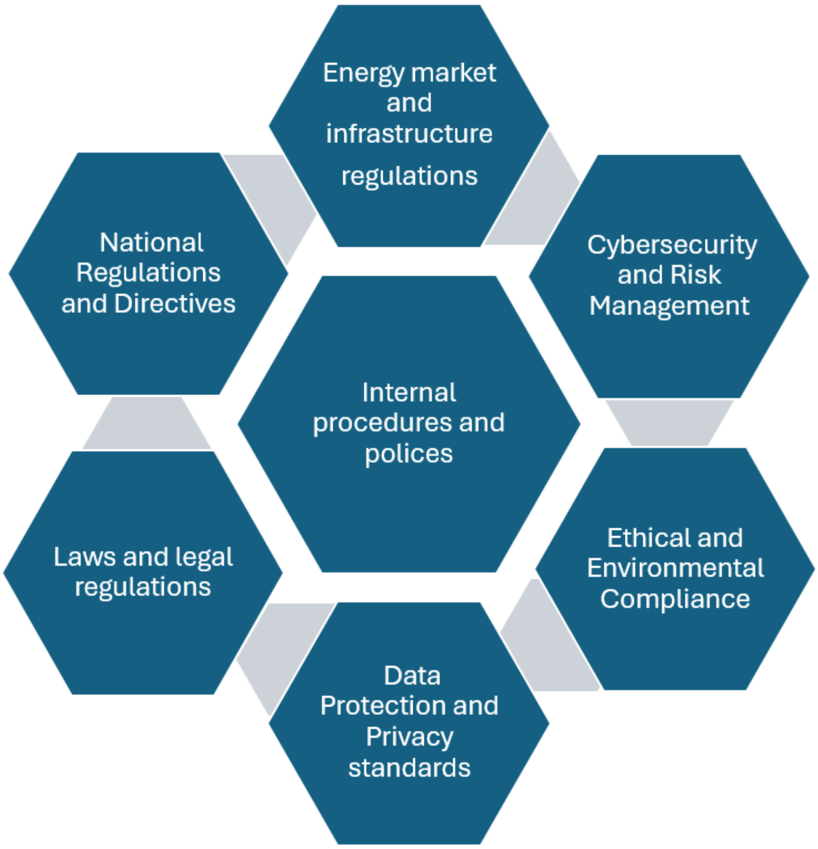


Figure 8 - Categories of legal and regulatory requirements that apply to TwinEU project

- Adherence to **NIS** and **NIS2 directive** [9] - The Network and Information Systems (NIS) Directive and the updated version, the NIS2 Directive are directives that aim to improve cybersecurity of the system.
- Adherence to **ISO/IEC 27001 standard** [25] and **local cybersecurity laws** – Compliance to the improvements of the Information Security Management System (ISMS) based on the system's needs.
- **RED II** [26] and **RED III** [11] – Compliance with the EU Renewable Energy Directive - Adherence to the energy policies that defines requirements to improve RES penetration into energy systems.
- **REMIT** (Regulation on Wholesale Energy Market Integrity and Transparency) [27] aims to improve integrity and transparency of the energy markets in Europe.
- **Data Act** [12] – It is the law that regulates data markets – Compliance with this law enables data-driven transformations and modernisations. Data Acts also regulates how data is accessed, shared, and used across different fields.
- **Regulations (EU) 2019/943** [28] and **(EU) 2019/944** [29] are two key regulations within the European Union's Clean Energy for All Europeans package. Their scope is energy sector.
- **Regulation 2017/1485** [30] is focused on system operation within the European Union. It regulates electricity transmission networks.
- **Regulation (EU) 2017/2195** [31] gives the guidelines for capacity mechanisms within the electricity market in EU.
- Energy Efficiency Directive (**EED**) [32] – a key driver of Europe's energy transition.
- Clean Energy for All Europeans Package (**CEP**) [33] – an adaptation of the European energy policy framework to facilitate the transition away from fossil fuels toward cleaner energy.

- **EU AI Act** [34] – Compliance to the EU Artificial Intelligence Act (AI Act) that aims to regulate the artificial intelligence systems.
- **The European Green Deal** [13] – Aligned with the strategy to achieve climate neutrality by 2050.
- Respecting **National Laws** - Compliance with the National Regulations and Restrictions of each Member regulations, such as Electricity Law of Cyprus, that define how electricity is collected, stored, processed, and transferred. Among other spheres of interest, the laws define how electricity systems reach security, safety, and reliability standards. Data sovereignty laws regulate collection, processing, storage, and sharing of data in particular regions or country. In Germany, The Federal Data Protection Act (BDSG) that aligns with the EU's GDPR and strict environmental regulations under the Federal Emission Control Act (BImSchG) are very important, but also Energy Industry Act, and the Renewable Energies Act. The French Data Protection Act (Loi Informatique et Libertés) ensures GDPR compliance. In Italy, The Personal Data Protection Code ensures compliance with GDPR. Each EU country has its own national laws that have an impact on the TwinEU ecosystem.
- **National regulatory requirements** - They are defined by national regulatory agencies, such as the Greece's Regulatory Authority for Energy, Waste and Water (RAAEY), Cyprus Energy Regulatory Authority (CERA), Hungarian Energy and Public Utility Regulatory Authority (HEA/MEKH), Transmission System Operator (TSO) – MAVIR Zrt., Hungarian Competition Authority (GVH), Ministry for Energy Affairs in Hungary. In Bulgaria: Energy Act of Bulgaria; Energy from Renewable Sources Act of Bulgaria; Integrated energy and climate plan of the Republic of Bulgaria for the period from the year 2021 until 2030; NC CACM; NC FCA; NC System Operation; NC Emergency and Restoration; TSO Grid Code of Bulgaria; DSO Grid Code of Bulgaria; RfG Code; Market rules in Bulgaria. Federal Network Agency (Bundesnetzagentur), In Bulgaria: Energy and water regulatory commission - Regulatory agency of Bulgaria; Ministry of Energy of Bulgaria; Ministry of Foreign Affairs of Bulgaria; Ministry of Finance of Bulgaria; Ministry of Regional Development and Public Works of Bulgaria. In Cyprus, the national regulatory framework relevant to the TwinEU project is primarily supervised by the Cyprus Energy Regulatory Authority (CERA). The Electricity Market Law of 2003 (Law No. 122(I)/2003 regulates the electricity market in Cyprus. The Natural Gas Market Law (Law No. 183(I)/2004), CERA's Regulatory Decisions and Guidelines, the Transmission System Operator (TSO) of Cyprus, Law 125(I)/2018 are among the crucial regulatory requirements in Cyprus for the TwinEU project. National regulatory requirements for the rest of participating EU countries are also considered in detail. They are thoroughly examined to ensure alignment and compliance.
- **Anonymization** – Perform modifications so privacy data are no longer identified and recognized.

Internal Compliance Policies and **Procedures** define the framework for operations inside of the TwinEU Federated DT platform. More about them is defined in the next Subsection 2.5.6.1.2.

2.5.6.1.2 Internal Compliance Policies and Procedures

Internal policies, procedures and frameworks are mandatory in order to define stable, interoperable, and efficient TwinEU Federated DT platform. They should comply with the standards, directives, codes and laws that are applying to the TwinEU ecosystem. Data and energy market regulations, as well as cybersecurity policies and sustainability packages shape the TwinEU system, and all internal procedures should adhere to them. Stakeholders should be well informed about their rights and obligation, so that can understand better their roles in the TwinEU project. This can be achieved with proper communication, meetings, documentations, and training. Clear guidelines should be defined on all aspects of the TwinEU project.

Figure 9 - Categories of Internal Policies and Guidelines in the TwinEU project

We can categorize the internal policies and guidelines into:

- **Data Management and Privacy Policies** – Data should be categorized based on the sensitivity and they have to be compliant to GDPR. Furthermore, sensitive data should be anonymized. Guidelines regarding processing data, storing, transferring, gathering and sharing should be created and followed. All data security regulations and laws have to be followed.
- **Cybersecurity and Risk Management Policies** – There should be defined management plan for identifying, reacting, and recovering from cyber-attacks. Access Control Policies and Risk Assessment need to be created, together with guidelines and usage of appropriate tools. The TwinEU project should be compliant with all cybersecurity standards and regulations, such as ISO/IEC 27001, NIS2, and NCCS.
- **Operational Procedures** - Performance Monitoring and Reporting as well as Incident handling should be set in place with guidelines how to perform tasks and services within the TwinEU project.
- **Quality Assurance and Testing Guidelines** – A set of guidelines on system testing, system updates, system reviews, and continuous improvements including various performance metrics guideline.
- **Communication and Collaboration Guidelines** - Guidelines for communicating with stakeholders, pilot partners, market operators, developers, regulatory bodies, and third-party service providers. Overall collaboration among all teams in the TwinEU ecosystem is necessary.
- **Ethical and Environmental Policies** – Policies that define data sovereignty, sustainability, ethical AI, alignment with the European Green Deal, and social responsibility and equity should be created and used.
- **Incident and Crisis Management** - Procedures for effective communication in moments of crisis such as a power outage or cyber-attack. Disaster recovery includes backing up data and

information, system recovery procedures, and restoring it to a proper state. Several notification methods should be set in the TwinEU project.

- **Overall Compliance and Regulatory Frameworks** – The TwinEU Federated DT platform should be compliant with all regulatory and legal procedures that apply to it, such GDPR, NIS2, REMIT, RED III, and the EU AI Act. Furthermore, internal procedures, review, and audits must be in place and adhere to these frameworks.
- **Training and Awareness Guidelines** – Training of all partners in the TwinEU project for security awareness and regulatory compliance.

2.5.6.1.3 Challenges in the Regulatory Environment

One of the aims of the TwinEU project is to deploy robust and interoperable digital twin solutions that are compliant to all the crucial legal and regulatory requirements. It is important to have up-to-date information about the status of the regulatory environment important to TwinEU Federated DT system in EU and on the national levels. To achieve these goals, research has been conducted, and dedicated questionnaire was sent to all the relevant stakeholders. The results have been analysed and taken into consideration. They have been valuable for understanding different scopes and impact of various directives and codes on the TwinEU ecosystem.

The primary regulatory bodies or authorities governing the energy sector within the TwinEU project are **European Commission**, **EU Regulatory Agencies**, and **national regulatory agencies** for the energy system. Renewable Energy Directive (RED II), EU Cyber Resilience Act, NIS/NIS2 Directives, Internal Electricity Market Directive (IEMD) – Directive (EU) 2019/944 (encourages cross-border coordination), GDPR, Regulation on the Internal Market for Electricity (EU) 2019/943 are among the regulations that directly impact the TwinEU project.

- To operate across multiple countries requires alignment with numerous, possibly conflicting, national laws and EU directives. Regulations can differ among countries and there could be different regulatory bodies.
- Investment in compliance infrastructure can be costly and also may require additional staff and time to be adopted.
- Rigorous compliance with standards and regulations may lead to harder adoptions of innovative technologies and reduce interoperability among systems in the TwinEU Federated DT platform.
- Data management may have some constraints while operating under the specific laws and directives. The Digital Twin system's utilities and operability may be restricted in these conditions.
- Adherence to environmental and sustainability regulations is defined on the EU level, but each country may have its own implementation and these implementations can vary.
- As regulations continuously change and evolve, the TwinEU partners should be up-to-date to the latest standards and regulations.

How to address regulatory challenges:

- Collaborate with stakeholders to ensure compliance with all EU, national and regional regulations. Talk with local experts regarding legal matters and national laws.
- Create strategies to ensure compliance with regulatory requirements on all levels of the TwinEU project. Invest in compliance infrastructure.
- Reference Architecture should be based on modular, scalable, and interoperable systems that adhere to standards and laws.

- Adopt software and tools to follow the latest standards and compliance with the regulations and laws.
- Be aligned with the latest state of the regulatory environment for the project, be aware of the newest standards, directives and laws. Monitor all the changes in regulations that could impact the TwinEU project. Compliance cost can add up to the operational costs
- Hold trainings and give guidelines for all partners in the TwinEU project so they are aligned with the regulatory environment.

To ensure compliance with regulatory requirements throughout the TwinEU project lifecycle, several risk assessments should be carried out. Extensive reviews of tens of documents, including EU and national regulatory frameworks, have to be done to ensure compatibility. The feedback loop that includes stakeholders, pilot sites, and partners from different WPs is a method to achieve compliance with relevant regulations. These approaches have ensured that the TwinEU actions have been consistent with the regulatory demands.

Harmonising the TwinEU project operations with the EU regulatory framework is crucial. When considering GDPR, ethics requirements have been analysed. For addressing regulatory challenges and ensuring compliance within the Smart Grid sector, engaging with regulatory bodies early in the project lifecycle to understand their expectations and requirements has been necessary - strong, early communication with national regulators and EU-level bodies (e.g. ACER, ENTSO-E, and CEER). Ensuring that all Smart Grid technologies used in the TwinEU project comply with cybersecurity and data privacy regulations, particularly the NIS Directive and the GDPR should be done. Cross-border coordination is central point for Smart Grid technologies to function effectively across different member countries.

The specific regulatory requirements that can be identified as potential barriers or challenges to the implementation of the TwinEU project are requirements such as Regulation (EU) 2019/943 and the Network Code on Demand Response. Regulatory barriers and restrictive market access rules for energy communities, storage systems, and aggregators in some regions may limit the integration of renewables and delay the economic sustainability of prosumers in the TwinEU project, despite the Clean Energy Package's goals. Segmented national regulations across EU member states, particularly around grid connection and market access, can complicate the deployment of standardized Smart Grid solutions in the TwinEU project, with some countries imposing stricter requirements or more complex licensing processes than the others. Furthermore, 2019/944 and 2024/1788 [36] state the separation among DSO, TSO and producers, making less simple the data exchange among them. Also, the data exchange between the DSO and TSO can be limited by the actual cybersecurity needs, in order to protect the data security of both of them. The TwinEU project will develop and implement digital twin solutions considering all the major regulations, codes, and directives. Any cases of potential barriers will be recorded where detected.

2.5.6.2 Analysis of Societal and Ethical Impact

2.5.6.2.1 Evaluation of the Societal Impacts on the TwinEU Architecture

Potential social influence and effect on the implementation of the TwinEU Federated DT system is presented in this subsection. The focus is on the main aspects of proposed regulatory environment and how each regulation, that is important to the TwinEU system, can contribute to a socially responsible solutions and fair energy transition.

- Compliance with grid codes, including ENTSO-E (European Network of Transmission System Operators for Electricity) grid code adds to societal stability because of reliable electricity supply that is one of the objectives of grid codes. They prevent disruptions and improve confidence and transparency in energy markets. Consumer rights are guaranteed. The grid codes promote sustainability and carbon neutrality.

- Adherence to the Common Information Model (CIM) enables system operators to work properly, and have better grid management, monitoring and data exchanges by following consistent data models and formats. CIM can also reduce power outages and enhance grid resilience.
- The NCCS improves cybersecurity standards and lowers cyber threats. One of its objectives is to defend the electricity grid and prevent economic damage.
- GDPR empowers individuals and enables transparency.
- NIS and NIS2 Directives enables societal stability through promoting resilience of energy services and platforms against cyber-attacks.
- RED II and RED III elevate Renewable Energy Resources (RES) usage and reduce greenhouse gas emissions which improves air quality and public health. It is important for environmental sustainability and consumer empowerment.
- Data Act have impact on private data of individuals, as it requires that data are used and shared in research, modernization processes, and public services. It ensures that data from European Union is owned and shared across EU. It aims to stop data breaches.
- The AI act can bring many advantages to the systems that utilize AI and define relationships and usage of data by different entities. It promotes respect of privacy laws such as GDPR in AI-driven systems. Accountability should be taken in consideration, as AI technologies can make autonomous decisions that can be harmful in some way to individuals or society as a whole. Furthermore, AI systems can automate some processes that can lead to job losses. On the other hand, AI platforms can bring benefit to many sectors such as health, climate research, and sustainability.
- REMIT objective is to prevent insider trading and market manipulation. With its rules, it enables transparency and monitoring of market activities by regulatory bodies. It enhances overall operations of the energy markets, including market efficiency, price stability, fair market access, and consumer protection. Furthermore, it promotes usage of RES and cross-border energy trading.
- ISO/IEC 27001 standard help reaching full data protection and privacy. It builds trust in organizations and elevates consumer roles and security.
- Regulations (EU) 2019/943 and (EU) 2019/944 are both aligned with the European Green Deal. They support the process of digitalization of energy assets and systems.

2.5.6.2.2 Ethical Aspects of TwinEU Regulatory Context

This subsection puts an emphasis on ethical principles that are related to compliance with regulatory requirements in the TwinEU project. Ethical issues may arise during the implementation of technical and legal frameworks because these frameworks have an impact on fairness, transparency, accountability, and social responsibility. The following principles are an overview of the main ethical dimensions relevant to the TwinEU project:

- Fairness and Social Justice
  - Grid Codes (ENTSO-E): Have an effect on preventing discrimination of the poorer strata of society, enable reliable services, and protect vulnerable customers, although their implementation may lead to unequal access to electricity.
  - CIM Implementation: Promotes social justice through improved grid efficiency, enabling RES integration, data sharing and combating climate change. Drawbacks may arise if the increased data sharing exposes sensitive information.

  - RED II and RED III: Risk of unequal access to novel infrastructure in poorer and vulnerable communities is taken into account.
  - REMIT: Have an impact on fairness through the regulation of energy markets and enabling affordable energy prices for all social groups. Ethical consideration is that it may lead to disproportionate burden on small market participants.
- Privacy, Data Protection, and Freedom from Surveillance
  - GDPR: Enforce strong protection of the privacy of all individuals, but may put limitations on the innovations based on data.
  - NIS and NIS2: Make cybersecurity stronger, but may raise ethical dilemmas related to the surveillance.
  - NCCS: Protects public safety and critical infrastructure, but may lead to higher surveillance and lower level of personal liberties.
  - AI Act: AI Act promotes trust in AI systems, making them socially acceptable. On the other hand, AI Act may add to the risks of unauthorised use of personal data, surveillance, and privacy violations.
- Transparency and Accountability
  - ISO/IEC 27001: Stimulates responsibility, transparency, and protection of the rights of individuals in the context of information security, but sharing too much information internally or externally could expose sensitive data.
  - Data Act: Promotes transparency in data usability, but may favour large corporations over small businesses, which can raise questions about fairness.
- Equality and Non-Discrimination
  - AI Act: Needs guidance in order to combat race, gender, or age biases, to have ethical use of AI. This open issue is of great importance to all systems that use AI.
- Responsibility Toward Sustainability
  - European Green Deal & Environmental Regulations (EU 2019/943 and EU 2019/944): Have an objective to reduce emissions and support sustainability. An ethical open issue is that it should not add to ecological inequity. These regulations need to ensure that large, comprehensive projects that introduce RES do not endanger vulnerable social groups with legacy infrastructure.
  - CIM & Grid Codes: Support sustainability through integration of RES and reliable systems, and in that way, reinforce societal responsibility in combating climate change. On the other hand, in some cases may lead to encouraging short-term optimization over long-term sustainability.

2.5.7 TwinEU Cybersecurity and Data Privacy Requirements

TwinEU must ensure that its federated Digital Twin platform operates securely and complies with the data protection laws across all pilot implementations. This section consolidates cybersecurity, data privacy, regulatory compliance, and societal requirements for TwinEU, drawing on insights from the architecture design (D3.1 [20]), WP2 stakeholder and use case analyses (D2.1 [18], D2.2 [19]), and preliminary findings and ongoing work from the pilot demonstrations (D5.1 (not completed), D5.2 (not completed), D5.3 [21]). Given TwinEU's pan-European scope, the approach is multifaceted: it safeguards data flows and operational integrity within a diverse landscape of national and EU regulations, addresses stakeholder concerns (technical, business, and societal), and aligns with industry best practices. All requirements here build upon the regulatory baseline defined in detail in Section 2.5.6 of this deliverable and reflect Task 3.4's focus on societal, legal, and business considerations.

At its core, TwinEU's strategy for security and privacy is **security-** and **privacy-by-design**. The TwinEU Reference Architecture integrates security from the outset; for example, it aligns with the IDSA [38] and GAIA-X [39] standards to create a secure data exchange zone. Each data connector in the TwinEU Data Space uses certificate-based mutual authentication and encrypted communication, ensuring that only authenticated and authorized interactions occur across organizational boundaries. Additionally, the TwinEU middleware enforces strict access controls, monitors user and system activities, and employs anomaly detection to pre-empt unauthorized behaviour.

In summary, TwinEU's platform is built to be secure, trustworthy, and compliant by design, providing a foundation on which all federated digital twin services can operate safely.

2.5.7.1 Compiling and Analysing the Relevant EU Frameworks for Data Protection

To develop a robust data protection strategy, it is essential to clearly understand and systematically map relevant European legal and regulatory frameworks that govern data privacy and cybersecurity. These frameworks are already comprehensively combined in Section 2.5.6.1 of this deliverable, which serves as the regulatory baseline. This section focuses on how each framework informs TwinEU's practical implementation across its pilot sites. Key EU frameworks and standards include:

- **GDPR (General Data Protection Regulation)** [10]: GDPR defines requirements for lawful processing, data minimization, privacy by design, and data subject rights. TwinEU pilots (e.g. smart meter data) aim to minimize personal data processing and enforce measures such as anonymization, consent, and transparency. GDPR's integrity and confidentiality principles directly inform TwinEU's security controls, including encryption and access control.
- **NIS2 Directive (Directive (EU) 2022/2555)** [9]**:** NIS2 introduces cybersecurity risk management obligations for essential and important entities. TwinEU pilots incorporate NIS2-compliant practices such as risk assessments, incident detection and notification (notifying authorities within 72 hours for significant incidents), supply chain security, and continuous monitoring.
- **EU Data Governance Act** [40] **& Data Act** [12]: These acts promote trustworthy data sharing and interoperability. TwinEU implements secure, standardized APIs for data exchange, maintains detailed audit logs, and defines clear governance rules for data exchange, ensuring compliance with these acts' transparency and accountability provisions.
- **ISO/IEC 27001** [16]: This international standard for ISMS (Information Security Management Systems) is adopted across TwinEU pilots. It supports the implementation of security policies, risk assessments, access controls, and audit mechanisms, fostering continuous improvement and accountability.
- **IEC 62351** [41] and **IEC 62443** [35]**:** These standards guide cybersecurity for power systems. IEC 62351 addresses secure communication protocols (e.g., SCADA), while IEC 62443 supports OT network segmentation, device hardening, and secure-by-design development. TwinEU applies both standards in its pilot implementations.
- **National and Energy Sector Regulations**: TwinEU pilots also comply with relevant national laws and sector-specific rules. For example, REMIT [27] mandates secure logging and monitoring of market transactions, which is reflected in pilots handling market data.
- **Additional EU Initiatives**: In addition to the core frameworks, TwinEU considers several emerging and sector-specific regulations. The AI Act [34], which is expected to enter phased enforcement from 2024 onward, introduces a risk-based compliance model for AI systems, requiring transparency, human oversight, and data governance for high-risk applications. Furthermore, the CRA (Cyber Resilience Act) [43] and eIDAS 2.0 [44] are monitored to ensure

future compliance with secure product development and digital identity requirements. TwinEU also aligns with ENISA cybersecurity guidelines [42] to reinforce best practices in cloud, supply chain, and incident response management.

To operationalize the regulatory frameworks outlined above, each framework is systematically mapped to specific implementation strategies and pilot site use cases. The Table 13 below presents this mapping in the form of a compliance and security matrix. It links each major EU regulation or standard to its core data protection or cybersecurity requirement, describes how TwinEU addresses it in practice, and identifies the relevant use cases where these requirements are applied:

Table 13 - Compliance and Security Matrix for TwinEU

Framework / Standard Name	Requirement Description	TwinEU Implementation Strategy	Relevant Use Case(s)	Justification
GDPR (EU 2016/679)	Lawful processing, data minimization, privacy by design, data subject rights	Anonymization, consent management, access control, encryption, and transparency mechanisms across pilots	Ge05, Ge06, Ib09, Ib12, BG09	These use cases involve processing or exchanging personal or operational data (e.g., grid measurements, flexibility offers, market participation) where anonymization, consent, and data minimization are required.
NIS2 Directive (EU 2022/2555)	Cybersecurity risk management, incident detection, supply chain security, 72h breach notification	Risk assessments, continuous monitoring, incident response plans, and secure supply chain practices	NL01, FR01, IT01, EM-CY-02, Ib04	These use cases involve real-time grid operation, cyberattack detection, contingency analysis, or cross-border coordination, all of which require robust cybersecurity, incident response, and supply chain security.

EU Data Governance Act & Data Act	Trustworthy data sharing, interoperability, transparency, and accountability	Federated dataspace with secure APIs, audit logs, and governance rules for data exchange	Ge07, EM-GR-01, BG10, Hu03, Ib10	These use cases require trustworthy, auditable, and transparent federated data exchange, automated interfaces, or data sharing agreements between multiple operators or market actors.
ISO/IEC 27001	Information Security Management System (ISMS) including policies, risk assessments, and audits	Security policies, access control, encryption, audit trails, and continuous improvement processes	NL01, Ge07, Hu01, EACL-IT-01, Ib10	These use cases require secure data lifecycle management, access control, and auditability, as they involve sensitive operational data, market transactions, or grid planning.
IEC 62351 and IEC 62443	Secure communication protocols (IEC 62351) and OT cybersecurity (IEC 62443)	SCADA protection, OT segmentation, device hardening, and secure-by-design development in pilots	NL01, NL02, FR01, Ge01	These use cases involve SCADA integration, OT system protection, or secure communication between grid components.
National and Energy Sector Regulations	National laws and sector-specific rules (e.g., REMIT)	Secure logging and monitoring of market transactions, compliance with national cybersecurity mandates	Ib04, Hu03, Ib10, EM-GR-01, EACL-IT-01	These use cases involve market operations, cross-border exchanges, or grid planning subject to national or sector-specific regulations.
Additional EU Initiatives	AI Act, Cyber Resilience Act (CRA), eIDAS 2.0, ENISA guidelines	Risk-based AI compliance, secure product development,	BG02, BG03, BG04, Ib01, Ib02, Hu01	These use cases involve AI-based forecasting, risk-based

		digital identity integration, and ENISA-aligned practices		compliance, or digital identity management.

2.5.7.2 Defining Data Protection and Cybersecurity Guidelines

To operationalize compliance, TwinEU has established a set of actionable data protection and cybersecurity guidelines that bridge legal requirements and technical measures. These guidelines cover both organizational policies and technical controls, ensuring that data is handled securely throughout the platform and pilots. They are aligned with the regulatory frameworks outlined in Section 2.5.7.1 and the Compliance and Security Matrix (Table 13), and are summarised in Table 14 below:

- **Data Minimization and Anonymization:** Data collection is minimized, preferring aggregated or anonymized datasets. This guideline operationalizes GDPR's data minimization principle (Art. 5(1)(c)) [10]. In practice, TwinEU's digital twin models emphasize the use of system data (e.g. grid measurements, network topology, market prices) without attaching personal identifiers. For example, the German pilot's digital twin of the distribution grid processes prosumer electricity usage profiles in aggregated form, eliminating privacy risks at source.
- **Consent and Transparency:** In any scenario where personal data or identifiers might be involved, TwinEU ensures proper consent is obtained and that data subjects are informed about how their data is used, consistent with GDPR Articles 6 and 7 [10]. Although the project does not plan to process end-user personal data extensively, this guideline ensures preparedness for future extensions or voluntary data contributions. TwinEU components are expected to include privacy notices in user interfaces (e.g., dashboards, mobile apps), and to support data subject rights (access, rectification, erasure) in line with GDPR. This not only satisfies legal obligations but also fosters trust among users. According to stakeholder interviews in D2.1 [18], such transparency and user engagement are essential for addressing concerns around digital energy technologies.
- **Secure Data Storage and Transmission:** All data at rest in TwinEU databases or data lakes will be stored securely (encrypted when appropriate, access-controlled), and all data in transit between TwinEU components is transmitted over encrypted channels. This aligns with GDPR Article 5(1)(f) [10], NIS2 [9], and ISO/IEC 27001 [16]. Industry-standard encryption mechanisms are planned (e.g., TLS for APIs, encrypted tunnels for inter-datacentre links, strong symmetric encryption such as AES-256 for sensitive backups). The Bulgarian pilot's DT exchange platform uses HTTPS and MQTT over TLS to protect operational data. These practices are further guided by IEC 62351 [41] and IEC 62443 [35]. Additionally, data integrity checks (e.g. digital signatures, hash verification) are applied to critical data transfers, such as the Dutch-French pilot shares grid models.
- **Access Control and Identity Management:** TwinEU enforces strict access control policies to ensure that only authorized personnel, services, or components can access certain data. This includes role-based access control (RBAC) and, where feasible, attribute-based access control. All access will be authenticated using strong authentication mechanisms, including multi-factor authentication for administrative access. An IAM (Identity and Access Management) service will be integrated, potentially leveraging OAuth2.0[7] and the European Digital Identity

[7] OAuth2.0 authorization framework is a protocol that allows a user to grant a third-party web site or application access to the user's protected resources, without necessarily revealing their long-term credentials or even their identity [73].

framework (eIDAS 2.0) for cross-border authentication and trust services. Audit trails are maintained to support GDPR [10] accountability and NIS2 [9] compliance.

- **Data Governance and Ownership:** As a federated system, TwinEU requires clear governance rules on data ownership, sharing, and accountability. For any dataset ingested or generated, ownership and permissible uses must be defined and respected. TwinEU acts as a processor or intermediary, following the data owner's instructions. For instance, in the Slovenian pilot, a data use agreement ensures that DSO asset data is for agreed purposes. All data handling processes are documented (source, purpose, retention, etc.), aligning with GDPR Article 30 and internal governance best practices. Ongoing assessments will ensure compliance with evolving regulations. This implies potential updates to policies as laws evolve (for example, adjusting to any new privacy regulation if it comes into force during the project).
- **Retention and Deletion:** TwinEU defines retention periods for each data category and ensures secure deletion or archiving. This supports GDPR's storage limitation principle and good cybersecurity hygiene. TwinEU will not keep data longer than necessary for the project's aims. Each pilot should define retention periods for various data categories. For example, raw high-frequency sensor data in the Hungarian pilot may be retained only for the duration of analysis, while derived models or results (without personal data) may be stored longer. Secure deletion methods (e.g. cryptographic erasure, multiple overwriting) are used to prevent data remanence.
- **Incident Response for Data Breaches:** TwinEU will define a formal incident response plan. This includes prompt notification of affected partners or individuals and cooperation with authorities, in line with GDPR Article 33 and NIS2. For example, if a cloud server were compromised, the coordination team would isolate the incident, assess its scope, notify relevant authorities, and remediate. Continuous monitoring (via IDS/IPS systems and audit logs) supports early detection and mitigation, reflecting lessons from real-world incidents.

Table 14 below presents a consolidated overview of these guidelines, by linking them to regulatory and technical requirements and pilot-specific examples:

Table 14 - TwinEU Data Protection and Cybersecurity Guidelines

Guideline	General TwinEU Principle	Pilot Examples	Regulatory Basis
Data Minimization & Anonymization	Collect and use only data essential for TwinEU's purposes. Prefer anonymized or aggregated data to personal data. Ensure no unnecessary personal identifiers are present in datasets. All personal data fields are reviewed and justified.	*German Pilot:* Uses only aggregated load profiles for prosumers. No individual household identifiers are stored. *Italian Pilot:* Focuses on grid sensor and DER data; personal data of EV owners or prosumers is not collected at all, following a privacy-by-design approach.	GDPR Art. 5(1)(c), Art. 25
Consent & Transparency	Obtain clear consent from individuals if personal data is involved; provide transparent information on data use. All users and data providers are	*Eastern Mediterranean Pilot:* If community energy data were used, participating prosumers sign consent forms detailing data usage. In practice, the	GDPR Art. 6, Art. 7, Art. 12–14

	informed of what data is collected and why. Privacy notices are embedded in TwinEU tools.	pilot avoided needing consent by not using any private individual's data. *Iberian Pilot:* Data sharing agreements explicitly outline data purposes and include clauses that participants can audit how their data is used (ensuring transparency and trust).	
Secure Storage & Transmission	Apply strong encryption and security controls for data at rest and in transit. Use TLS for all communications, encrypted databases or containers for sensitive data, and strict firewalling. Regularly patch and update systems to protect against vulnerabilities in data storage/transmission components.	*Bulgarian Pilot:* SCADA-to-Digital Twin data link is secured via VPN with TLS encryption (per IEC 62351). Historical grid data stored in the pilot's database is encrypted. *Dutch-French Pilot:* Exchanges grid models via a secure data space connector which automatically encrypts data in transit and enforces usage control policies.	GDPR Art. 5(1)(f), Art. 32; IEC 62351-3; NIS2 Art. 21
Access Control & Identity Management	Enforce role-based access control (RBAC) for all TwinEU systems. Each user/service has a unique identity; use multi-factor authentication for critical access. Principle of least privilege: users only access data necessary for their role. Maintain an identity federation for cross-organization access with audit trails.	*Hungarian Pilot:* Operators and analysts have separate roles, e.g., only the TSO's admin account can push new grid model data into the Twin, whereas DSO users have read-only access to results relevant to their network. *Slovenian Pilot:* Since multiple organizations collaborate, they use a federated login (each partner's credentials mapped to TwinEU roles). Access logs are reviewed monthly by the pilot's security lead.	GDPR Art. 32; ISO/IEC 27001 Annex A.9; eIDAS 2.0
Data Governance & Ownership	Define ownership for each dataset and adhere to usage restrictions. Data providers retain ownership and control; TwinEU acts as custodian. Implement data sharing agreements specifying permissible use, retention, and onward sharing. Any third-party data usage requires approval. Ensure compliance with Data Governance Act (DGA)	*Iberian Pilot:* Multiple stakeholders (TSO, DSO, MO) contribute data. A governance board in the pilot approves any new data use cases. For example, market data provided by OMIE cannot be used by TSOs outside TwinEU's scope without OMIE's consent. *Dutch-French Pilot:* A memorandum of understanding between RTE	EU Data Governance Act Art. 5–7; GDPR Art. 28

	principles for data sharing neutrality.	and TenneT governs cross-border data exchange, including clauses that data received is only used for the agreed TwinEU simulation and not for other competitive purposes (preventing misuse and ensuring trust).	
Retention & Deletion Policy	Set and enforce data retention limits. Different data categories have defined retention periods (e.g. raw data retained X months, processed results Y years). After expiry, data is securely deleted (wiped or archived in locked storage if needed for audit). Regularly purge data that is no longer needed to minimize risk.	*German Pilot:* Real-time simulation data is retained for 6 months for analysis, then automatically purged by a script, leaving only yearly summary metrics. *Eastern Med. Pilot:* At project end, all collected raw data from the local grid is exported to a secure archive for the partner utility and wiped from TwinEU servers, ensuring no lingering copies.	GDPR Art. 5(1)(e), Art. 17
Incident Response (Data Breaches)	Establish and drill a data breach response procedure. If a data breach is suspected or confirmed: contain incident, notify relevant partners and authorities within required timelines, investigate and close vulnerabilities, and document the incident and response. Perform post-incident analysis to improve future resilience.	*All Pilots:* Should have local incident response contacts to coordinate with for example, TwinEU central management, if a breach of the TwinEU node occurs.	GDPR Art. 33–34; NIS2 Art. 23–24

2.5.7.3 Defining Best Practices

Beyond formal guidelines and compliance, TwinEU actively integrates industry best practices and lessons learned from both past projects and standardization bodies to enhance cybersecurity and data privacy. Best practices are iterative and often go beyond minimum compliance, aiming for excellence in security and resilience. In Deliverable D3.1 (Twin EU Open Reference Architecture) [20], the need for such best practices was identified, particularly in Section 9, which examines use cases from the perspective of data privacy and cybersecurity and derives additional reference architecture requirements. Additionally, Deliverable D2.1 [18] and D2.2 [19] survey numerous Horizon 2020 projects (such as OneNet, CyberSEAS, EnergyShield) and highlight common challenges and solutions in digitalizing the energy sector, including the need for robust security frameworks and data sharing protocols. TwinEU leverages these insights to adopt a best-of-breed approach:

- **Adoption of Proven Security Frameworks:** TwinEU aligns with several internationally recognized cybersecurity guidelines and standards, including ISO/IEC 27001 [16] for information security management systems, the NIST Cybersecurity Framework [45] for holistic resilience planning, IEC 62351 [41] for secure communication in power systems, and IEC 62443 for industrial control system security. These frameworks provide a structured approach to protecting digital twin components across IT and OT boundaries and are reflected in TwinEU's architectural choices as documented in D3.1 [20] and pilot-level security planning in WP5 deliverables.

- **Defence in Depth (Multi-Layered Security):** TwinEU employs a multi-layered defence strategy, ensuring that if one control fails, others still protect the system. This includes network-level defences (firewalls, network segmentation between IT and OT environments of the pilots), application-level defences (secure coding practices, code review, and penetration testing of TwinEU software components), and data-level defences (encryption, access controls as described). Each pilot is encouraged to implement network segmentation strategies that digital twin components from critical operation systems, in line with best practices recommended by IEC 62443. While specific implementations vary, the principle of isolating IT and OT environments with controlled interfaces is a recognized cybersecurity measure for preventing lateral movement and cascading attacks. As a specific measure, TwinEU also requires secure configuration management: default passwords are changed, unnecessary services disabled, and systems hardened, following best practice benchmarks (like CIS Benchmarks [72]).
- **Privacy by Design & Security by Design:** From the architecture phase (as documented in D3.1 [20]) through to implementation, TwinEU integrates privacy and security considerations in the design of every component. This is evident in the TwinEU Open Reference Architecture which explicitly includes a "Trust, Security and Data Sovereignty" layer. Best practice dictates that rather than bolting on security later, it should be an integral part of system requirements. TwinEU followed this by including cybersecurity requirements as part of the initial requirements gathering (Section 2.5.5 of this deliverable and Section 6.3.2 of D3.1 [20] on non-functional requirements which list security and privacy requirements). The principle of least privilege in software design is also enforced: microservices in the TwinEU architecture only get the minimum permissions they need (e.g., a forecasting service can read input data but cannot modify security settings). Additionally, TwinEU embraces privacy-by-design techniques such as data pseudonymization (if personal data were to be used, it would be replaced with pseudonyms or tokens, with the identity data kept separately and securely). While currently TwinEU avoids personal data, this shows foresight in case circumstances change.
- **Interoperability and Standards Compliance:** An important best practice, especially in the smart grid context, is adhering to standards to ensure interoperability, security and sovereignty. TwinEU aligns with the SGAM (Smart Grid Architecture Model) not just for functional interoperability but also to systematically address security at each layer. For instance, at the Communication layer of SGAM, TwinEU mandates use of standard secure protocols (TLS, MQTT with TLS, HTTPS, IEC 62351 extensions for power protocols). At the Information layer, TwinEU promotes use of common data models (CIM) with proper data validation to prevent injection of malicious data, a lesson learned from OneNet and other projects that stress standardized data exchange reduces errors and attack surfaces. At the Component layer, best practice is to use certified devices when possible (for example, RTUs or PMUs used in pilots should comply with IEEE 1686 or have undergone cybersecurity testing). SGAM alignment promotes Data Sovereignty, since the data provider remains always in control of their data even after sharing it. This is achieved by data usage policies, **policy enforcement points (PEPs)** and **contract negotiation.** Deliverable D2.2 [19] discussed how no unified security framework for DTs existed and recommended international standards (NIST, ISO, etc.) be used. TwinEU converges various compliance needs into a unified matrix (as seen

in Table 13) and ensures each pilot maps its implementation to at least one known standard or guideline.

- **Continuous Monitoring and Improvement:** Cybersecurity and data protection are not "set-and-forget" tasks. A best practice is to continuously monitor the system for threats and to regularly re-evaluate and improve security controls. TwinEU will implement this by deploying monitoring tools (e.g. IDS (intrusion detection systems) on networks, application log monitors) to catch unusual activities in real time. For instance, TwinEU can employ anomaly detection on data streams, if a digital twin starts receiving values outside expected parameters at odd times, it could indicate a malfunction or intrusion, triggering an alert. Moreover, TwinEU's governance includes periodic security reviews as part of the general functionality testing: the consortium will proceed to assess (at least annually, or after any major incident) of the security posture and privacy compliance of the platform. These reviews consider changes in the threat landscape, new regulatory developments, and feedback from pilots. By engaging early and continuously with regulatory bodies, TwinEU can anticipate and adapt to evolving compliance expectations. In addition, each pilot is encouraged to explore cyber drill scenarios, although coordinated exercises are not yet consistently implemented across all sites. TwinEU's incident response plan includes a "lessons learned" step to ensure improvements after any incident. The project also follows developments from ENISA [42] and others. By building a culture of continuous improvement, TwinEU stays proactive. This directly addresses stakeholder concerns: as D2.1 [18] reported, energy stakeholders worry that rapid digitalization increases cyber risks and requires ongoing vigilance. TwinEU's commitment to monitoring and iterative enhancement demonstrates to TSOs/DSOs and regulators that the platform will not stagnate in the face of new threats but will evolve to maintain a high security and privacy standard.
- **Cross-Border Collaboration and Information Sharing:** Cyber threats in the energy sector are often global or regional, and no entity has a complete picture alone. A best practice for improving resilience is to participate in information sharing initiatives to learn about emerging threats and share anonymized incident information. TwinEU embraces this collaborative approach and encourages participation in cross-border information sharing efforts such as EE-ISAC (European Energy Information Sharing and Analysis Centre [69]) or ENTSO-E's cybersecurity working groups. These are monitored as part of future collaboration opportunities rather than current project deliverables. By doing so, TwinEU partners can exchange non-sensitive details about any threats or near-misses they observe and receive early warnings about threats seen elsewhere. D2.1 [18] highlighted that cross-border collaboration and threat intelligence sharing are increasingly important for cybersecurity in the energy domain. In line with NIS2's [9] emphasis on cooperation and ENISA's [42] promotion of threat information sharing, TwinEU positions itself to contribute to and benefit from collective knowledge. For example, the Iberian pilot might coordinate with a European cybersecurity network to report any novel attack attempt it encountered, or the project's security leads might attend Horizon Europe cluster meetings on cybersecurity to exchange lessons with peer projects (hypothetical). By sharing anonymized incident reports and mitigation strategies, TwinEU helps the broader community and in return gains insights that bolster its own defences. This cooperative stance enhances collective resilience and shows regulators and stakeholders that TwinEU is proactive and well-integrated into the EU's cybersecurity ecosystem.
- **Training and Awareness:** Human factors remain one of the weakest links in cybersecurity, so continuous training and awareness-raising are considered essential best practices. TwinEU will institute a security training awareness program for all personnel involved in the project, from

developers to system operators. Each partner organization commits that relevant staff will undergo cybersecurity informative sessions, for example, how to recognize phishing emails, how to handle sensitive data, and how to report incidents. NIS 2 explicitly requires that essential entities train their staff in cybersecurity, and TwinEU aligns with this by mandating at least annual training refreshers. Many pilots also incorporate hands-on drills or tabletop exercises. By fostering a culture of security mindfulness, TwinEU reduces the likelihood of an accidental breach caused by human error or social engineering. This focus on people complements the technical measures: even the best technology can be undermined by an unaware user, so TwinEU strives to ensure everyone is on board with security. In essence, the project treats cybersecurity as a shared responsibility.

Overall, these best practices ensure that TwinEU's cybersecurity and data protection measures are state-of-the-art and resilient. The combination of compliance (Section 2.5.7.1), concrete guidelines (Section 2.5.7.2), and best practices (this section) provides a 360° approach under Task 3.4: legal requirements are met, operational policies are in place, and the system design is robust and continuously improving. Many of these best practices (adopting NIST CSF [45], defence in depth, privacy-by-design, etc.) go beyond what is strictly mandated but are crucial for operational trustworthiness. They address the "grey areas" of societal and business expectations, for instance, an energy company considering using TwinEU will be assured not just that "we comply with GDPR," but that we actively train our staff, test our defences, follow the latest standards, and plan for the unexpected. This level of diligence is necessary in the energy sector, where cybersecurity incidents can have significant safety and economic consequences. TwinEU incorporates lessons from prior projects and aligns with widely recognized frameworks to define a strong baseline for cybersecurity and data protection across federated digital twin infrastructures.

2.5.7.4 Identifying Potential Cybersecurity Threats and Vulnerabilities

Even with strong preventive measures and best practices, understanding potential threats and system vulnerabilities is vital. This subsection details how TwinEU approaches threat identification, the types of threats considered (drawing on both energy-sector experience and general IT/OT security knowledge), and how vulnerabilities are assessed and prioritized for mitigation.

- **Unauthorized Access (Insider or External Intrusion)**: The risk that an unauthorized person or malware gains access to TwinEU systems or data, either by hacking in from outside or via insider misuse of credentials. This could lead to data theft, manipulation, or sabotage of TwinEU's digital twin operations. Potential vulnerabilities include weak passwords, unpatched software, or misconfigured access controls.
  TwinEU's Countermeasures: Strong authentication (MFA), strict RBAC policies, network segmentation, and monitoring of access logs are implemented to prevent and detect unauthorized access. In addition, periodic security assessments or penetration tests are recommended to detect control gaps, in line with ISO 27001 best practices.
- **Malware and Ransomware Attacks:** The introduction of malicious software that could infect TwinEU servers or services. Malware might exfiltrate sensitive data or disrupt computations, while ransomware could encrypt TwinEU data or systems, impeding operations until a ransom is paid. The energy sector has seen tailored malware (e.g. Industroyer [37], which targets power grids) and thus TwinEU treats this threat seriously.
  TwinEU's Countermeasures: All servers and endpoints run updated anti-malware defences; software supply chain is managed carefully to avoid introducing infected components. Rigorous patch management is intended to be implemented across all TwinEU environments

to close known vulnerabilities that malware might exploit. Where feasible, offline or segregated data backups are maintained to enable recovery in case of data corruption or ransomware attacks, avoiding the need to pay ransom. Additionally, the network-level segmentation limits malware spread, and monitoring of system behaviour via IDS (Intrusion Detection Systems) or similar tools is encouraged across pilots to support early anomaly detection.

- **Denial-of-Service (DoS/DDoS) Attacks:** An attacker could flood TwinEU's platform or networks with excessive traffic or deliberately trigger heavy computational loads, aiming to make the TwinEU services unavailable or unresponsive. For a platform delivering near real-time grid insights, loss of availability can delay critical decisions or erode trust.

  TwinEU's Countermeasures: The architecture is designed to be scalable and to include DDoS (Distributed Denial of Service) protection (e.g. cloud-based DDoS mitigation services or rate-limiting on APIs). Network traffic is monitored for spikes, and filtering mechanisms drop illegitimate traffic. On the application side, queries are sanity-checked to prevent abusive calls that could cause resource exhaustion. While not all pilots have explicitly documented deployment of dedicated DDoS countermeasures, such controls are recommended in accordance with ISO 27001 and NIS2, and future platform rollouts are expected to incorporate scalable protection mechanisms. These measures align with energy infrastructure best practices, since DDoS on critical systems is a known threat.
- **Data Integrity Attacks (Spoofing or Manipulation):** Rather than outright disabling systems, an attacker might subtly manipulate the data going into or out of TwinEU to cause incorrect outputs. For example, injecting false sensor readings, altering model parameters, or tampering with data in transit (e.g., Man-in-the-Middle attack) could lead TwinEU's analytics to provide misleading results (which, if trusted by operators, could cause operational mistakes). This kind of attack undermines the integrity of the decision support TwinEU provides.

  TwinEU's Countermeasures: All data inputs from the field are authenticated and validated e.g. sensors feeding TwinEU have digital signatures or come through secure gateways, so their provenance is confirmed. TwinEU also implements plausibility checks: if a data point is wildly outside expected range or a simulation result defies known physical constraints, it flags it for review. Using standard data models (CIM [8]) with defined validation rules helps here. Additionally, any human inputs or external data are subject to verification steps. Pilots are encouraged to implement data validation mechanisms and anomaly detection models tailored to their operational domains, even though digital signatures on all inputs may not yet be standardized. By maintaining data integrity, TwinEU ensures trust in its digital twin outputs.
- **Supply Chain and Third-Party Component Risks:** TwinEU relies on various third-party libraries, open-source tools, and potentially cloud infrastructure. These external components might harbour vulnerabilities that could provide backdoors into TwinEU's system.

  TwinEU's Countermeasures: An inventory of all third-party components is maintained, and updates are monitored. Security patches for libraries or platforms are applied promptly. TwinEU's CI/CD pipeline includes dependency vulnerability scanning. Moreover, where feasible, TwinEU uses certified or trusted versions of components and avoids unnecessary dependencies. Although a formal, harmonized SBOM policy is not yet mandated across all pilots, implementing such inventories and automated security scans is considered best practice and recommended for all future deployments. In contracts with any cloud or service provider, security requirements and audit rights are included. This reduces the risk of an upstream weakness compromising TwinEU.

- **Cyber-Physical Attacks:** Although not directly a vulnerability of TwinEU's software, a scenario of concern is a coordinated attack that bridges cyber and physical realms. For example, using TwinEU's presence in the system to affect physical grid operations (or vice versa). An attacker might attempt to feed malicious control suggestions via TwinEU that could harm the grid or exploit a grid disturbance to slip past cyber defences. Past incidents like the Ukraine power grid attack show how cyber-physical attacks can have cascading effects [46].
  TwinEU's Countermeasures: TwinEU is not a direct control system; it does not directly dispatch control commands to devices without human validation (decoupling from real-time control prevents automatic cascades). Also, any control recommendations from TwinEU undergo sanity checks in the control room environment. This, combined with the network isolation mentioned earlier, means even a compromised TwinEU scenario cannot immediately translate to physical damage; operators have the final say and fallbacks exist (manual control can override digital twin outputs). This architectural separation between decision support and actuation is a foundational safety feature, but it is recommended that pilots regularly test these human-in-the-loop mechanisms to ensure reliability in emergency scenarios.

2.5.7.5 Recommending a Business Continuity Plan (BCP) to Ensure Operational Security

To ensure operational security and system resilience within the TwinEU federated DT ecosystem, a BCP (Business Continuity Plan) is proposed. This plan aims to maintain service availability during cyber or physical disruptions, while aligning with EU regulatory requirements mentioned in the above sections.

Identified Challenges:

The following challenges necessitate the establishment of a structured BCP:

- Cybersecurity assessments across several pilots evaluated the potential impact of threats such as man-in-the-middle, denial-of-service (DoS), spoofing, phishing, and false data injection attacks. While not all pilots reported direct exposure, these threat vectors can be identified as critical risks to DT stability and data integrity.
- Interoperability and orchestration have been recognized as critical needs across the TwinEU ecosystem. While not all pilots explicitly reported issues, the German pilot explored interfacing components and real-time data exchange mechanisms (e.g., via DPsim [70] and VILLASnode [71]), and the Slovenian pilot identified significant interoperability gaps related to standardized data formats and protocols. These challenges are particularly relevant to the SGAM communication and information layers, which underpin secure and efficient DT integration.
- Data exchange in use cases depends on continuous and trusted operations between TSOs, DSOs, and MOs, making operational disruption a critical risk factor.
- EU policy frameworks such as NIS2 [9] and CER [47] emphasize the need for risk-based resilience measures, verifiable recovery capabilities, and structured risk mitigation planning for essential and critical infrastructure.

Objectives of the BCP:

The BCP is designed to:

- Safeguard the operational integrity of core DT services across all pilots during adverse events.
- Ensure defined RTO (Recovery Time Objectives) and RPO (Recovery Point Objectives) for essential functions are met.

- Implement secure fallback communication and orchestration mechanisms to preserve federated data and service continuity.
- Fulfil legal obligations related to cybersecurity, data availability, and operational resilience.

Business Continuity Strategy:

Digital Twin Federation Resilience

- Distributed orchestration redundancy is proposed, based on containerized service deployment architectures to allow for automated failover.
- Fault isolation and node-level resilience were demonstrated in pilots including the Dutch and Cypriot DTs, where fallback control functions were modelled.
- The TwinEU Dataspace Protocol (DSP) plays a critical role in maintaining secure, policy-based data exchange ensuring that federated DTs remain interoperable and auditable.

Grid and Market Operational Continuity

- Use cases such as UC-Ib04 illustrate abnormal market behaviour detection, forming the basis for resilient market operations.
- The TwinEU framework supports secure coordination among TSOs, DSOs, and MOs through defined use cases (e.g., UC-Ib15), incorporating risk mitigation protocols and emphasizing resilience, data integrity, and operational continuity. While the fallback protocols with redundancy and mirrored logging are not explicitly defined, the non-functional requirements and cybersecurity guidelines suggest that such features are expected components of the overall secure and fault-tolerant architecture.
- Cyber-physical coordination scenarios are explicitly considered: TwinEU’s advisory architecture ensures that even if DT outputs are compromised, human validation and fallback control systems prevent cascading failures (D5.2 (not completed)).

Cybersecurity Measures and Data Protection

- Threat response strategies within the TwinEU framework emphasize real-time anomaly detection and incident response mechanisms, aligning with ISO 27001 and NIS2 risk management principles. While encrypted backups and identity federation mechanisms are not explicitly detailed, the overall architecture promotes robust access control, regulatory compliance, and system-level resilience to support coordinated threat mitigation and recovery.
- Privacy-preserving federated data space architectures, supported by canonical data models, are designed to promote interoperability, data integrity, and secure information exchange across TwinEU’s DT ecosystem.

Proposed Recovery Objectives: The following RTO (Recovery Time Objectives) and RPO (Recovery Point Objectives) values in Table 15 are proposed as reference benchmarks, informed by established best practices in critical infrastructure sectors. These values do not represent current performance levels across all TwinEU pilots but are intended to guide future service-level objectives, resource allocation, and fallback strategy development.

RTO refers to the maximum acceptable duration that a system or service can remain unavailable following a disruption before operational impacts become significant. RPO defines the maximum allowable data loss in terms of time i.e., how far back data must be recovered to resume normal operations.

These metrics help prioritize recovery planning for critical functions such as digital twin services, market coordination, and secure data exchange within the TwinEU ecosystem. While the proposed values reflect typical expectations for high-availability systems in the energy sector, where even brief service interruptions can have cascading consequences, formal targets remain to be validated across all pilot implementations.

Table 15 - Proposed RTO/RPO Targets for TwinEU

Function	RTO (hr)	RPO (hr)	Rationale
Core DT Services	1	0.5	DTs are essential for real-time monitoring and control. A 1-hour RTO ensures minimal disruption to grid operations.
Market Operation Coordination	2	1	Market processes can tolerate slightly longer recovery but must resume quickly to avoid cascading effects.
Federated Data Exchange	1	0.5	Ensures continuity of cross-entity data flows (TSO–DSO–MO), critical for synchronized operations.
Secure Communication Interfaces	0.5	0.25	Communication channels are foundational for all coordination and fallback mechanisms; must be restored rapidly.

Governance and Revision Cycle

- Post-incident review processes are established to incorporate lessons learned, enabling the adjustment of operational and technical safeguards to strengthen system resilience and inform future responses.
- The BCP is subject to periodic review, particularly following significant incidents or shifts in the regulatory landscape. Updates are guided by feedback from pilot activities, incident evaluations, and evolving cybersecurity and resilience requirements.

Training and Preparedness

- The Dutch-French pilot site leverages DT technologies to simulate realistic network scenarios including contingencies and cyberattack effects for the purpose of training system operators and supporting scenario-based readiness assessments. These simulations facilitate operator debriefing and contribute to evaluating grid stability and operational responses.

- DT-based scenario simulations conducted across pilot sites support the assessment and refinement of operational procedures. While the frequency and coordination of joint simulation exercises are not formally specified, these activities contribute to continuous learning and may inform future updates to continuity planning practices.

Proposed Metrics for BCP Effectiveness: To ensure continuous improvement, the following KPIs are proposed as standard metrics that TwinEU pilots can track over time. While not all of them are currently implemented across all pilots, they are grounded in industry-standard operational resilience practices and align with NIS2 [9] and ISO 27001 [16] guidance:

- **Mean Time to Recovery (MTTR):** MTTR is a standard operational resilience metric used to measure how quickly a system or service can be restored after a disruption. MTTR can be derived by logging downtime duration and comparing it with RTO targets to assess recovery performance and highlight areas needing improvement.
- **Incident Frequency and Severity:** Tracking the number and criticality of incidents is essential to monitor trends, evaluate resilience, and prioritize mitigations. This KPI can be logged via the CMS (Cybersecurity Management System) and pilot site reports. This metric is useful for identifying recurring vulnerabilities or high-impact failure modes.
- **Percentage of Successful Fallback Activations:** This metric is best assessed during pilot-specific drills or controlled simulation scenarios. Its consistent collection is recommended to validate fallback reliability.
- **Compliance with Notification Timelines**: TwinEU should monitor whether each pilot meets the expected notification timelines (e.g., 4h for NCCS, 24h for CER) following a breach or major incident, in accordance with NIS2 [9] and CER [47]. Logging incident timestamps will facilitate compliance tracking.

These KPIs and BCP strategies are not intended to be prescriptive but rather provide a maturity framework that pilots can adapt and enhance throughout the TwinEU project lifecycle. Their successful integration will contribute to measurable improvements in resilience and regulatory alignment. In conclusion, TwinEU's BCP integrates evidence-based recommendations from technical, cybersecurity, and organizational dimensions to ensure the continuous delivery of critical energy grid services under adverse conditions. The plan directly supports the project’s operational resilience strategy while maintaining regulatory alignment with EU cybersecurity and infrastructure mandates. By embedding fallback mechanisms, simulation-based training, and a structured governance cycle into the platform’s lifecycle, TwinEU ensures that resilience is not reactive but proactively designed, validated, and continuously improved.

3 Technical specifications of open interoperable Federated DT design

3.1 General description

Technical specifications for open and interoperable Federated Digital Twin (DT) design are key enabling technologies that support federation and interoperability among DTs. This process has been structured using the SGAM (Smart Grid Architecture Model) framework [22], recognized for its neutral and systematic approach for smart grid architecture design. The SGAM framework, along with other complementary architectural methodologies, has been further elaborated in Deliverable D3.1 [20].

The SGAM is a three-dimension framework that illustrates the different interoperability layers on the depth axis, the energy conversion chain from generation to customer premises on horizontal axis, and the zones from process level up to market on the vertical axis. The initial purpose of SGAM was to identify gaps in the standardization process of Smart Grids. As its acceptance grew within the energy community, SGAM evolved into a widely used framework for designing Smart Grid architectures. Over time, it has become a standardized tool for consistently describing Smart Grid system architecture.

SGAM incorporated multiple perspectives and methodologies to support the design and implementation of Smart Grids. To achieve this, it maps and visualizes use cases across its various layers, helping to establish a unified architectural mode. The overarching goal is to provide a foundation for analysing and realizing diverse Smart Grid architectures while fostering a shared vision and common language among all stakeholders.

SGAM defines five interoperability layers: business, function, information, communication, and component. In the scope of this deliverable, we focus on the component, communication, and information layers, which respectively refer to the physical and logical actors, communication channels and protocols, and data structures/models used in the interaction between Digital Twins.

The objective here is to clearly define the actors and components involved during Digital Twin interactions with emphasis on achieving semantic and syntactic interoperability. These specifications aim to ensure that DTs from different domains, stakeholders, or systems can interact in a federated manner.

3.2 Methodology

The proposed methodology follows a bottom-up approach, starting with the definition of the SGAM layers based on the Use Cases identified in WP2 and the initial architecture design of the DTs. Once the architecture for each UC is defined, the involved DTs are identified, and a generalisation process is carried out by modelling one SGAM layer per interaction type such as TSO-DSO, DSO-MO, and TSO-MO.

These individual interaction layers are then merged into a unified SGAM representation, integrating all relevant DTs and their mutual interactions across the component, communication, and information layers.

The initial modelling was applied to the Iberian pilot, which served as the reference case for building the first version of technical specifications for digital twin federation generalised architecture. A collaborative modelling environment was set up using draw.io, enabling the UC leaders to contribute directly to the architecture definitions. Each UC was assigned to a dedicated workspace, pre-filled with its corresponding component layer serving as a background template, see Figure 10. This approach allowed each leader to focus on defining the relevant components first, before subsequently adding the communication and information layers based on this initial structure.

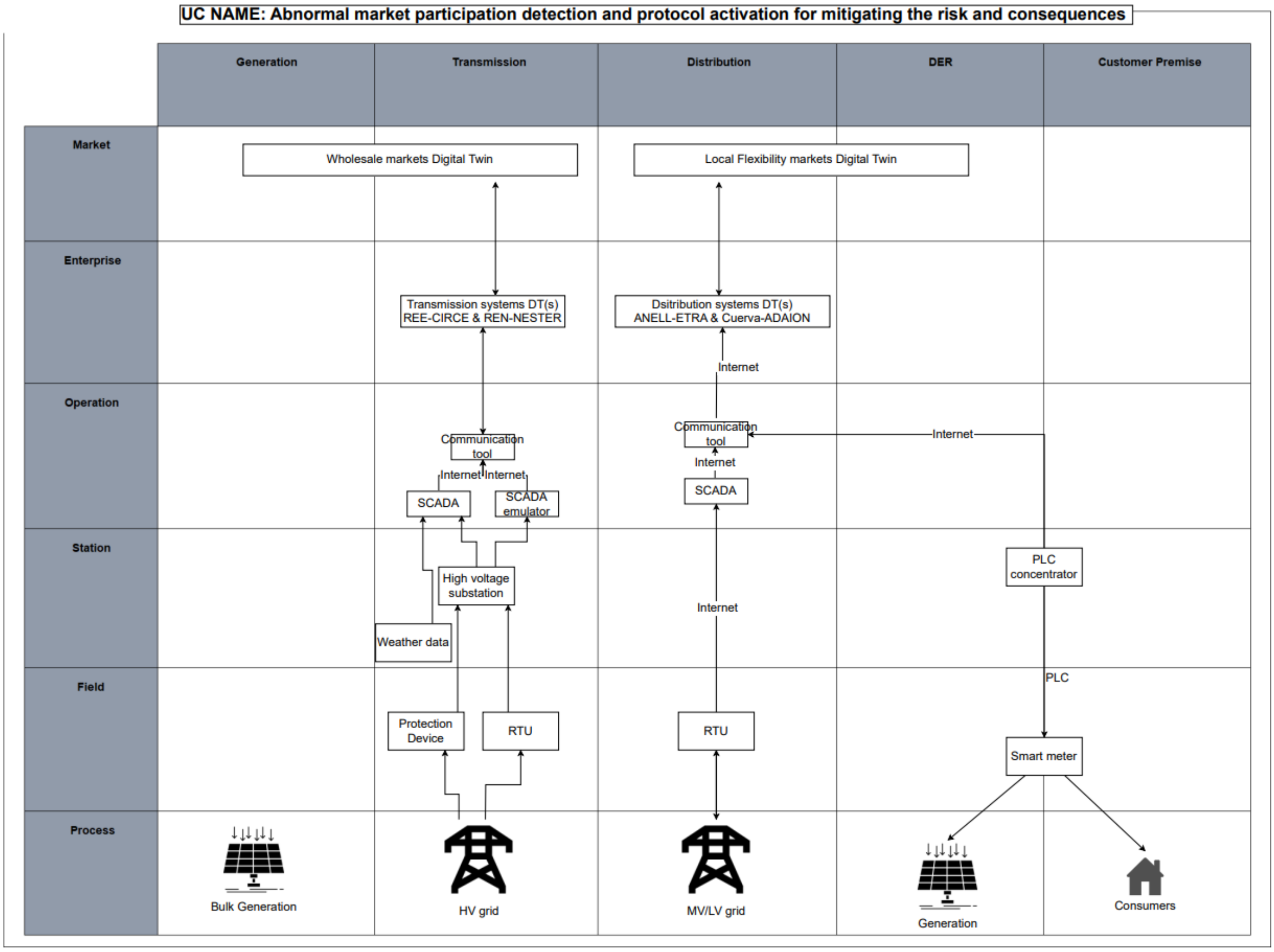


Figure 10 - Use case component layer example

All these Use Case-specific layers resulted in intermediate SGAM layer views for each interaction type (see Annex D). These were then clustered based on the Digital Twins involved and the nature of their interactions. An example of such an interaction between two DTs is illustrated in Figure 11.

Once the interactions between Digital Twins were modelled across the three SGAM layers a generalisation process was carried out. This task involved analysing and abstracting all identified interactions to define common patterns in terms of communication protocols, intermediary components, and types of information exchanged.

Through this process, the different DTs were catalogued and their interactions classified, allowing the creation of a generalised architecture for the Iberian pilot. The outcome of this consolidation work is presented in Annex D which summarises both the identified DTs and the interaction features across the relevant SGAM layers.

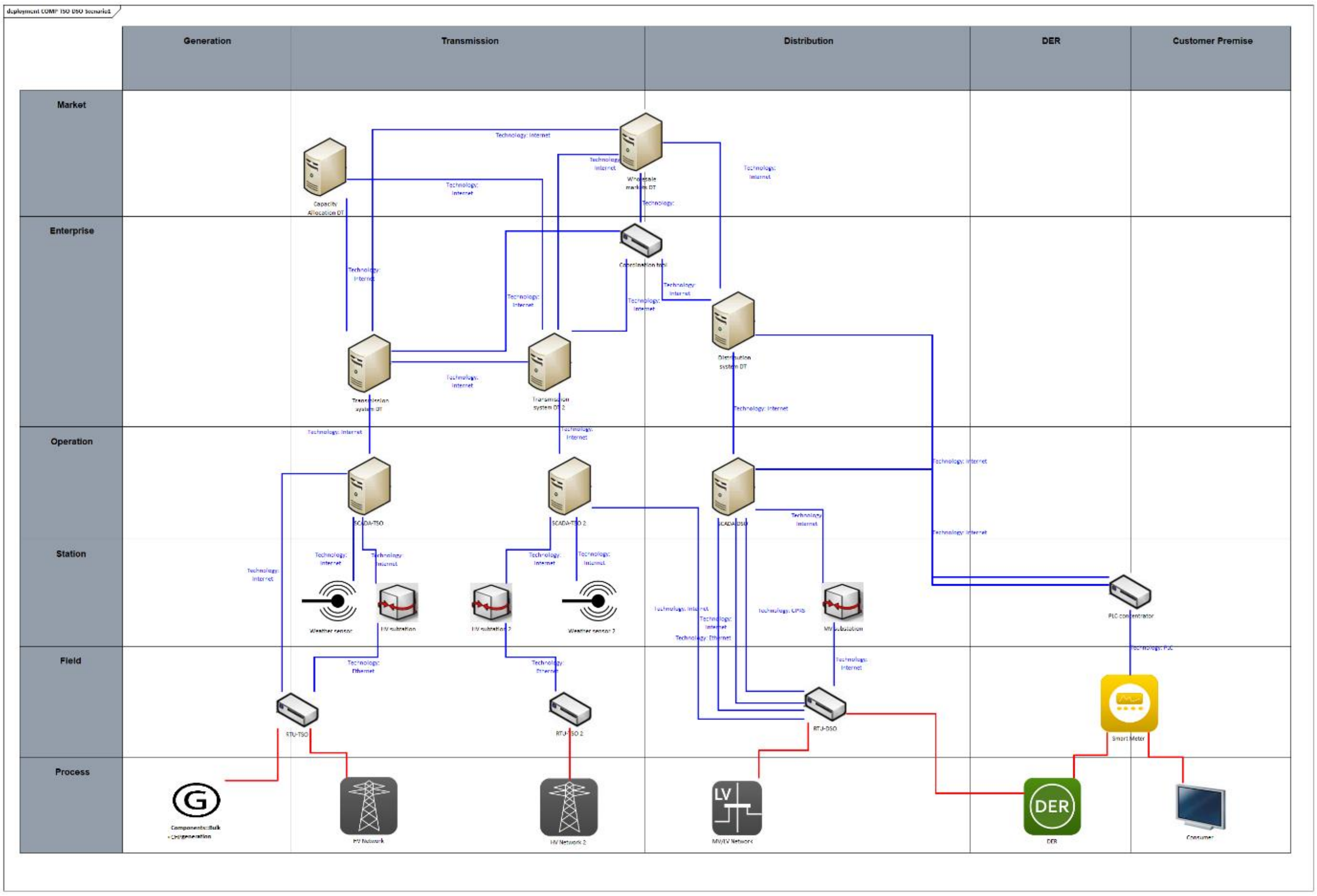
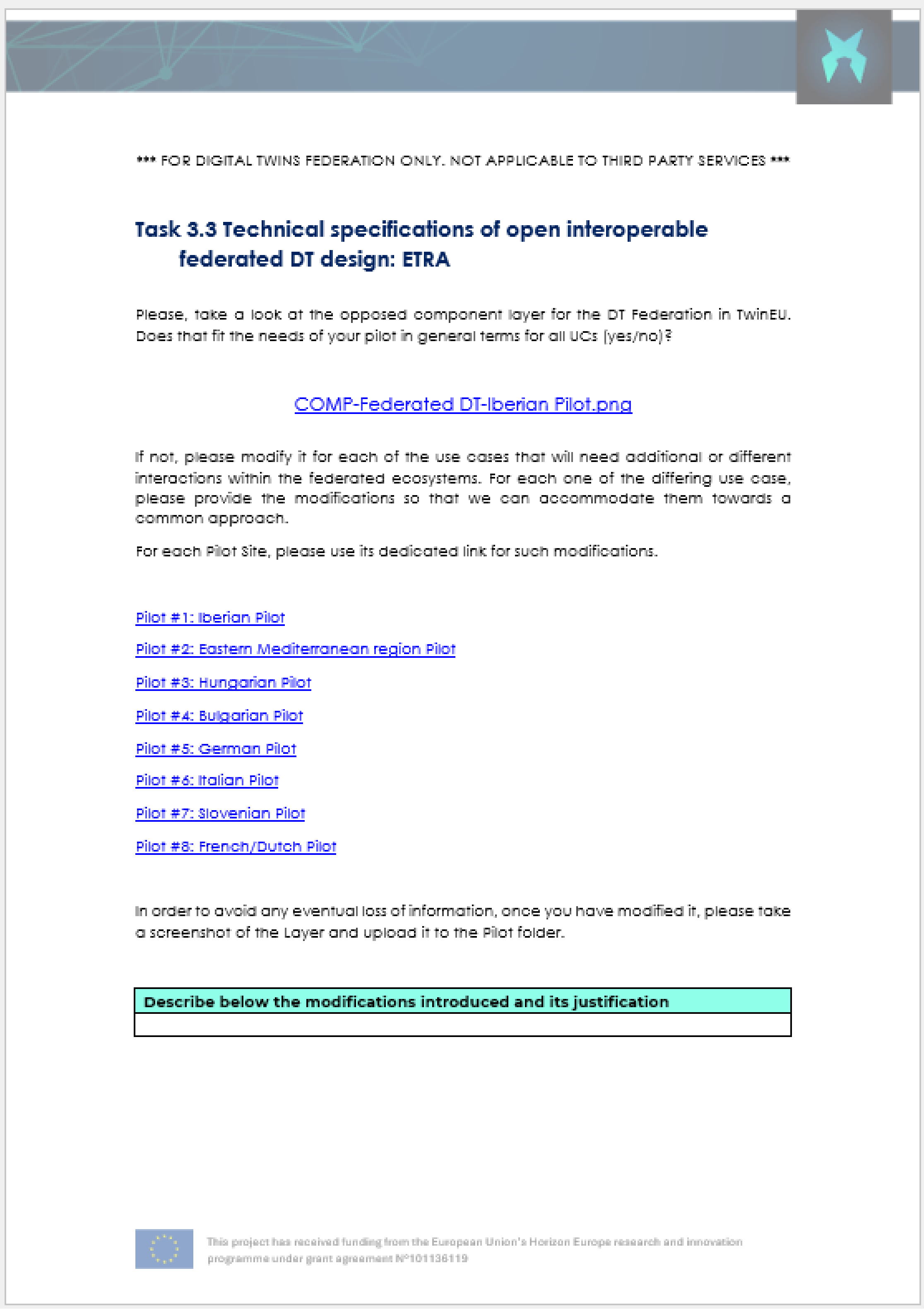


Figure 11 - Iberian Pilot TSO-DSO interaction component layer

To validate and potentially extend the generalised architecture derived from the Iberian pilot, a feedback template was distributed to the other pilots, see Figure 12. The objective of this template was to assess whether the proposed interaction model fulfilled the requirements of their respective Use Cases. In cases where the generalised model did not fully reflect their needs, pilots were asked to replicate the SGAM modelling process for their own scenarios, including the definition of the component, communication, and information layers.

As a result, inputs were collected from all pilots except the Hungarian one, due to the alignment of Hungarian Use Cases with the proposed architecture. Enabling the iteration towards a second version of the generalised federated DT architecture (see Annex D.2). By incorporating these additional Use Case perspectives, the updated model included new communication protocols, intermediary components, DT actors, and data exchanges, ultimately supporting the fulfilment of Milestone 4 for the definition of the first draft version of TwinEU Open Reference Architecture at Month 12.

Once the second version of the generalised architecture was completed, by incorporating inputs from all pilots, a refinement process was carried out to simplify and consolidate the SGAM layers. Given the high number of identified connections, this step focused on reducing complexity by aggregating actors and DTs operating within similar zones and domains, in alignment with the actor types already defined in Deliverable D3.1 [20].



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Task 3.3 Technical specifications of open interoperable federated DT design: ETRA

Please, take a look at the opposed component layer for the DT Federation in TwinEU. Does that fit the needs of your pilot in general terms for all UCs (yes/no)?

COMP-Federated DT-Iberian Pilot.png

If not, please modify it for each of the use cases that will need additional or different interactions within the federated ecosystems. For each one of the differing use case, please provide the modifications so that we can accommodate them towards a common approach.

For each Pilot Site, please use its dedicated link for such modifications.

Pilot #1: Iberian Pilot

Pilot #2: Eastern Mediterranean region Pilot

Pilot #3: Hungarian Pilot

Pilot #4: Bulgarian Pilot

Pilot #5: German Pilot

Pilot #6: Italian Pilot

Pilot #7: Slovenian Pilot

Pilot #8: French/Dutch Pilot

In order to avoid any eventual loss of information, once you have modified it, please take a screenshot of the Layer and upload it to the Pilot folder.

Describe below the modifications introduced and its justification

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement N°101136119

Figure 12 - SGAM architecture iteration process feedback template for pilots.

Additionally, the outcomes of Task 2.3, which are presented in detail in the following section, as well as the analysis conducted for D3.1 [20], were used to further refine the component, communication, and information layers. This iterative consolidation led to the final, refined architectures depicting the technical specifications for open and interoperable DT interaction, which are presented in Section 3.4.

3.3 Summary of the main technical requirements and limitations gathered in WP2 – T2.3

T2.3, *Key digital technologies boundary conditions and requirements*, produced as one of its final results the identification of a set of high-level requirements to enable the seamless coordination and cooperation of DTs in the TwinEU continuum, leveraging the prior analysis performed on the constraints of existing DTs and the restrictions posed when utilizing digital technologies, including AI and HPC. Table 16 depicts the list of the high-level requirements to enable the seamless coordination and cooperation of DTs in the TwinEU continuum. Additional information of each one of them related to a complete description, the systems they involve and the DTs they are applicable to can be found in D2.2 [19].

Table 16 - List of high-level requirements to enable the seamless coordination and cooperation of DTs in the TwinEU continuum

Technical requirement ID	Name
Tech_01	All DTs should have the capacity to be connected to the TwinEU's dataspace
Tech_02	Real-time Data Synchronization
Tech_03	Decentralized Data Architecture
Tech_04	DTs must incorporate secure protocols
Tech_05	TwinEU must ensure a certain level of Data Quality and its validation
Tech_06	Automated Data Exchange Interfaces
Tech_07	Dynamic Data Sharing Policies
Tech_08	Hybrid employment of edge and cloud computing mechanisms
Tech_09	Data Exchange Performance Metrics for Continuous Improvement
Tech_10	Data Exchange Feedback Loops for Continuous Improvement
Tech_11	Data Space federation techniques and data exchange infrastructure
Tech_12	Inter-Twins Data Sharing Agreements
Tech_13	Secure Data Transmission Protocols
Tech_14	Event-Driven Data Exchange
Tech_15	API-driven data space connectors compatibility
Tech_16	Access Control Mechanisms
Tech_17	Secure Software Development
Tech_18	Compliance with Data Protection Laws
Tech_19	RT data sharing and coordination
Tech_20	Grid planning service enablement through TSO-DSO coordination in the TwinEU architecture
Tech_21	Powerflow optimisation service enablement through TSO-DSO coordination in the TwinEU architecture
Tech_22	Enhanced shared situational awareness service enablement through TSO-DSO coordination in the TwinEU architecture
Tech_23	Grid stability enhancement service enablement through TSO-DSO coordination in the TwinEU architecture
Tech_24	DSO-TSO data shared on grid observability
Tech_25	TSO-DSO data shared on technical restrictions
Tech_26	Data exchange improvement for RT DTs operation between TSO through RCC

Tech_27	Interoperability of MO's systems with TSO/DSO Systems
Tech_28	AI models Real-Time Data Integration
Tech_29	AI services integration with DTs
Tech_30	Data models for the AI services
Tech_31	Communication models
Tech_32	HPC infrastructure Dynamic Resource Allocation / Resource management
Tech_33	HPC services Real-Time Processing and timely data availability
Tech_34	HPC Services data transfer and interoperability services
Tech_35	HPC System Security and Compliance
Tech_36	HPC System Scalability and Load Management
Tech_37	HPC System support for Distributed Computing
Tech_38	HPC System support for Parallel Computing
Tech_39	HPC Services compatibility with Batch Processing Model
Tech_40	HPC Services compatibility with hard time limits

These high-level technical requirements were used in the iterative process of the SGAM architecture production to include them into the different layers so that the TwinEU functional specifications are fully compliant with them.

The mapping exercise of relating each technical requirement to the architectural sector where they belong was done in the context of T3.1 and reported in D3.1 (section 7.2) [20].

3.4 Architectural technical specifications of TwinEU's federated DTs ecosystem

After the whole process was completed, this section reports the final technical specifications based on the SGAM methodological framework.

3.4.1 TwinEU's federated DTs ecosystem description

As mentioned in Section 3.2, the inputs from all pilots were considered in the final version of the technical specifications for the TwinEU federated Digital Twins (DTs) ecosystem. The refined component, communication, and information layers are presented in the following sections.

Within these layers, the TwinEU dataspace framework acts as an additional actor and mechanism to enable secure and interoperable data exchange among participants. Since many pilots included components such as coordination tools and data exchange platforms, the TwinEU framework offers a valuable opportunity to provide the necessary services for decentralized, secure, and interoperable data exchange between components. Further information about the Dataspace will be available in D4.1.

Overall, these layers provide a comprehensive overview of the entire value chain of digital twins and their federation. They clarify exactly what information is retrieved, how it is processed, where it is analysed and stored, and how it is presented to end-users or stakeholders. This perspective encompasses not only the IT components involved but also the communication protocols and standards used for data exchange, as well as the types of data and information being exchanged.

The integration of the component, communication, and information layers within the SGAM framework establishes a solid foundation for the technical specification of the TwinEU federated digital twins' ecosystem. The following sections will provide a more detailed description of each layer, highlighting their specific roles and contributions to the overall architecture.

3.4.2 TwinEU's SGAM component layer

The component layer constitutes the foundation for the subsequent SGAM layers, identifying the key systems, devices, and DTs involved in the TwinEU ecosystem. It represents the physical placement of all systems and components. Figure 13 provides an overview of the domains and zones mapped to each component following the SGAM model, while Table 17 lists the defined components, along with their respective domain, zone, and type.

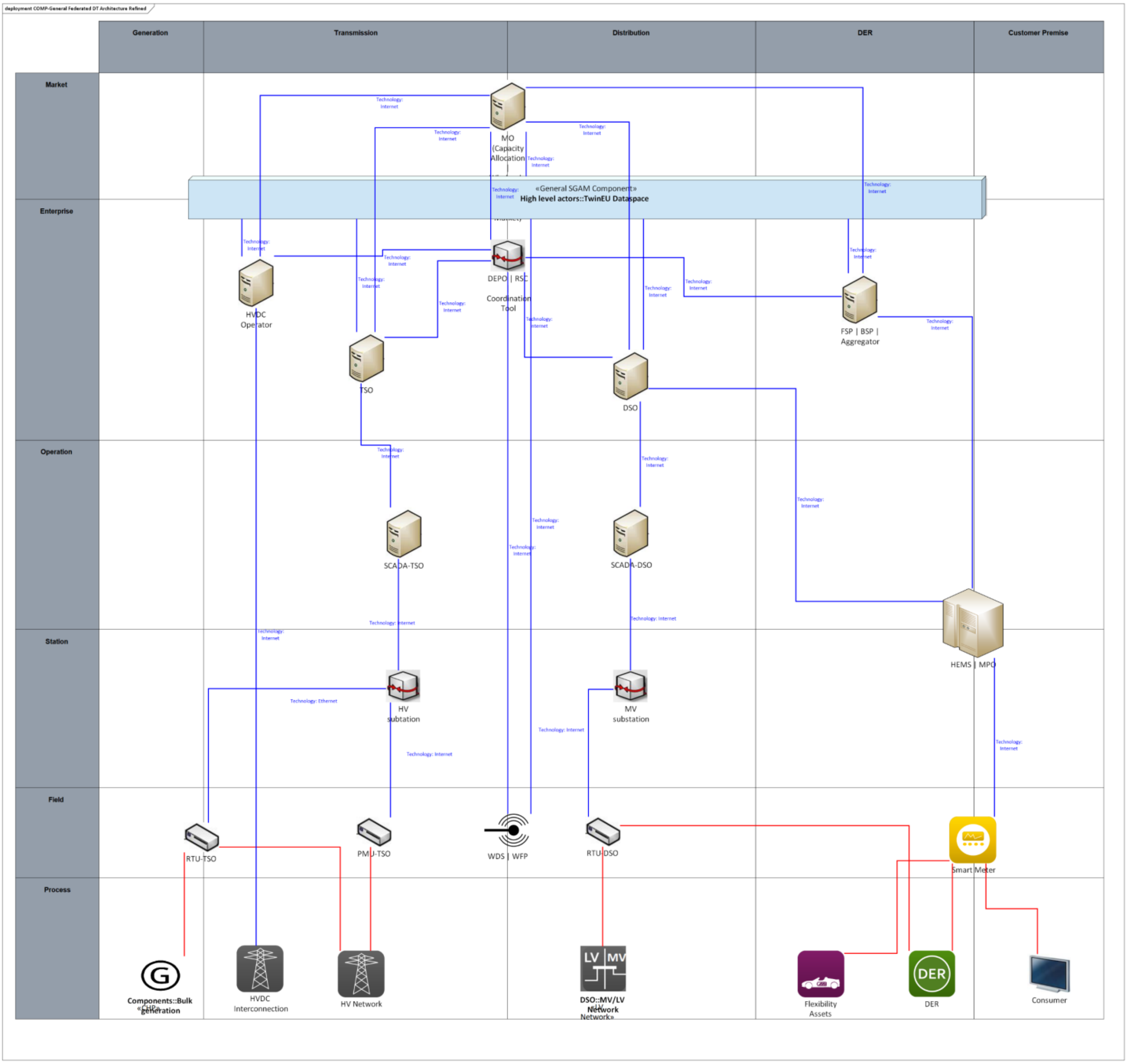


Figure 13 - Final DT federation SGAM component layer

In terms of architecture, the components can be grouped according to their functional level and zone:

- **Process Zone**: This area includes field-level devices and systems responsible for measurement, monitoring, and control. Here, the most relevant elements are the physical assets to be monitored, including sensors and meters deployed at prosumer and consumer premises, High Voltage and Low Voltage networks and bulk generation.
- **Field, Station, and Operation Zones**: These zones host the gateway components, which aggregate data from the process zone and transmit it to higher-level systems. A special focus is placed on components like HEMS (Home Energy Management Systems) and MPOs (Metering Point Operators), which appear across multiple Use Cases and pilots. These DTs handle the collection, monitoring, and preliminary analysis of data from residential or commercial users, both consumers and prosumers.
- **Enterprise Zone**: This zone integrates the core Digital Twins that are in charge of analysis, simulation, and service provision across the energy value chain. Four main DT categories have been identified in this zone: HVDC Operator DT, TSO DT, DSO DT, FSP/BSP/Aggregator DTs. Each of these entities operates within their corresponding domains and consumes the data provided by gateways to perform forecasting, scenario simulation, and real-time decision-making.

  TSO-DSO coordination is supported by components such as the Data Exchange Platform Operator and/or the Regional Security Coordinator (RSC). These components enable the exchange of key artefacts like grid models and analysis results between TSOs, DSOs, and other participants, supporting coordinated grid operation and system security.
- **Market Zone:** The Market Operator DT, including roles such as Capacity Allocation Entities, is responsible for managing both wholesale and local flexibility markets. This DT coordinates with the enterprise-level actors mentioned above to ensure the integration of market mechanisms with grid operation.

Table 17 - Final DT federation SGAM component list

Component	Zone	Domain	Component type
Bulk Generation	Process	Generation	Network
HVDC Interconnection	Process	Transmission	Network
HV Network	Process	Transmission	Network
MV/LV Network	Process	Distribution	Network
Flexibility Assets	Process	DER	Asset
Distributed Energy Resources	Process	DER	Asset
Consumer	Process	Customer Premises	Asset
RTU-TSO	Field	Generation & Transmission	Device
PMU-TSO	Field	Transmission	Device
Weather Data Supplier (WDS) |Weather Forecast Provider (WFP)	Field	Transmission & Distribution	External application | Digital Twin
RTU-DSO	Field	Distribution	Device

Smart Meter	Field	DER & Customer Premises	Monitoring System
HV substation	Station	Transmission	Gateway
MV substation	Station	Distribution	Gateway
Home Energy Management System (HEMS) | Metering Point Operator (MPO)	Station & Operation	DER & Customer Premises	External application | Digital Twin
SCADA-TSO	Operation	Transmission	Monitoring System
SCADA-TSO	Operation	Distribution	Monitoring System
HVDC Operator	Enterprise	Transmission	Digital Twin
TSO	Enterprise	Transmission	Digital Twin
Data Exchange Platform Operator (DEPO) | Regional Security Coordinator (RSC)	Enterprise	Transmission & Distribution	External application
DSO	Enterprise	Distribution	Digital Twin
Flexibility Service Provider (FSP) | Balancing Service Provider (BSP) | Aggregator	Enterprise	DER	Digital Twin
TwinEU Dataspace	Enterprise & Market	All	TwinEU application
Market Operator (MO) | Capacity Allocation	Market	Transmission & Distribution	Digital Twin

To enable secure, decentralised, and interoperable interactions among all identified Digital Twins, the TwinEU Dataspace Framework is introduced as a middleware layer. This component facilitates communication, acts as a service enabler, and ensures trusted data exchange and service discovery across domains. It plays a central role in bridging ecosystem actors and scaling the interoperability between DTs.

3.4.3 TwinEU's SGAM communication layer

The communication layer defines the protocols and communication channels used to ensure reliable, secure, and interoperable data exchange between the components and DTs identified in the component layer. It illustrates the protocols and mechanisms that enable interoperable data exchange between components and systems within the Smart Grid. This exchange occurs through information objects or data models, such as grid models and CIM. Figure 14 provides an overview of the SGAM zones and domains in which these technologies are positioned, and Table 18 summarises the main protocols used, including their description and typical application.

Each communication protocol has been mapped to specific zones and domains of the SGAM framework, depending on its functional scope and use case. These protocols support different communication paradigms (e.g., service-oriented messaging, publish-subscribe, file transfer, real-time streams) and operate in environments ranging from constrained field-level devices to enterprise-level systems.

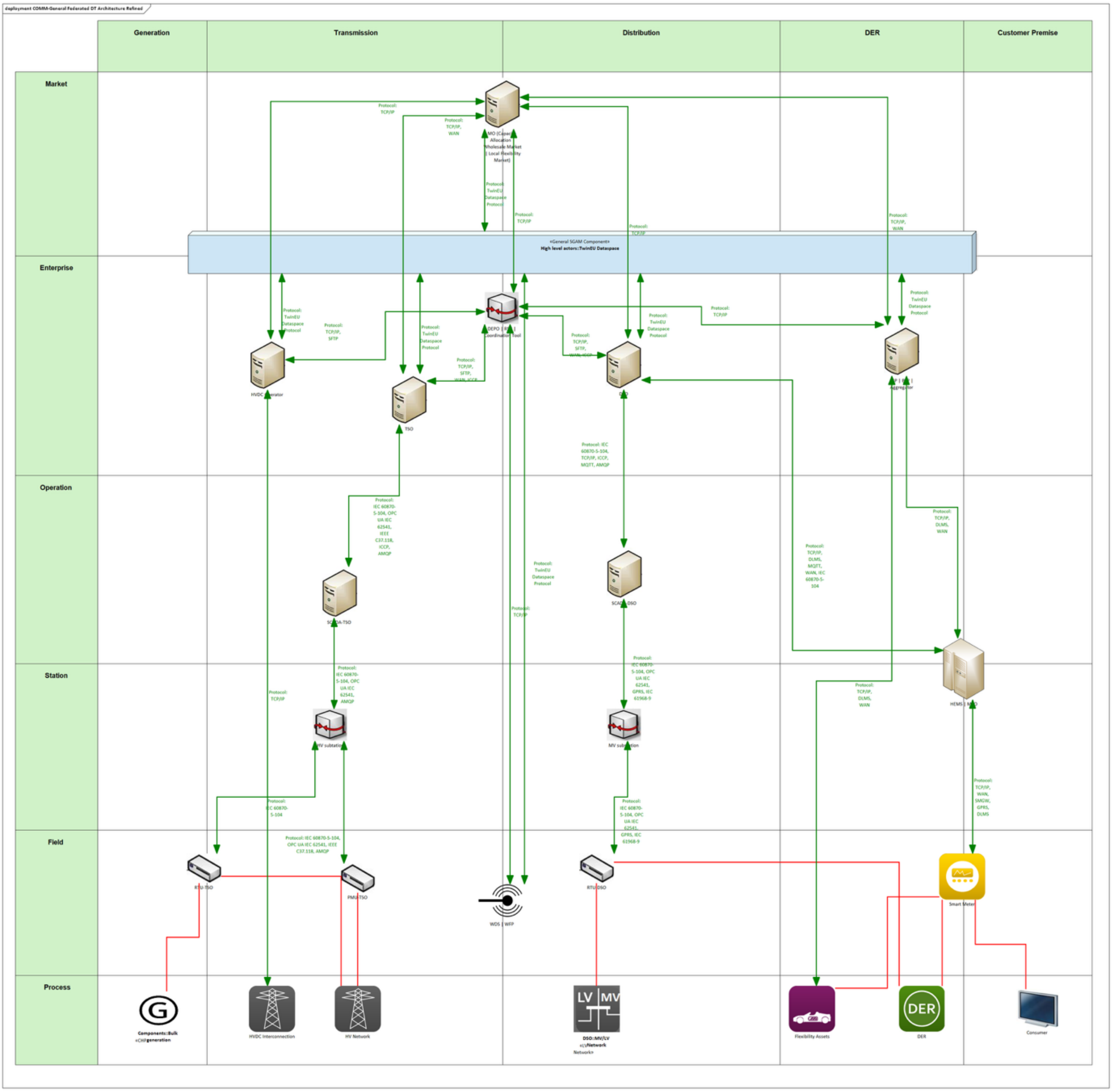


Figure 14 - Final DT federation SGAM communication layer.

For transmission and distribution grid systems, a significant number of well-established, standardised protocols are used. These include:

- **IEC 60870-5-104 and IEC 60870-6/TASE.2 (ICCP):** commonly used for communication between SCADA systems, substations, and control centres in high, medium, and low-voltage environments ([48], [49]).

- **IEC 62541/OPC UA and IEEE C37.118.2 / IEC 61850-90-5:** used for data acquisition, control, and synchrophasor communication in advanced automation and protection systems ([50], [51], [52]).
- **IEC 61968-9:** supports standardised data exchange for metering and control operations in distribution networks [53].
- **GPRS:** still used in certain use cases as a communication layer for field-deployed devices in mobile or less connected environments [54].
- **AMQP:** applied for reliable messaging between distributed middleware services, especially to orchestrate interactions in control systems [55].

Regarding DER and customer-premises communication, protocols tend to focus on secure data extraction from smart meters and assets via gateways, such as HEMS or MPOs. Typical protocols include:

- **DLMS/COSEM:** widely adopted in smart metering systems for standardised communication over diverse media [56].
- **TCP/IP, WAN, and GPRS:** supporting general connectivity across local and wide area networks ([57], [58], [59], [54]).
- **SMGW (Smart Meter Gateway):** enabling secure and standardised communication between metering infrastructure and external systems [60].

Between gateway-level components (HEMS, MPOs, SCADA, etc.) and enterprise digital twins, protocols such as ICCP, MQTT, and HTTP-REST are used.

For communication between DTs at the enterprise and market level, common protocols include:

- **TCP/IP and SFTP:** for robust, secure file or data transfers (e.g., simulation outputs, grid models, KPIs) ([57], [58], [61]).
- **HTTP-REST:** enabling interoperable API-based access to services [62].
- **WAN and ICCP:** supporting large-scale data exchange between TSOs, DSOs, and supporting entities ([59], [49]).

Additionally, messaging protocols like MQTT and AMQP are widely applied in heterogeneous environments to decouple producers and consumers of data, improving scalability and interoperability across systems.

Finally, the TwinEU Dataspace Protocol is defined as a solution that supports decentralised, trusted data exchange across digital twins. It defines mechanisms for service and data discovery, contract negotiation, and secure transactions, ensuring compliance with International Data Spaces association (IDSA) data sovereignty and interoperability principles. This protocol plays a key enabling role in connecting digital twins within the federated ecosystem.

Table 18 - Final DT federation SGAM communication technologies involved list.

Communication Technology	Description
MQTT	It is an ISO standard (ISO/IEC PRF 20922). Lightweight communication protocol based on publisher and subscribers to topics. It works on top of the TCP/IP protocol. Protocol is agnostic of the data exchanged. In Crossbow the data will be sent in JSON format.

IEC 60870-5-104	It is an extension of IEC 101 protocol with the changes in transport, network, link & physical layer services to suit the complete network access.
IEC 60870-6/TASE.2	Also known as ICCP, it is an Inter-Control Centre Communications Protocol used by utility organizations throughout the world to provide data exchange over wide area networks (WANs) between utility control centres, utilities, power pools, regional control centres, and Non-Utility Generators.
IEC 61850-90-5/IEEE C37.118.2	IEC/TR 61850-90-5:2012(E) provides a way of exchanging synchrophasor data between PMUs, PDCs WAMPAC (Wide Area Monitoring, Protection, and Control), and between control centre applications.
TCP/IP	Transmission Control Protocol/Internet Protocol is a suite of communication protocols used to interconnect network devices on the Internet. TCP ensures reliable transmission while IP handles addressing and routing. It serves as the foundation for many higher-level protocols like HTTP, FTP, and MQTT.
HTTP-REST	Representational State Transfer (REST) is a software architectural style that defines a set of constraints to be used for creating Web services. Web services that conform to the REST architectural style, termed RESTful Web services (RWS), provide interoperability between computer systems on the Internet. RESTful Web services allow the requesting systems to access and manipulate textual representations of Web resources by using a uniform and predefined set of stateless operations. Other kinds of Web services, such as SOAP Web services, expose their own arbitrary sets of operations.
WAN	Wide Area Network refers to a telecommunications network that extends over a large geographical area for the primary purpose of computer networking. WANs are used to connect local area networks (LANs) and other types of networks to enable communication over long distances.
SFTP	SSH File Transfer Protocol is a network protocol that provides secure file access, transfer, and management over a reliable data stream. Built on SSH (Secure Shell), it ensures encryption and integrity of data being transferred.
AMQP	Advanced Message Queuing Protocol is an open standard protocol for asynchronous message queuing. Designed for reliability, security, and interoperability between different messaging systems, it supports queuing, routing, and message orientation.
DLMS	Device Language Message Specification is a standard for communication with smart meters and energy management systems. Defined by the IEC 62056 series, it enables exchange of metering data in electric utilities through various transport layers.
IEC 62541/OPC UA	Open Platform Communications Unified Architecture is a machine-to-machine communication protocol for industrial automation. It is platform-independent, service-oriented, and focuses on secure, reliable, and structured information exchange.
GPRS	General Packet Radio Service is a packet-oriented mobile data standard on 2G and 3G cellular communication systems. It enables moderate-speed

	data transfer, supporting applications such as mobile internet and SMS-based communication.
IEC 61968-9	This part of IEC 61968 focuses on the interface for meter reading and control via XML messaging. It supports integration between enterprise systems and smart meters, allowing standardized data exchange for meter values, control commands, and configuration.
SMGW	Smart Meter Gateway is a secure communication unit in smart metering systems. It connects the local metering infrastructure with external networks, enabling secure data transmission to energy suppliers or market operators while enforcing data privacy and access control.
TwinEU Dataspace Protocol	Protocol designed to support decentralized data exchange across digital twins in data spaces. It governs the discovery, negotiation, and trusted data transactions between participants, aligning with principles of data sovereignty and interoperability.

3.4.4 TwinEU's SGAM information layer

The information layer in the SGAM model describes what data is exchanged between components and Digital Twins (DTs) in the TwinEU ecosystem, independently of the underlying communication technologies or physical infrastructures. The information layer is divided into three different sublayers:

- The **Information Object layer**, which defines the types of data exchanged (e.g., weather data, market bids, grid models). See Figure 15.
- The **Canonical Data Model layer**, which identifies the data models and standards that structure and semantically define this information. See Figure 16.
- The **Standard and Information Object Mapping layer**, which maps the relationships between the information objects, canonical models, and ecosystem components, showing clear interdependencies and reuse across actors. See Figure 17.

The identification of information objects focuses on classifying the data required and exchanged across transmission, distribution, DER, and customer premises use cases.

In transmission and distribution networks, core information flows include the exchange of electrical measurements originated at field and process zones and retrieved by Digital Twins at higher levels. In the opposite direction, control commands, setpoints, and settings are sent from DTs to grid assets for regulation and control purposes. In case of HVDC networks, control settings and setpoints are especially relevant, forming the basis for real-time control loops.

From DER and customer premises, data exchanged includes electrical values, and flexible asset information, all crucial for operation forecasting and flexibility management. This data is typically collected through gateways such as HEMS or MPOs.

Between Digital Twins at enterprise level, the main information flows are grid models, power flow results, new simulated scenarios and flexibility and ancillary service requests.

These data objects are either inputs for planning and operation or outputs from analytic and simulation services, often meant to be consumed by other DTs.

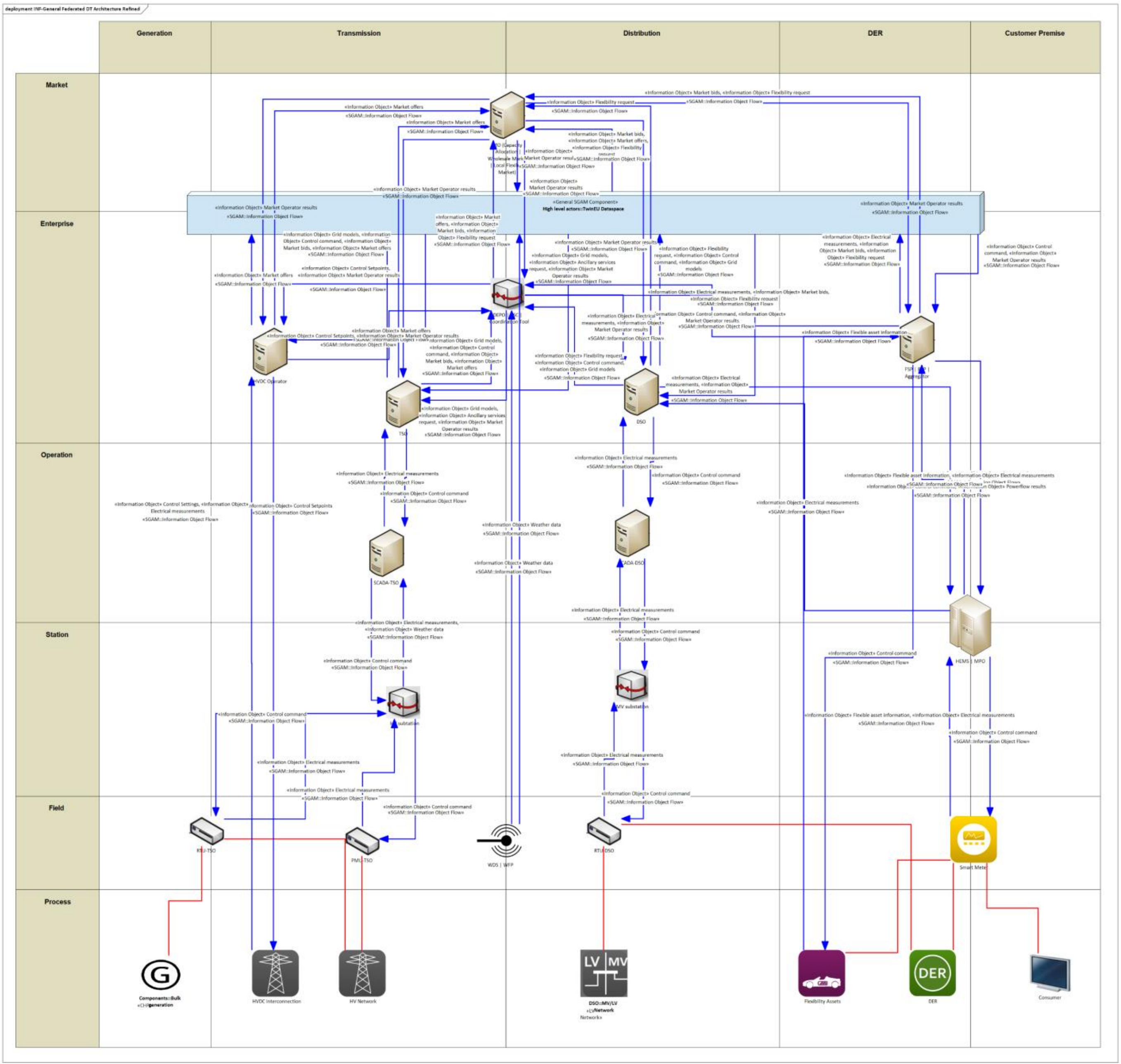


Figure 15 - Final DT federation SGAM information layer

Regarding market interactions, actors send structured offers and bids to the Market Operator DT, which responds with market results, including clearing prices and awarded volumes. These exchanges play a key part in integrating market-based mechanisms into grid operation and flexibility.

All information objects and their descriptions are detailed in Table 19.

Table 19 - Final DT federation SGAM Information Objects list

Information Objects	Description
Weather data	Environmental information such as temperature, pressure, wind speed, solar irradiation, and humidity. Relevant for forecasting renewable generation (e.g. PV/wind) and grid resilience analysis.

Powerflow results	Calculated electrical parameters across the grid, including voltages, currents, power losses, loading, and status of grid elements based on a specific scenario or operational state based over defined timeseries.
New simulated scenarios	Modelled future or alternative operating conditions including changes in load, generation, contingencies, or network configuration, used for predictive analysis and planning.
Market Operator results	Outcomes of market clearing processes, including accepted offers and bids, balancing results, prices, and activation schedules communicated to participants by the Market Operator.
Market offers	Structured information submitted by market participants to sell energy or flexibility, including quantity, price, and time window parameters.
Market bids	Requests by consumers, aggregators, or operators to buy/sell energy reserve, or flexibility, defining desired quantities, prices, and operational constraints.
Grid models	Representations of the electrical network, including topology, parameters, connectivity, and asset data, used for simulation, analysis, and operations.
Flexible asset information	Data related to flexible resources such as batteries, controllable loads, or DERs, including capabilities, location, availability, and operational constraints.
Flexibility request	Formalized request for demand or generation adjustment addressed to a flexibility provider or aggregator, including required magnitude, timeframe, and location.
Electrical measurements	Real-time or historical values for key electrical quantities (e.g., voltage, current, frequency, power) captured by sensors or smart meters across the network.
Control Settings	Configuration parameters for devices and systems, defining limits, operational modes, timing, and ranges for local or remote-control applications.
Control Setpoints	Target values sent to controllable assets or grid devices (e.g. voltage, power factor, active/reactive power), which influence their operation in a regulated manner.
Control command	Instruction to act on a grid asset or system component (e.g., switch breaker, activate inverter mode), typically within SCADA, or EMS operations.
Ancillary service request	Request to provide support services (e.g. frequency regulation, voltage support, spinning reserve) essential to maintaining power system reliability and security.

The canonical data model layer defines the structure, semantics, and standards used to represent the information objects across components. These models enable semantic interoperability and assure that data exchanged is understandable and usable independently of its source.

In field and process zones, there is a strong prevalence of mature, standardised models, including: IEC 60870 (102/104) and IEC 61850 for SCADA and substation automation, IEC 62056 (DLMS/COSEM) for smart metering, IEC 62541 (OPC UA) and IEEE C37.118 for measurements and automation and Modbus for industrial devices.

Some models are custom or proprietary, such as those used by SCADA systems, HEMS units, or individual platform providers. Many of these models are still under development within the scope of the project.

Several actors already adopt established standards. DSOs and Market Operators using customized CITRIC or JWS formats, Grid model exchange formats such as IEC 61970-CGMES and IEC 62325-CIM, are critical for TSO/DSO collaboration and planning simulations.

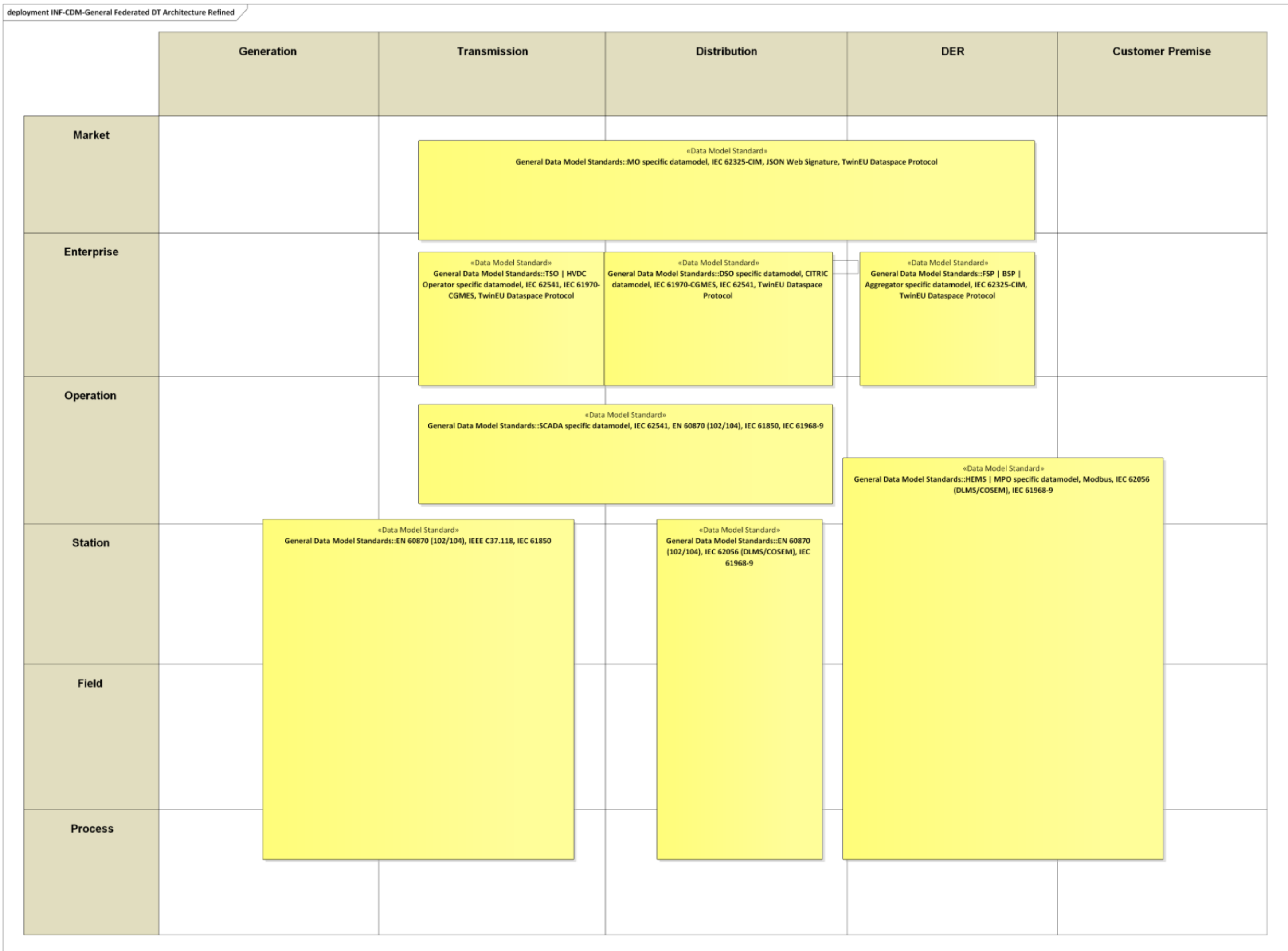


Figure 16 - Final DT federation SGAM Canonical Data Model.

The TwinEU Dataspace has significant potential to unify these models: it allows for definition of flexible data structures, enforces metadata tagging, schema sharing, and governance enforcement. It functions as an interoperability facilitator and promotes the alignment of data models.

All canonical data models and their descriptions are detailed in Table 20.

Table 20 - Final DT federation SGAM Data Models list.

Data Models	Description
IEC 60870 (102/104)	Data model for telecontrol in power systems, used mainly for SCADA communication. IEC 60870-5-102 is focused on energy metering, while 104 maps the protocol over TCP/IP, providing real-time monitoring and control data points [48].
IEC 61850	Object-oriented data model designed for substation automation systems. It structures measurement, control, and event data as Logical Nodes, enabling interoperability between IEDs from different vendors [52].
IEC 61968-9	Part of the CIM family, it defines standard messages for meter reading and control, enabling integration between AMI systems and utility backend systems using XML or web services [53].
IEC 61970-CGMES	Common Grid Model Exchange Specification is an extension of CIM for TSO-level data exchanges. It supports grid planning, forecast, and operational coordination across control areas [63].
IEC 62056 (DLMS/COSEM)	Structured model for metering data, based on "Device Language Message Specification" and "COmpanion Specification for Energy Metering". It defines data objects and communication profiles for smart meters [56].
IEC 62325-CIM	Applies the CIM model to electricity market domain. Supports business processes and data exchanges in energy trading, including scheduling and market clearing mechanisms [64].
IEC 62541	Defines the OPC UA data model, offering a unified, extensible representation of devices, their services, and state information, used in industrial automation and energy systems [50].
IEEE C37.118	Synchrophasor data model that enables time-synchronized measurements of electrical waves across power systems using Phasor Measurement Units (PMUs) [51].
Modbus	Register-based data model widely used for industrial devices. Offers discrete and analogue data access for sensors and actuators with minimal overhead [65].
JSON Web Signature	Defines a format for signing structured data using JSON. It supports data integrity and authentication in distributed systems, such as data spaces and APIs [66].
TwinEU Dataspace protocol	Data model associated with the IDSA initiative focused on digital product passports and interoperability; it supports decentralized, trusted data sharing with metadata and schema descriptions [67].
HEMS | MPO specific data model	Home Energy Management Systems and Metering Point Operators may define proprietary models for energy usage, flexibility potential, device control, and bidirectional communication with external actors.
SCADA specific data model	Customized data representation for SCADA systems, typically based on tags or point identifiers, covering telemetry, status, alarms, and control commands.
TSO | HVDC Operator specific data model	Tailored data models for Transmission System Operators and HVDC platforms, often extending CGMES or IEC 61850 to reflect operational requirements and specialized equipment monitoring.

DSO specific data model	Distribution System Operators may adopt CIM-based or proprietary models to represent grid topology, loads, DERs, and operational data for monitoring and automation systems.
CITRIC data model	Domain-specific model focused on flexibility assets, market interactions, and IoT integration. Exact structure would depend on project specifications.
FSP | BSP | Aggregator specific data model	Data models developed by Flexibility Service Providers, Balancing Service Providers, or Aggregators. Include representations of DER flexibility, schedules, availability, and market interaction data.
MO specific data model	Market Operator specific data structures for bid, market clearing, pricing, and settlement processes.

The final layer presents a mapping between the identified information objects, their canonical data models, and the components exchanging them.

There is a reuse and standardisation of models, especially in the field and process layers, where robust industrial standards dominate.

The interconnection between actors is notable, showing that the same data objects (e.g. grid models, flexibility requests) are shared among different kinds of DTs, often using similar data models.

This mapping helps identify potential for harmonisation, gaps in semantic alignment, and areas where standardisation would most benefit interoperability.

The SGAM information layer in TwinEU highlights a broad variety of data types and models used across domains and zones. While legacy systems rely on well-established standards, achieving true interoperability in a federated DT ecosystem requires alignment at the semantic level.

The TwinEU Dataspace Framework addresses this need by enabling the definition and governance of common data models, ensuring trusted and standardised data exchange between Digital Twins. As such, it is a key enabler for building a unified, interoperable, and scalable DT federation ecosystem.

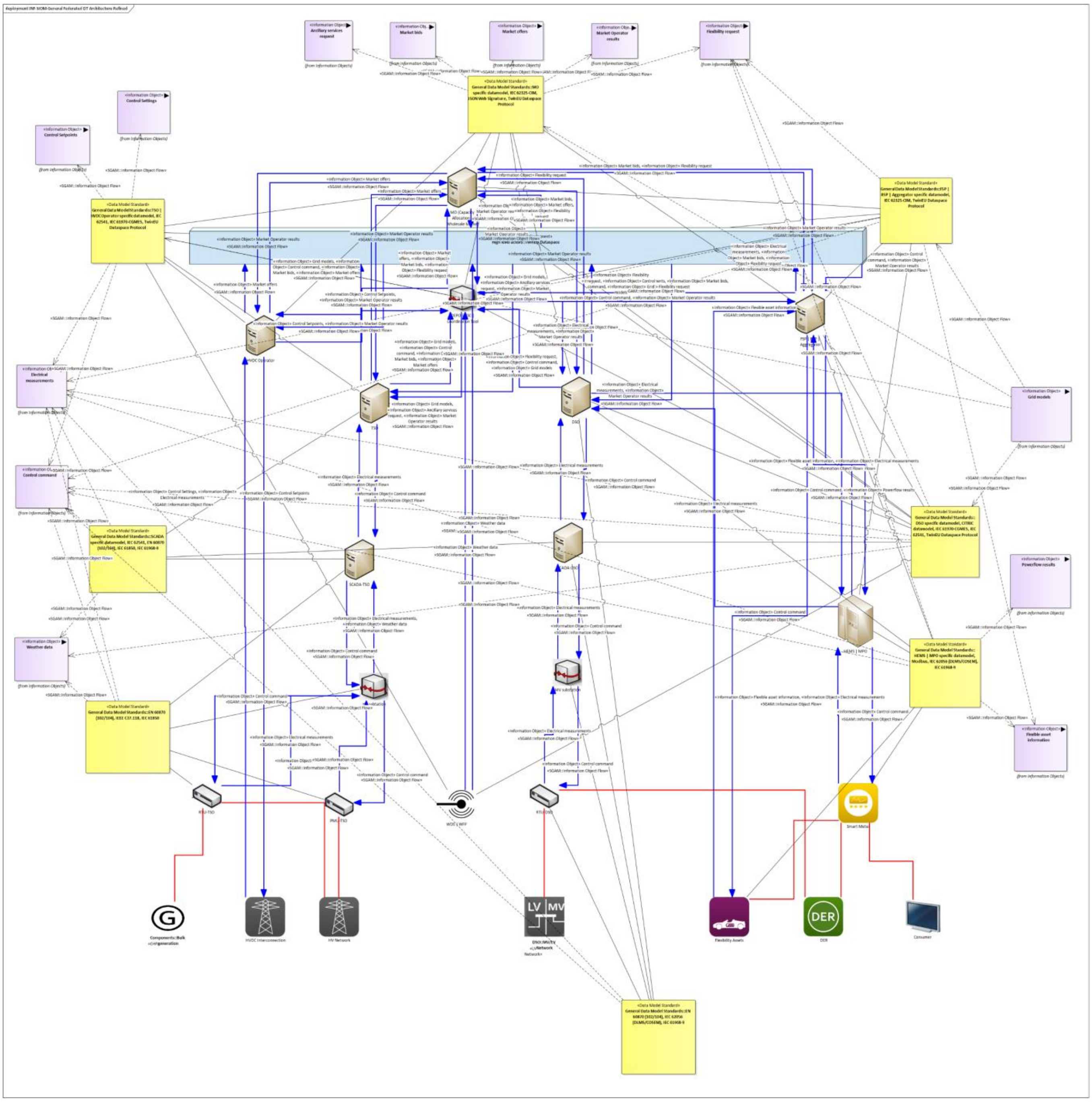


Figure 17 - Final DT federation SGAM Standard and Information Object Mapping.

4 Conclusions

This final version of the Functional and Technical Specifications for the TwinEU Federated DT platform represents a key technical milestone for the project.

The activities reported has consolidated a comprehensive set of foundations for the implementation of the TwinEU Federated DT platform. It has resulted in the definition of functional and non-functional requirements that extend across the entire ecosystem, together with TwinEU demonstrator requirements reflecting concrete use cases. Furthermore, it has established technical specifications based on the SGAM framework, ensuring interoperability and scalability, while also embedding cybersecurity, data privacy, and regulatory compliance as integral elements of the design.

This work conducted under WP3, in coordination with WP2, WP4, and the demonstrators (WP5–WP8), has ensured that all requirements, specifications, and architectural elements are technically feasible, consistent, and validated through feedback from implementation and DEMO activities.

The results achieved will serve as the technical foundation for the subsequent phases of TwinEU project. In the short term, they provide the baseline for WP4, which will focus on developing the TwinEU Federated DT infrastructure by translating the defined specifications into concrete architectural implementations and core services. In parallel, the DEMO work packages (WP5–WP8) will build upon these requirements to deploy, test, and validate Digital Twin services in real operational environments, ensuring that the platform is scalable, interoperable, and adaptable to different European, national and regional contexts. This two-level progression, first at the platform level (WP4) and then through real-world demonstrations (WP5–WP8), ensures that the system can be validated both technically and operationally, closing the loop between design, implementation, and validation.

Looking forward, some recommendations can be made to maximise the impact of this work. It will be crucial to ensure continuous cross-WP alignment, maintaining strong feedback loops between WP4 implementation activities and the DEMO pilots to refine specifications iteratively. Equal importance should be given to standardisation and data space integration, with active involvement in European initiatives to ensure long-term interoperability and scalability beyond the project lifetime. Finally, particular attention should be paid to cybersecurity and data privacy, integrating them not only as formal requirements but also as verifiable criteria during implementation and validation.

References

[1] ISO/IEC 25010:2023 - Systems and software engineering — Systems and software Quality Requirements and Evaluation (SQuaRE) — Product quality model. [Online]. Available: https://www.iso.org/standard/78176.html.

[2] Non-Functional Requirements in Software Engineering, Author: Lawrence Chung, Brian A. Nixon, Eric Yu, John Mylopoulos, book; Springer Science & Business Media, 6. 12. 2012. – 441 pages, https://link.springer.com/book/10.1007/978-1-4615-5269-7.

[3] Functional requirements, non-functional requirements, and architecture should not be separated –A position paper, Barbara Paech, Allen H. Dutoit, Daniel Kerkow, Antje von Knethen, 2002. [Online] http://www.refsq.org/.

[4] Non-Functional Requirements, Elicitation Guideline for Agile Methods, M. Younas, D.N.A. Jawawi, I. Ghani, R. Kazmi, 2017, Journal of Telecommunication, Electronic and Computer Engineering (JTEC), 9(3-4), 137–142. Retrieved from https://jtec.utem.edu.my/jtec/article/view/2933.

[5] Functional requirements and non-functional requirements: a survey, Zhou, Jun Ying (2004) Functional requirements and non-functional requirements: a survey. Master's thesis, Concordia University, [Online]. Available: https://spectrum.library.concordia.ca/id/eprint/7991/.

[6] A systematic review of non-functional requirements mapping into architectural styles. Nouman, M., Azam, M., Saleh, A. M., Alsaeedi, A., & Abuaddous, H. Y. (2023). Bulletin of Electrical Engineering and Informatics, 12(2), 1226–1236. https://doi.org/10.11591/eei.v12i2.4081.

[7] OneNet EU Horizon 2020 project: https://www.onenet-project.eu/.

[8] ENTSO-E codes and CIM. [Online] https://www.entsoe.eu/network_codes/ , https://www.entsoe.eu/data/cim/.

[9] NIS2, "Network and Information Security Directive". [Online]. Available: https://nis2directive.eu/.

[10] General Data Protection Regulation (GDPR), [Online]. Available: https://gdpr-info.eu/.

[11] Renewable Energy Directive (RED), [Online]. Available: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en.

[12] Data Act. [Online]. Available: https://digital-strategy.ec.europa.eu/en/policies/data-act .

[13] European Green Deal, [Online]. Available: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.

[14] ISO 25000 STANDARDS. [Online]. Available: https://iso25000.com/index.php/en/iso-25000-standards (accessed Sep. 09, 2021).

[15] Managing Regulatory Compliance in Business Processes. Sadiq, Shazia & Governatori, Guido. (2015). Handbook on Business Process Management 2: Strategic Alignment, Governance, People and Culture, Second Edition. 10.1007/978-3-642-01982-1_8. [Online]. Available: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=06fc6495e2a54591fb0de21850858bfe53099b5c.

[16] ISO/IEC 27001:2022 - Information security, cybersecurity and privacy protection — Information security management systems — Requirements. [Online] https://www.iso.org/standard/27001.

[17] "ENHANCING PROJECT QUALITY THROUGH EFFECTIVE REQUIREMENTS MANAGEMENT." Wawak, Sławomir. *International Journal for Quality Research* 19.1: 151-168. [Online]. Available: https://ijqr.net/journal/v19-n1/10.pdf.

[18] TwinEU: "D2.1 Digitalization challenges and opportunities in the future energy system" [Online] Available: https://twineu.net/wp-content/uploads/2025/01/TwinEU_D2.1_V1.0.pdf.

[19] TwinEU: "D2.2 TwinEU Use Cases, pan-European scenarios and KPIs" [Online] Available: https://twineu.net/wp-content/uploads/2025/07/TwinEU_D2.2_v1.0-3.pdf .

[20] TwinEU: "D3.1 TwinEU Open Reference Architecture" [Online] Available: https://twineu.net/wp-content/uploads/2025/07/TwinEU_D3.1_v1.0.pdf.
[21] TwinEU: "D5.3 Testing propagation of threat detection on market activities with DT" [Online] Available: https://twineu.net/wp-content/uploads/2025/05/20250331_ETRA_TwinEU_D5.3_pu_v1.pdf.
[22] CEN-CENELEC-ETSI Smart Grid Coordination Group, "SGAM User Manual: Applying, testing & refining the Smart Grid Architecture Model Version (SGAM), Version 3.0," Nov. 2014. [Online]. Available: https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC_Topics/Smart%20Grids%20and%20Meters/Smart%20Grids/4_sgcg_methodology_sgamusermanual.pdf.
[23] Enershare Project - The Energy Data Space for Europe. [Online]. Available: https://enershare.eu/
[24] NCCS, The Network Code on Cybersecurity. [Online]. Available: https://www.entsoe.eu/network_codes/nccs/.
[25] ISO/IEC 27001:2022 - Information security, cybersecurity and privacy protection — Information security management systems — Requirements. [Online]. Available: https://www.iso.org/standard/27001.
[26] Renewable Energy – Recast to 2030 (RED II). [Online]. Available: https://joint-research-centre.ec.europa.eu/welcome-jec-website/reference-regulatory-framework/renewable-energy-recast-2030-red-ii_en.
[27] REMIT (Regulation on Wholesale Energy Market Integrity and Transparency). [Online]. Available: https://eur-lex.europa.eu/eli/reg/2011/1227/oj/eng.
[28] Regulations (EU) 2019/943. [Online]. Available: https://eur-lex.europa.eu/eli/reg/2019/943/oj/eng.
[29] Regulations (EU) 2019/944. [Online]. Available: https://eur-lex.europa.eu/eli/dir/2019/944/oj/eng.
[30] Regulation (EU) 2017/1485. [Online]. Available: https://eur-lex.europa.eu/eli/reg/2017/1485/oj/eng.
[31] Regulation (EU) 2017/2195. [Online]. Available: https://eur-lex.europa.eu/eli/reg/2017/2195/oj/eng.
[32] Energy Efficiency Directive (EED)- a key driver of Europe's energy transition. [Online]. Available: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en.
[33] Clean Energy for All Europeans Package (CEP). [Online]. Available: https://www.entsoe.eu/cep/.
[34] AI Act - The EU Artificial Intelligence Act. [Online]. Available: https://artificialintelligenceact.eu/.
[35] ISA/IEC 62443 Series of Standards. [Online]. Available: https://www.isa.org/standards-and-publications/isa-standards/isa-iec-62443-series-of-standards.
[36] Directive (EU) 2024/1788. [Online]. Available: https://eur-lex.europa.eu/eli/dir/2024/1788/oj/eng.
[37] L. Bader et al., "Comprehensively Analyzing the Impact of Cyberattacks on Power Grids," Jul. 2023, doi: 10.1109/eurosp57164.2023.00066. Available: https://arxiv.org/pdf/2305.09390
[38] IDSA Rulebook. [Online]. Available: https://docs.internationaldataspaces.org/ids-knowledgebase/idsa-rulebook
[39] Gaia-X, "GAIA-X Framework A Federated Secure Data Infrastructure". [Online]. Available: https://gaia-x.eu/gaia-x-framework/
[40] European Data Governance Act. [Online]. Available: https://digital-strategy.ec.europa.eu/en/policies/data-governance-act
[41] IEC 62351 – Cyber Security Series for the Smart Grid. [Online]. Available: https://syc-se.iec.ch/deliveries/cybersecurity-guidelines/security-standards-and-best-practices/iec-62351/

[42] ENISA Technical Implementation Guidance. [Online]. Available: https://www.enisa.europa.eu/sites/default/files/2025-06/ENISA_Technical_implementation_guidance_on_cybersecurity_risk_management_measures_version_1.0.pdf.
[43] Cyber Resilience Act (CRA). [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R2847.
[44] eIDAS Electronic Identification and Trust Services Regulation [Online]. Available: https://digital-strategy.ec.europa.eu/en/policies/eidas-regulation
[45] The NIST Cybersecurity Framework (CSF) 2.0. [Online]. Available: https://nvlpubs.nist.gov/nistpubs/CSWP/NIST.CSWP.29.pdf.
[46] Huang, B., Majidi, M., & Baldick, R. (2018). Case Study of Power System Cyber Attack Using Cascading Outage Analysis Model. Power and Energy Society General Meeting. https://doi.org/10.1109/PESGM.2018.8585921.
[47] Critical Entities Resilience Directive (CER). [Online]. Available: https://www.critical-entities-resilience-directive.com/.
[48] International Electrotechnical Commission, IEC 60870-5-104: Telecontrol equipment and systems – Part 5-104: Transmission protocols – Network access for IEC 60870-5-101 using standard transport profiles, 1st ed. IEC, 2006. [Online]. Available: https://webstore.iec.ch/en/publication/25035.
[49] International Electrotechnical Commission, IEC TR 60870-6-505:2002+AMD1:2005 CSV, Telecontrol equipment and systems – Part 6-505: Telecontrol protocols compatible with ISO standards and ITU-T recommendations – TASE.2 User guide. IEC, 2005. [Online]. Available: https://webstore.iec.ch/en/publication/3764.
[50] International Electrotechnical Commission, *IEC 62541: OPC Unified Architecture – Parts 1–13*. IEC, 2020. [Online]. Available: https://webstore.iec.ch/en/publication/61109.
[51] Institute of Electrical and Electronics Engineers, *IEEE Standard for Synchrophasor Data Transfer for Power Systems*, IEEE Std C37.118.2-2011. IEEE, 2011. [Online]. Available: https://standards.ieee.org/ieee/C37.118.2/4921/.
[52] International Electrotechnical Commission, *IEC TR 61850-90-5: Communication networks and systems for power utility automation – Part 90-5: Use of IEC 61850 to transmit synchrophasor information according to IEEE C37.118, Technical Report IEC TR 61850-90-5:2012(E)*. IEC, 2012. [Online]. Available: https://webstore.iec.ch/en/publication/6026.
[53] International Electrotechnical Commission, *IEC 61968-9:2024 – Enterprise business function interfaces for utility operations – Part 9: Interfaces for meter reading and control*, 3rd ed. IEC, 2024. [Online]. Available: https://webstore.iec.ch/en/publication/75041.
[54] 3rd Generation Partnership Project (3GPP), *TS 23.060: General Packet Radio Service (GPRS); Service description; Stage 2*, v15.0.0, 3GPP Release 15, 2018. [Online]. Available: https://www.etsi.org/deliver/etsi_ts/144000_144099/144060/15.00.00_60/ts_144060v150000p.pdf
[55] OASIS, *Advanced Message Queuing Protocol (AMQP) Version 1.0*, OASIS Standard, 2014. [Online]. Available: https://docs.oasis-open.org/amqp/core/v1.0/os/amqp-core-complete-v1.0-os.pdf.
[56] DLMS User Association, *DLMS/COSEM Specification for Smart Metering*, 2017. [Online]. Available: https://www.dlms.com/core-specifications/#COSEM.
[57] J. Postel, "Transmission Control Protocol," *RFC 793*, Internet Engineering Task Force (IETF), Sep. 1981. [Online]. Available: https://www.rfc-editor.org/info/rfc793.
[58] J. Postel, *RFC 791: Internet Protocol*, IETF, Sep. 1981. [Online]. Available: https://datatracker.ietf.org/doc/html/rfc791.

[59] Cisco, *What Is a WAN? Wide-Area Network*, Cisco Networking. [Online]. Available: https://www.cisco.com/site/us/en/learn/topics/networking/what-is-a-wan-wide-area-network.html?dtid=osscdc000283&linkclickid=srch.

[60] Bundesamt für Sicherheit in der Informationstechnik (BSI), *Smart Meter Gateway – Technische Richtlinie TR-03109*, Bonn, Germany, 2018. [Online]. Available: https://www.bsi.bund.de/SharedDocs/Downloads/DE/BSI/Publikationen/TechnischeRichtlinien/TR03109/TR03109-1.pdf?__blob=publicationFile&v=4.

[61] T. Ylonen and C. Lonvick, *RFC 4253: The Secure Shell (SSH) Transport Layer Protocol*, IETF, Jan. 2006. [Online]. Available: https://datatracker.ietf.org/doc/html/rfc4253.

[62] R. T. Fielding, *Architectural Styles and the Design of Network-based Software Architectures*, Ph.D. dissertation, University of California, Irvine, USA, 2000. [Online]. Available: https://ics.uci.edu/~fielding/pubs/dissertation/fielding_dissertation.pdf.

[63] International Electrotechnical Commission, *IEC 61970-600 Series (Common Grid Model Exchange Specification – CGMES)*: IEC, 2021. [Online]. Available: https://webstore.iec.ch/en/publication/61124.

[64] European Network of Transmission System Operators for Electricity (ENTSO-E), *CIM for Energy Market Communications: IEC 62325 Framework and Guidelines*, 2022. [Online]. Available: https://www.entsoe.eu/digital/common-information-model/.

[65] Modbus Organization, *MODBUS Application Protocol Specification V1.1b3*, North Grafton, MA, USA: Modbus Organization, Apr. 2012. [Online]. Available: https://modbus.org/docs/Modbus_Application_Protocol_V1_1b3.pdf.

[66] M. Jones, J. Bradley, and N. Sakimura, *RFC 7515: JSON Web Signature (JWS)*, Internet Engineering Task Force (IETF), May 2015. [Online]. Available: https://datatracker.ietf.org/doc/html/rfc7515.

[67] International Data Spaces Association (IDSA), *Dataspace Protocol Specification 2024-1*. Dortmund, Germany: IDSA, Jul. 2024. [Online]. Available: https://internationaldataspaces.org/offers/dataspace-protocol/.

[68] TwinEU - Digital Twin for Europe GitHub repository. [Online]. Available: []https://github.com/TwinEU-Digital-Twin-for-Europe/T3.2_Functional_specifications_of_pan-European_DT_design.

[69] EE-ISAC - European Energy Information Sharing & Analysis Centre [Online]. Available: https://www.ee-isac.eu/

[70] DPSIM - Real-Time Dynamic Power System Simulator. [Online]. Available: https://dpsim.fein-aachen.org/docs/

[71] VILLASframework. [Online]. Available: https://villas.fein-aachen.org/docs/.

[72] CIS (Center for Internet Security) Benchmarks. [Online]. Available: https://www.cisecurity.org/cis-benchmarks.

[73] OAuth 2.0 Authorization Framework. [Online]. Available: https://auth0.com/docs/authenticate/protocols/oauth.

Annex A - General System Use Cases

In this section are presented GSUCs in addition to the GSUC that is defined in the Section 2.5.3. It represents the comprehensive insight into all aspects of all six GSUCs.

Table 21 - General System Use Case 01 – GSUC_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);

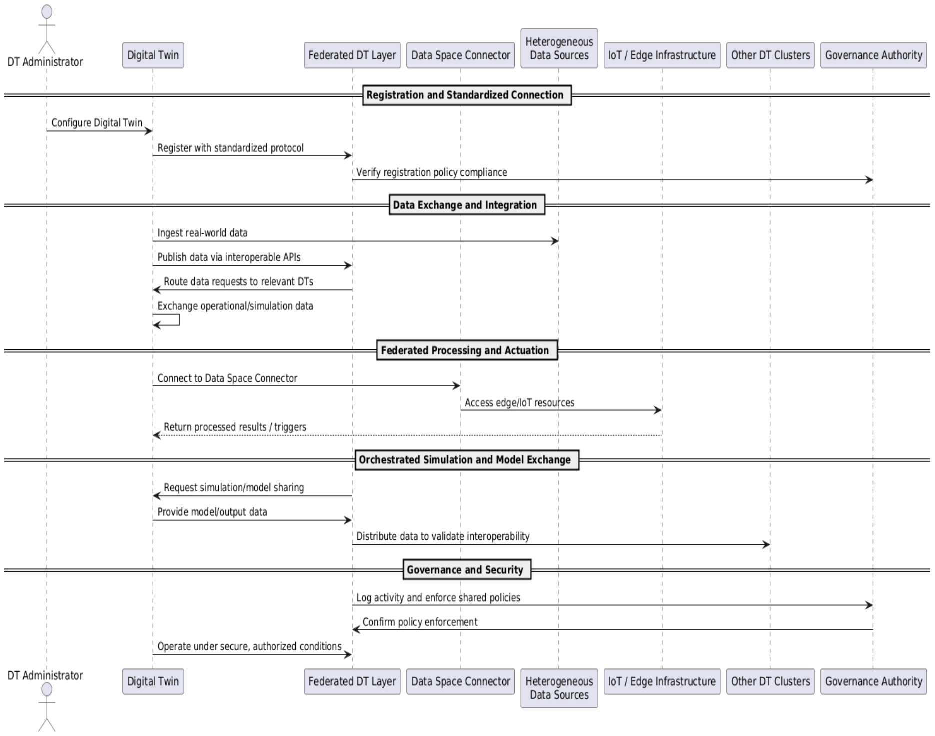
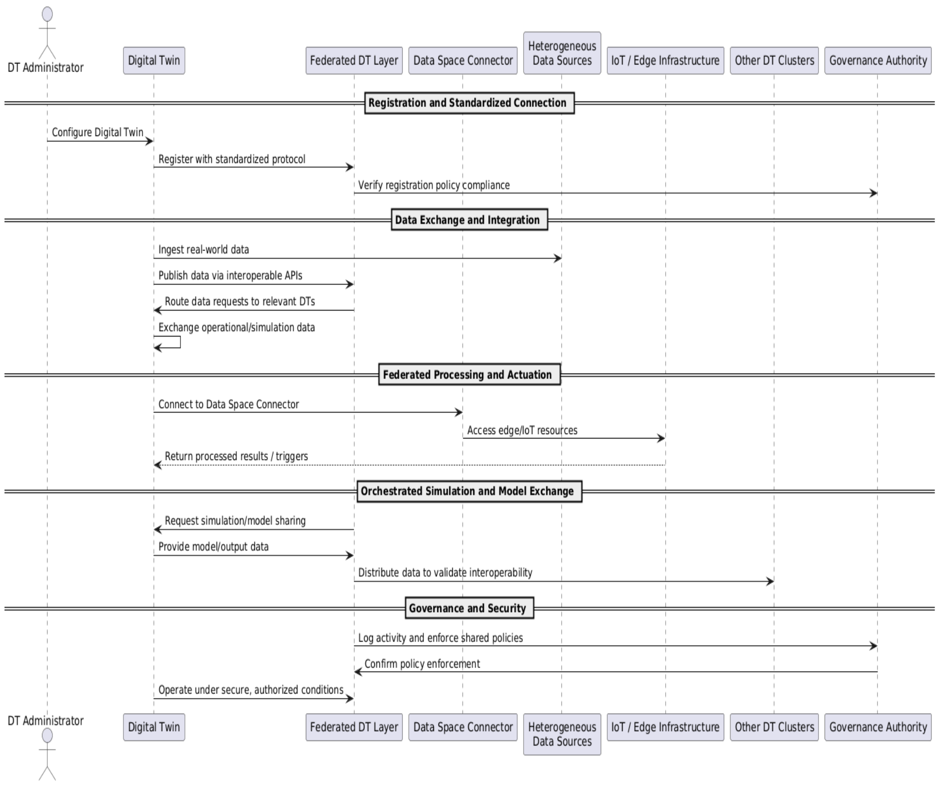
	Key Participants: Grid Operators, Policy Makers, Market Participants, and Domain Experts
Sequence Diagrams	 

Table 22 - General System Use Case 02 – GSUC_02

GSUC Name	**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.

<table>
<tr><td></td><td>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 modelling, 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.</td></tr>
<tr><td>Involved Platforms/ actors</td><td>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</td></tr>
</table>

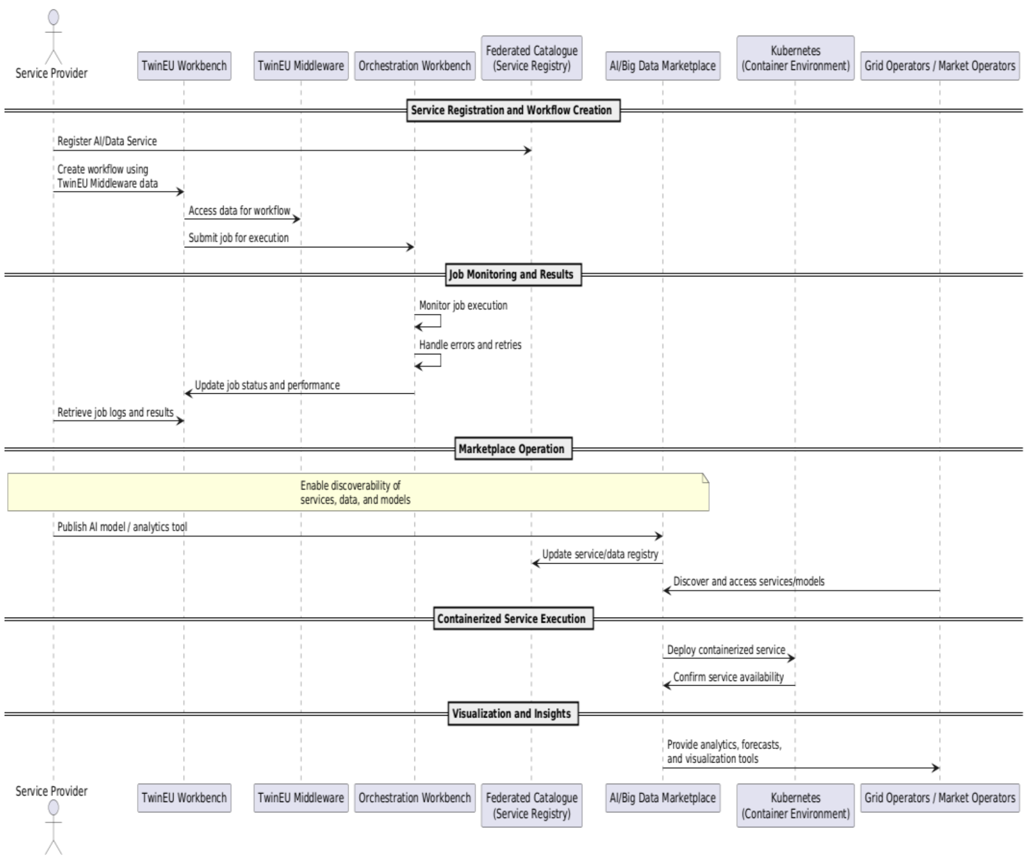
Sequence Diagrams	

Table 23 - General System Use Case 03 - GSUC_03

GSUC Name	**Integration of IoT devices and other data sources to TwinEU**
GSUC ID	GSUC_03
Objectives	• 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
Narrative	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

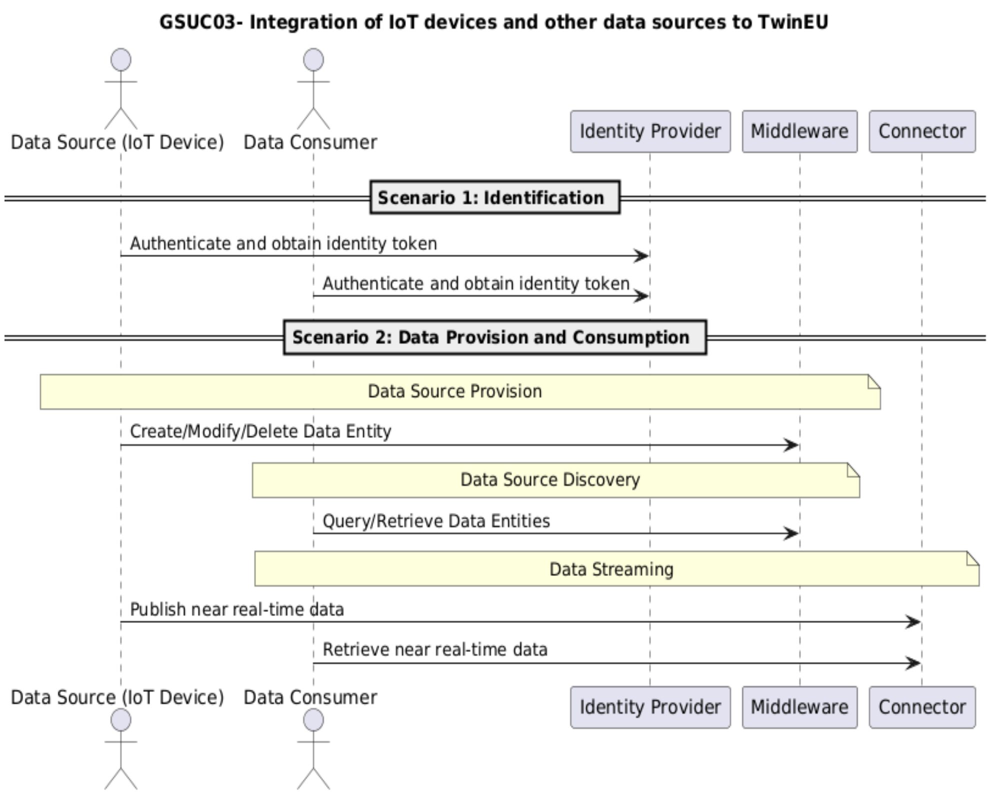
	protocols, ensuring secure and scalable data provision and consumption within TwinEU.
Steps	Scenario 1 – Identification: • Data sources and consumers are identified using TwinEU identity management mechanisms. Scenario 2 – Data Provision and Consumption: • Data Streaming Provision: Data Providers can create, modify, and delete data sources with near real-time data provisioning • Data Streaming Consumption: Data Consumers can retrieve or query streaming data
Involved Platforms/ actors	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)
Sequence Diagrams	

Table 24 - General System Use Case 04 - GSUC_04

GSUC Name	**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

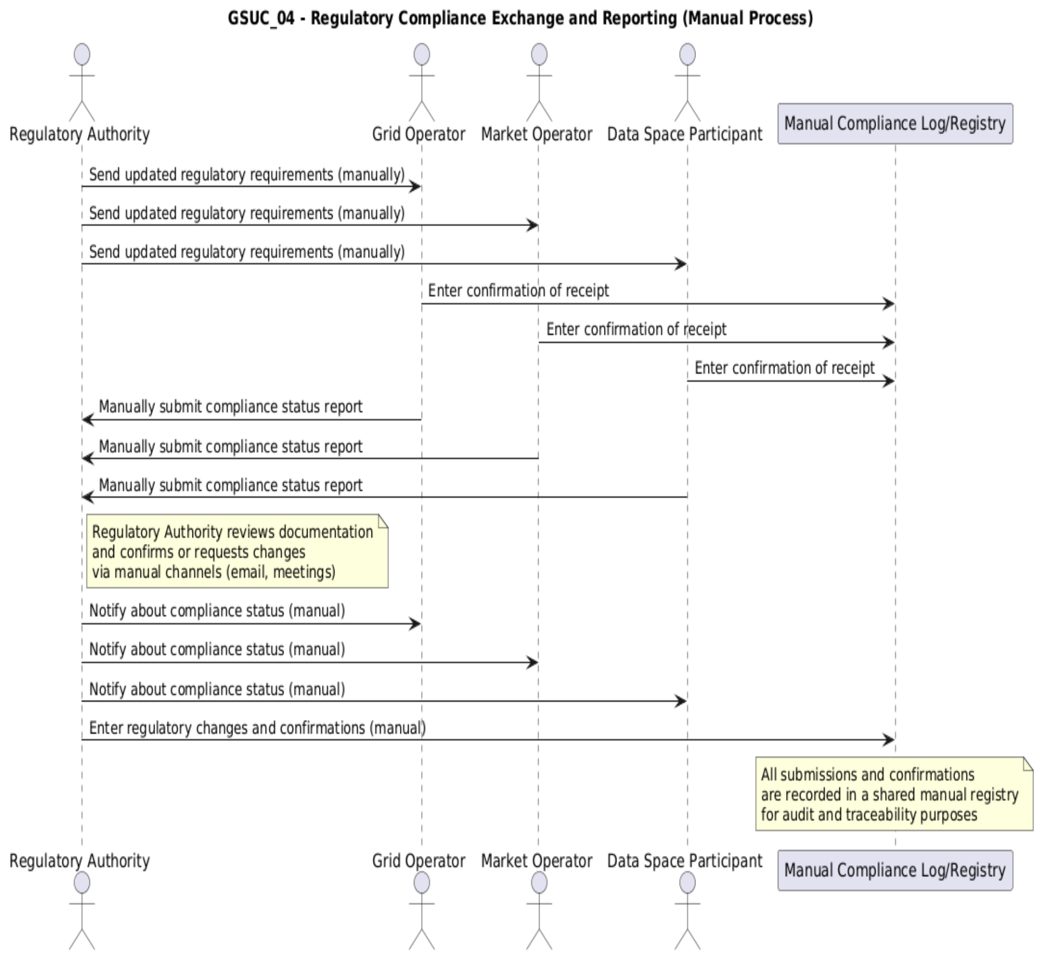
Sequence Diagrams	

Table 25 - General System Use Case 05 - GSUC_05

GSUC Name	**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.

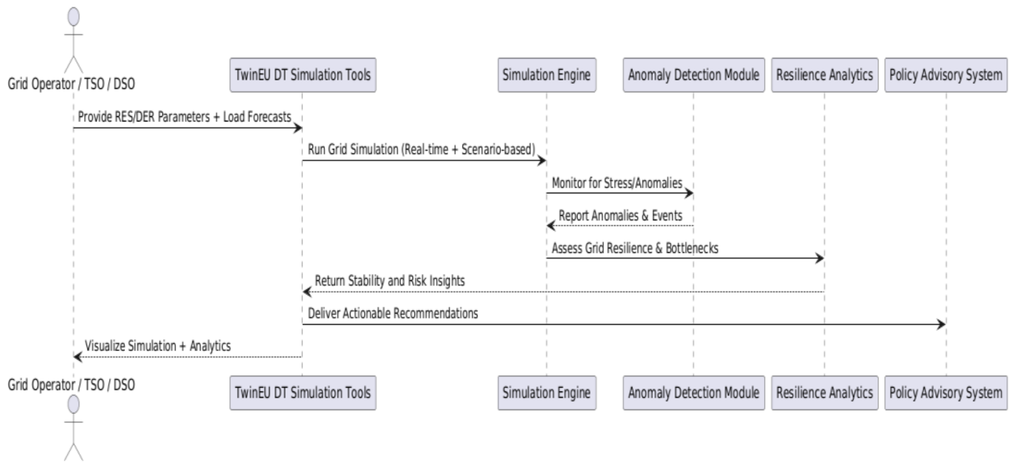
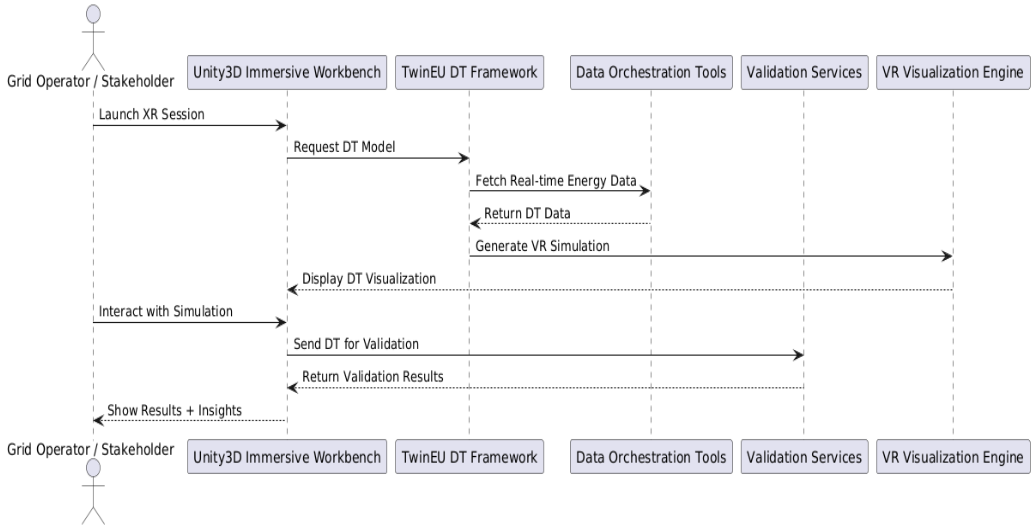
	The system uses parameterized simulation inputs provided by Transmission System Operators (TSOs) and Distribution System Operators (DSOs), including expected RES penetration profiles, load forecasts, and contingency events. The Digital Twin simulation tools within TwinEU process these parameters to: • 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 26 - General System Use Case 06 - GSUC_06

GSUC Name	**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, analyse 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 Key Participants: Grid Operators, TSOs, DSOs, Policymakers, Market Participants, and VR Experts
Sequence Diagrams	

Annex B - Non-Functional requirements

This section provides an overview of all NFURs defined at the TwinEU system level. Presenting all NFURs in a consolidated manner ensures a coherent view of the project-wide expectation and essential quality attributes.

Table 27 - Non-Functional Requirements on TwinEU system level

Requirement ID	Name	Category	Sub-category	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	Functional Correctness	The data exchanged between the DTs must maintain high accuracy and precision, particularly for critical grid parameters such as frequency, 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 /Functional appropriateness	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	Sub-category	Description
TwinEU_NFR_05	Compliance with Local Grid Codes and Standards	Functional Suitability	Functional Correctness /Functional 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	High Accuracy of Synthetic Outputs	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.
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	High-Accuracy Simulations	Functional Suitability	Functional correctness	The TwinEU system must ensure that scenario simulations accurately reflect the real grid behaviour, with errors in frequency, voltage, and current staying within a small margin (e.g. less than 5%), as validated against a defined base case.
TwinEU_NFR_11	Low-Latency Real-Time Data Processing and Communication	Performance Efficiency	Time Behaviour	The TwinEU system must manage real-time data efficiently. 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_12	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).

Requirement ID	Name	Category	Sub-category	Description
TwinEU_NFR_13	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.
TwinEU_NFR_14	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_15	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_16	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_17	High-Throughput Data Processing for Grid Analytics	Performance Efficiency	Capacity	The TwinEU system should support high throughput to handle the large volumes of information generated by grid models and predictive analytics.
TwinEU_NFR_18	Real-Time Simulations	Performance Efficiency	Time Behaviour	The system must process and simulate grid scenarios in real-time, without delays that could impact operational decision-making or the timeliness of results.
TwinEU_NFR_19	Precise Forecasting for power prediction	Performance Efficiency	Time Behaviour	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.

Requirement ID	Name	Category	Sub-category	Description
TwinEU_NFR_20	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.
TwinEU_NFR_21	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_22	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_23	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_24	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_25	System Capacity for Increasing Data Loads	Performance Efficiency	Capacity	The TwinEU system must be scalable to handle increasing data loads.
TwinEU_NFR_26	Support for Scalable European Grid Integration	Performance Efficiency	Capacity	The architecture must support regional expansions across European grids (ensuring that it can handle more RES connections and a larger LFM without compromising performance).
TwinEU_NFR_27	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.

Requirement ID	Name	Category	Sub-category	Description
TwinEU_NFR_28	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_29	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_30	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.
TwinEU_NFR_31	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_32	External Database and Model Communication	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_33	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.

Requirement ID	Name	Category	Sub-category	Description
TwinEU_NFR_34	Comprehensive Operational Documentation	Interaction Capability	Operability	The TwinEU system should provide a comprehensive documentation for all the envisioned operations.
TwinEU_NFR_35	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_36	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_37	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_38	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.
TwinEU_NFR_39	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_40	High Reliability with Minimal Failure Rate	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_41	Data Integrity and Error Detection	Reliability	Fault Tolerance	The TwinEU system could have strict error detection mechanisms to flag any inconsistencies in the data.

Requirement ID	Name	Category	Sub-category	Description
TwinEU_NFR_42	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_43	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_44	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_45	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_46	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. These logs should be easily accessible for audits, ensuring transparency in handling cybersecurity incidents.
TwinEU_NFR_47	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.

Requirement ID	Name	Category	Sub-category	Description
TwinEU_NFR_48	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_49	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_50	Regulatory Compliance and Flexibility Resource Qualification	Security	Accountability	The TwinEU system should comply to industry standards for flexibility resources and ensure regulatory compliance throughout the qualification process.
TwinEU_NFR_51	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_52	Regulatory Compliance for Renewable Energy and Grid Operations	Security	Accountability	The TwinEU system must adhere to national and international regulations regarding renewable energy forecasting and grid operation standards.
TwinEU_NFR_53	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 protection laws (e.g., GDPR) must be ensured for all personal or operational data processed by the system. Full GDPR compliance.

Requirement ID	Name	Category	Sub-category	Description
TwinEU_NFR_54	Data Anonymization and Confidentiality	Security	Confidentiality/Privacy	The TwinEU system must ensure the anonymization and confidentiality of the collected sensitive data.
TwinEU_NFR_55	Scalability for Future Expansion and Complex Operations	Maintainability	Modularity	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_56	Seamless Upgrade Support	Maintainability	Modularity/Adaptability	The TwinEU system should support future upgrades without major disruptions to the existing architecture.
TwinEU_NFR_57	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_58	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_59	Feedback-Driven Modifiability	Maintainability	Modifiability	The TwinEU system should be modifiable based on the feedback collected during the evaluation phase of the demonstrations.
TwinEU_NFR_60	Code Clarity and Documentation	Maintainability	Analysability /Modularity	Code should be well documented and understandable.

Requirement ID	Name	Category	Sub-category	Description
TwinEU_NFR_61	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_62	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_63	Adaptive Data Integration Capability	Flexibility	Scalability	It must be capable of adapting to new datasets or sources of data.
TwinEU_NFR_64	Platform and Environment Independence	Flexibility	Adaptability	The TwinEU system must be platform and environment agnostic.
TwinEU_NFR_65	Deployment Flexibility	Flexibility	Installability	The TwinEU system must be deployable in any environment (e.g., using Kubernetes, Docker or similar approach).
TwinEU_NFR_66	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).
TwinEU_NFR_67	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_68	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.

Requirement ID	Name	Category	Sub-category	Description
TwinEU_NFR_69	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_70	Safety Warning and Prevention	Safety	Hazard warning	The TwinEU system should provide timely warnings to prevent actions that could compromise safety.
TwinEU_NFR_71	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_72	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 C - Functional Requirements

This section outlines FURs and related UCs, organized and grouped according to each TwinEU demonstrator (DEMO). This structured grouping ensures clarity in how the requirements are distributed across different demonstrators. DEMO 5 consists of Dutch-French, Eastern-Mediterranean, and one Iberian UC. DEMO 6 has Italian, Slovenian, Hungarian, and German UCs. DEMO 7 comprises of Slovenian, Hungarian, Eastern-Mediterranean, and Bulgarian UCs. Finally, DEMO 8 has Dutch-French and Iberian UCs.

C.1 DEMO 5: Demonstrations of digital twinning for cyber-physical grid resilience

This section shown which UCs are related to DEMO 5 and which FURs are derived for each UC.

Table 28 - DEMO 5: Demonstrations of digital twinning for cyber-physical grid resilience

Functional Requirement ID	Name	Description	Related Use case(s)
DT-CYB-01-NL01-01	Simulating Dynamic Behaviour	The system must develop a digital twin capable of simulating the dynamic behaviour of transmission systems.	NL01
DT-CYB-01-NL01-02	Simulate various types of cyberattacks	The system must simulate various types of cyberattacks focusing on communication systems. The physical performance of the power system will be simulated beyond real-time time frames, with findings and recommendations applicable to real-time operations.	NL01
DT-CYB-01-NL01-03	Cyberattack Impact Analysis on System Stability	The system must analyse the impact of the cyberattacks on system stability, focusing on impact of active/reactive power imbalances and cascading failures due to N-k disturbances.	NL01
DT-CYB-01-NL01-04	ML Algorithms for Monitoring and Anomaly Detection	The system should implement machine learning algorithms for real-time monitoring and anomaly detection, analysing network traffic and operational data to quickly identify deviations from normal patterns.	NL01
DT-CYB-01-NL01-05	Alert Operations	The system could alert operators to potential cyberattack threats.	NL01

Functional Requirement ID	Name	Description	Related Use case(s)
DT-CYB-01-NL01-06	Data Integration	The system should integrate data from various sources, including TSOs and DSOs, for suitable monitoring and analysis of the grid under cyberattack conditions.	NL01
DT-CYB-01-NL01-07	Secure Data Management and Accurate Time-Stamping for Real-Time Decision Support	The system must ensure data is accurately time-stamped to support real-time analysis and decision-making.	NL01
DT-CYB-01-NL01-08	Simulate Operation Scenarios	The system must simulate the impact of selected interesting operation scenarios	NL01
DT-CYB-04-FR01-01	Simulation Scenario Management for Training Exercises	The system should allow the game master to configure and execute training scenarios that involve events affecting the power and communication networks (e.g., wind variations, cyber-attacks, electrical grid faults).	FR01
DT-CYB-04-FR01-02	Cyber-Physical Simulation with Real-Time Updates	The system's cyber-physical simulator should process simulation data and scenario inputs, accurately simulating both physical and telecommunication network behaviours with one second update rate of simulated scenario to avoid lagging or freezing effects for operators.	FR01
DT-CYB-04-FR01-03	Integrated SCADA and Telecommunication Network Simulation	The system should include a SCADA simulator and telecommunication network simulator that displays the current network state to operators and receives control orders, simulating a real control room environment.	FR01
DT-CYB-04-FR01-04	Training Session Event Logging and Analysis	The system should record all meaningful events, operator actions, and system responses during training sessions for post-session debriefing and comparison of decision-support module effectiveness.	FR01
DT-CYB-04-FR01-05	Modular Integration for Decision-Support Tool Testing	The system must support integration of software modules, allowing for new decision-support tools or software automatons to be tested in training scenarios.	FR01

Functional Requirement ID	Name	Description	Related Use case(s)
DT-CYB-04-FR01-06	Realistic Cyber-Physical Interdependency Simulation	The cyber-physical simulator must accurately replicate real-world physics and cyber layers, including interdependencies between the power network and communication network, to provide realistic training conditions.	FR01
DT-CYB-04-FR01-07	Custom Scenario Creation and Event Consequence Management	The game master module must enable the creation of custom training scenarios, manage the consequences of various phenomena, such as notifications related to weather conditions. Specifically, it should focus on handling sequences triggered by weather events (e.g.: faults in the grid) rather than the weather conditions themselves.	FR01
DT-CYB-04-FR01-08	Smart Assistant Integration for Decision Support	The system must support the integration of smart assistant modules, which can autonomously analyse, support, or enhance operator decision-making during the simulation.	FR01
DT-CYB-04-FR01-09	Adaptive Closed-Loop Scenario Management	The System's game master must provide closed-loop scenario generation, enabling automatic scenario adjustments based on operators' actions and system responses during training sessions. This ensures realistic adaptation of scenarios in real-time.	FR01
DT-CYB-04-FR01-10	Synchronized Co-Simulation of Telecommunication and Cyber-Physical Systems	The system must enable co-simulation between the WAN telecommunication simulator and cyber-physical simulator, allowing synchronized event simulation across the network and power grid.	FR01
DT-CYB-04-FR01-11	Real-Time SCADA Interface with Cyber-Physical Integration	The SCADA interface should functionally mirror real SCADA systems, using data flows similar to those in an actual control room. It should display real-time updates of network status and allow operators to send commands to the cyber-physical simulator without noticeable delay.	FR01
DT-CYB-02-EM-CY-01-01	DSO Coordination for DER Power Regulation	The system must enable the DSO to coordinate flexible Distributed Energy Resources (DERs) for active and reactive power regulation.	EM-CY-01
DT-CYB-02-EM-CY-01-02	Real-Time DER Monitoring and Thermal Limit Control	The system must support real-time monitoring and control of DERs to prevent thermal limit violations in local distribution grids.	EM-CY-01

Functional Requirement ID	Name	Description	Related Use case(s)
DT-CYB-02-EM-CY-01-03	Facilitation of Local Flexibility Market Clearing	The system should facilitate the clearing of flexibility services through a local ancillary services market. The system must support bidirectional communication between market operators and DERs for service bidding and clearing.	EM-CY-01
DT-CYB-02-EM-CY-01-04	Grid Capacity Optimization Through DER Flexibility	The system should optimize the utilization of existing grid capacity by leveraging DER flexibility. It must allow DERs to participate actively in grid management, contributing to congestion relief.	EM-CY-01
DT-CYB-02-EM-CY-01-05	Data integration	The system must integrate data from various sources, including DER status, and market data.	EM-CY-01
DT-CYB-02-EM-CY-01-06	Advanced Congestion Prediction and Management	The system should support advanced analytics to predict and manage potential congestion scenarios.	EM-CY-01
DT-CYB-02-EM-CY-01-07	Digital Twin Framework for Grid Scenario Analysis	The system should provide a realistic representation of the grid's physical layer for scenario analysis. The system must implement a digital twin framework for simulating grid conditions and the impact of DER actions.	EM-CY-01
DT-CYB-02-EM-CY-01-08	Cyberattack Impact Simulation on Distribution Grid Operations	The system must be capable of simulating and analysing the impact of cyberattacks on distribution grid operations.	EM-CY-01
DT-CYB-02-EM-CY-01-09	Creation and Analysis of Operational Scenarios for Power Imbalances and Cyber-Attacks	The system should support the creation and analysis of various operational scenarios, such as intense power imbalances and cyber-attacks.	EM-CY-01
DT-CYB-03-IB04-01	Abnormal Market	The system must detect and identify abnormal market participation patterns based on pre-defined thresholds and criteria for wholesale and local flexibility markets. (The system must detect abnormal market participation activities.)	Ib04
DT-CYB-03-IB04-02	Real-Time Cybersecurity Monitoring for Digital Twin Operations	The system's RT operational modules of the involved DTs must continuously monitor transactions in real-time for signs of cyber-attacks or irregular behaviour from market participants.	Ib04
DT-CYB-03-IB04-03	Flag Suspicious Market Activities	The system should flag suspicious market activities, such as unusual bidding patterns.	Ib04

Functional Requirement ID	Name	Description	Related Use case(s)
DT-CYB-03-IB04-04	Risk Identification and Management with AI-Driven Threat Analysis	The system must identify and manage potential risks (propose remedial actions to mitigate identified risks) and could classify them by severity. The AI agent should identify potential risks related to system stability, overloads, or other critical issues in the power grid. The system must flag high-risk conditions and provide detailed risk analysis. The system must evaluate and identify potential cybersecurity threats across both wholesale and local flexibility markets by analysing data & communication between stakeholders (TSO, DSO, and MO).	Ib04
DT-CYB-03-IB04-05	Rapid Threat Information Sharing and Response Activation	The system should facilitate the swift sharing of threat detection information between all levels of the electricity system, ensuring that countermeasures are activated without delay.	Ib04
DT-CYB-03-IB04-06	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-CYB-03-IB04-07	Real-Time Threat Response and Market Transaction Security	The system must enable real-time protocol activation, allowing immediate response to identified threats to prevent the escalation of market disruptions. The DT should automatically execute pre-configured actions to secure market transactions based on the severity and type of abnormal market behaviour.	Ib04

C.2 DEMO 6: Demonstration of digital twinning for grid management, operation and monitoring

This section shows which FURs are defined for each specific UC that belongs to the DEMO 6.

Table 29 - DEMO 6: Demonstration of digital twinning for grid management, operation and monitoring

Functional Requirement ID	Name	Description	Related Use case(s)
DT-O&M-03-IT01-01	TSO Defense System Scenario Simulation	The system must be able to simulate various scenarios that trigger the TSO defense system.	IT01

Functional Requirement ID	Name	Description	Related Use case(s)
DT-O&M-03-IT01-02	Frequency and Voltage Behaviour Analysis for System Stability	The system must be capable of acquiring data related to frequency, current and voltage behaviour following an event, providing insights into system stability and security.	IT01
DT-O&M-03-IT01-03	Manual Sensitivity Analysis for Defense System Performance	The system must allow sensitivity analyses considering the evolution of system parameters and future scenarios, allowing for the assessment of the defense system's performance under varying conditions. The sensitivity analysis is based on manual data variation.	IT01
DT-O&M-03-IT01-04	Geographically Distributed Real-Time Simulator Integration	The system shall support the integration of geographically distributed Real-Time Simulators (RTS) between different facilities, such as Terna and Ensiel, to simulate more complex grid frameworks. It will be available only in presence of permissions from the TSO and DSO.	IT01
DT-O&M-03-IT01-05	Hardware-in-the-Loop (HIL) Protection and Control Testing	The system must interface with real hardware devices (also using power hardware in the loop approach) to test protection and control logics under near-real conditions safely.	IT01
DT-O&M-03-IT01-06	Real-Time Monitoring of TSO Defense System Behaviour	The system must allow for real-time or quasi-real time monitoring of the TSO defense system's behaviour during simulations, providing visual and numerical feedback on key parameters like voltage, frequency, and equipment status.	IT01
DT-O&M-03-IT01-07	Scenario Generation and Execution for Defense System Testing	The system must be capable executing different scenarios based on predefined triggers or conditions, ensuring comprehensive testing of the defense system under various potential threats.	IT01
DT-O&M-03-IT01-08	Fault Injection for Defense System Response Testing	The system must include a feature to inject faults into the simulated grid (e.g., short circuits, line trips) to assess the defense system's response and effectiveness in mitigating cascading failures.	IT01
DT-O&M-03-IT01-09	Simulation Event Logging and Scenario Replay for Performance Analysis	The system must log all simulation events and provide the capability to replay specific scenarios to analyse the defense system's performance under identical conditions.	IT01

Functional Requirement ID	Name	Description	Related Use case(s)
DT-O&M-03-IT01-10	User Access Control	The system must allow different levels of user access to the server, ensuring that only authorized personnel can initiate or modify simulations, particularly when interfacing with physical devices.	IT01
DT-O&M-01-EACL-IT-01-01	Rule-Based System Utilization	The system should utilize several rules (machine readable rules) established in the system	EACL-IT-01
DT-O&M-01-EACL-IT-01-02	BIM Integration for Design Verification	The system could be integrated with BIM viewer to support the technical supervisors and contractors in verifying the design's completeness and coherence.	EACL-IT-01
DT-O&M-01-EACL-IT-01-03	BIM Model Generation for Design Compliance	The system could help designers to produce a BIM model that accurately reflects the design specifications, standards, and regulatory requirements.	EACL-IT-01
DT-O&M-01-EACL-IT-01-04	LOIN (Level of Information Need)	The system allows for sharing the LOIN (Level of Information Need) to ensure that the necessary level of detail and information is provided for each object in the digital twin.	EACL-IT-01
DT-O&M-01-EACL-IT-01-05	Optimized Data Sharing for Transparency in Digital Twin	The system should optimize data sharing within the digital twin, ensuring transparency and accessibility of information across all agents.	EACL-IT-01
DT-O&M-01-EACL-IT-01-06	Facilitation of Information Exchange Between Designer and TSO	The system must facilitate detailed information exchange between designer and validator (TSO).	EACL-IT-01
DT-O&M-01-EACL-IT-02-01	Automated BIM Model Compliance Verification Tool	The system must include an automated tool that checks the BIM model against preloadable rules (such as national regulations, TSO standards, and technical specifications for design validation). Verification rules must be set upstream and not by whoever uploads the project	EACL-IT-02
DT-O&M-01-EACL-IT-02-02	Geometrical Validation for Spatial Conflicts in Design	The system could validate the geometrical aspects of the design, ensuring there are no spatial conflicts or interferences in the proposed layout.	EACL-IT-02
DT-O&M-01-EACL-IT-02-03	Automated Check Report Generation	The system could provide a sort of report on the checks carried out and their results	EACL-IT-02

Functional Requirement ID	Name	Description	Related Use case(s)
DT-O&M-01-EACL-IT-02-04	Iterative TSO Project Approval Workflow	The system could include a workflow for TSO project approval, allowing for iterative feedback and updates to the design based on validation results.	EACL-IT-02
DT-O&M-01-EACL-IT-02-05	Information Content Check Report Generation	The system could generate a report on the checks carried out on the model in terms of information content	EACL-IT-02
DT-O&M-03-IT02-01	DT Network Model Validation	The system must validate the DT network model by comparing the simulation outputs with real-world data provided by the DSO. The system should ensure that the validation process accounts for real-time grid events, providing insights into voltage, frequency, and load variations.	IT02
DT-O&M-03-IT02-02	Manual Sensitivity Analysis for DER Penetration	The system should perform sensitivity analysis by simulating various levels of DER penetration in different network configurations (urban vs. rural). The sensitivity analysis is based on manual data variation, not done automatically	IT02
DT-O&M-03-IT02-03	Grid Behaviour Assessment for Medium and High-Density Regions	The system must assess grid behaviour under these scenarios, focusing on potential stability and operational challenges in both medium and high-density regions.	IT02
DT-O&M-03-IT02-04	Virtual Islanding Simulation and DER Behaviour Analysis	The system should simulate virtual islanding mode and evaluate how DERs behave in isolated grid sections, analysing their influence on voltage and frequency stability.	IT02
DT-O&M-03-IT02-05	MV-Level Data Monitoring and Storage for Analysis	There is no aggregation done by the system itself, but the aggregation at MV level is required as input. The system must monitor and store data on voltage, frequency, load profiles, and DER outputs for further analysis.	IT02
DT-O&M-03-IT02-06	Future Grid Scenario Modeling and Impact Analysis	The system could model future grid scenarios based on planned DER expansion and analyse their potential impacts on distribution and transmission grid stability.	IT02
DT-O&M-03-IT02-07	Resilience Improvement Based on Simulation Results	In the system, the results could be used also for resilience improvement. However. no resilience evaluation is expected to be done directly by the system	IT02

Functional Requirement ID	Name	Description	Related Use case(s)
DT-O&M-03-IT02-08	Single DER behaviour model	DERs' behaviour could be also modelled starting from single entity, per type, by comparing several generators from different types	IT02
DT-O&M-03-IT02-09	Single DER behaviour model validation	Single DERs' models could be used in simulation environment to validate the model and be ready for RTS	IT02
DT-O&M-03-IT02-10	Aggregated DERs behaviour model	Using single DERs' behaviour, an aggregated model will be included as asset	IT02
DT-O&M-03-IT02-11	Aggregated DERs behaviour validation	Aggregated DERs' models will be used in simulation environment to extend the Defence System use case	IT02
DT-O&M-03-IT02-12	Model dynamic behaviour of DERs	The system should model dynamic behavior of DERs in response to grid events in real time or near real time.	IT02
DT-O&M-03-IT02-13	Simulate Flex Resources Under Realistic Conditions	The system must support real-time simulation of the behavior of flexibility resources in a realistic scenario to verify their technical capabilities to provide flexibility services.	IT02
DT-O&M-01-EACL-IT-03-02	Display, navigate and query models	The system could be able to display, navigate and query BIM models of electrical stations.	EACL-IT-03
DT-O&M-01-EACL-IT-03-03	Pre-validation of the models	The system should perform pre-validation of the models. The system should enable early-stage design validation before final validation by the TSO	EACL-IT-03
DT-O&M-01-EACL-IT-03-04	Report for validation results	The system could provide a report outlining validation results.	EACL-IT-03
DT-O&M-04-GE-01	Legal Compliance	The system must ensure that flexibility solutions adhere to individual legal specifications for both network and market operator requirements.	Ge04, Ge05, Ge06, Ge07
DT-O&M-04-GE-02 DT-O&M-05-GE-01 DT-O&M-06-GE-27	Reporting and Documentation	The system must generate detailed reports on all important outcomes.	Ge all

Functional Requirement ID	Name	Description	Related Use case(s)
DT-O&M-06-GE-01	Collaboration Capability of Digital Twins	Part of the solutions in the system of digital twins (DTs) could collaborate.	Ge04, Ge07, Ge08
DT-O&M-05-GE-02	Grid Hosting Capacity Visualization and Integration	The system must provide a detailed visual map of grid hosting capacities, showing available and projected capacities for renewable energy sources like large-scale batteries, PV or wind farms. The grid hosting map must integrate data from the DSOs for all respective voltage levels in the distribution grids.	Ge08
DT-O&M-05-GE-03	Connection Request Submission and Capacity Evaluation	The system must allow users (third-party project developers) to submit connection requests and perform online connection checks for pre-connection evaluations. It must provide real-time data on available capacities within certain regions to facilitate decisions on new connections for renewable energy projects.	Ge08
DT-O&M-05-GE-04	Network Planning and Grid Hosting Capacity Management	The system must facilitate network planning by providing accurate data on available and projected grid hosting capacities, improving operational planning and decision-making. It should support DSO operations, including network configuration and network planning.	Ge08
DT-O&M-05-GE-05	Grid Maturity-Based Hosting Capacity Mapping	The system must account for different levels of grid maturity - in terms of different levels of data acquisition for the map and depending on the level of participation of the DSOs - across regions, ranging from early-stage to fully allocated grid capacities, and reflect this in the grid hosting map.	Ge08
DT-O&M-06-GE-02	User Interface for DSO Connection	The system must provide a user-friendly interface for DSOs to interact with connection request and envisioned tools.	Ge01
DT-O&M-05-GE-06	User Interface for DSO Connection	The system must provide a user-friendly interface for project developers to interact with connection request for early evaluation.	Ge08
DT-O&M-04-GE-03	Operator Interface for Data Viewing and Configuration	The system should have a user-friendly interface for operators to view chosen data and proposed actions, as well as allow user configuration of parameters and reporting.	Ge02, Ge03, Ge04, Ge05, Ge06

Functional Requirement ID	Name	Description	Related Use case(s)
DT-O&M-06-GE-03	Advanced Monitoring and Congestion Analysis Tools	The system must include advanced monitoring and congestion tools for detailed analysis of grid states and/or potential bottlenecks/congestions.	Ge03
DT-O&M-06-GE-04	Detection of Congestion Points	The system must detect and highlight potential congestion points within the grid.	Ge03
DT-O&M-06-GE-05	Bottleneck and Critical Grid State Alerting System	The system must provide alerts and notifications when potential bottlenecks or critical grid states are detected.	Ge01, Ge02, Ge03
DT-O&M-06-GE-06	Historical Data Storage and Congestion Prediction Analysis	The system must store historical data and support analysis to predict future congestion and grid states.	Ge01, Ge02, Ge03
DT-O&M-06-GE-07	Integration of Static Grid Models with Live Monitoring Data	The system must integrate static grid models with live monitoring data to provide a comprehensive view of the grid state.	Ge01, Ge02, Ge03
DT-O&M-06-GE-08	State Estimation for Dynamic Grid Topologies	The system must perform state estimations under changing grid topologies to identify current grid conditions.	Ge02
DT-O&M-06-GE-09	Real-Time Grid Utilization Monitoring for LV and additionally MV Levels	The system must support continuous real-time monitoring of grid utilization with the focus on LV, but also involving MV levels.	Ge01, Ge02
DT-O&M-06-GE-10	Real-Time Monitoring of LV and additionally MV Grid Utilization	The system must provide real-time monitoring of grid utilization with focus on Low Voltage (LV) and additionally Medium Voltage (MV) levels are also considered.	Ge01
DT-O&M-06-GE-11	Topology Monitoring and Automated Response System	The system should allow continuous monitoring of the current topology and respond automatically to changes in the grid structure.	Ge02
DT-O&M-06-GE-12	Distribution Grid Visualization with SCADA and Meter Data	The system must visualize the distribution grid with an accurate representation of measurement points and values using data from SCADA-like systems and intelligent meters.	Ge01

Functional Requirement ID	Name	Description	Related Use case(s)
DT-O&M-06-GE-13	Real-Time Data Integration for Grid Operators	The platform must integrate real-time measurements from various sources, including SCADA systems and intelligent meters, into a single view for the grid operator.	Ge01
DT-O&M-06-GE-14	In-Depth Grid Parameter Analysis	The system must enable in-depth analysis of key parameters such as voltage levels, and overall grid utilization.	Ge01
DT-O&M-06-GE-15	Voltage Level Monitoring and Threshold Violation Alerts	The system should provide statistics on voltage levels and notify operators of any threshold violations.	Ge03
DT-O&M-06-GE-16	Real-Time Grid State Estimation and Asset Load Monitoring	The system should estimate the state of the grid, including voltage levels and asset utilization, using the latest real-time data and switching states. It must notify operators when asset loading exceeds safe operational thresholds.	Ge01
DT-O&M-06-GE-17	Dynamic Grid Topology and State Estimation	The platform must accommodate changing grid topology and update the state estimation accordingly to reflect real-time conditions.	Ge02
DT-O&M-06-GE-18	Real-Time LV Topology and Measurement Integration	The system must integrate real-time topology data and measurements from SCADA-like systems, sensors, and meters at the LV level.	Ge02
DT-O&M-06-GE-19	Advanced Real-Time State Estimation for Dynamic Grid Parameters	Advanced state estimation algorithms must be developed to calculate grid parameters such as voltage, current, and asset loading in real-time. The algorithms must account for changes in grid topology, providing dynamic grid state updates based on real-time data.	Ge02
DT-O&M-06-GE-20	Digital Twin-Enhanced State Estimation and Grid Observability	The system should utilize Digital Twin (DT) information, including asset attributes, load, generation data, and topology, to enhance the accuracy of the state estimation process. It should use computational models to expand observability beyond direct measurement points to unmonitored grid areas.	Ge02
DT-O&M-06-GE-21	Automatic Grid State Update for Topology Changes	The platform must automatically adapt to topology changes and update the grid state accordingly, ensuring continuity in monitoring and estimation after network reconfigurations.	Ge02

Functional Requirement ID	Name	Description	Related Use case(s)
DT-O&M-06-GE-22	Historical Data Storage for Topology and State Estimation Analysis	The system should store historical data on topology changes and state estimations, allowing the DSO to analyse trends and past grid behaviours.	Ge02
DT-O&M-06-GE-23	Centralized Network Model with Real-Time LV Sensor Integration	The system must implement a centralized network model that continuously integrates real-time sensor data from low-voltage grids.	Ge01
DT-O&M-06-GE-24	Real-Time Grid State Estimation Including EV and Heat Pump Impact	The platform must perform continuous state estimations to assess real-time grid conditions, identifying potential bottlenecks caused by peaks in electricity consumption. State estimation should consider the impact of electric vehicles and heat pumps on grid load and energy flow.	Ge03
DT-O&M-06-GE-25	Real-Time Congestion Control with Non-Discriminatory Actions	The platform must generate control measures, such as demand-side management or grid reconfiguration, to alleviate congestion in real-time. Control actions should be non-discriminatory and respect grid users' rights, providing equal treatment for all.	Ge03
DT-O&M-06-GE-26	Adaptive Scheduling for Congestion Relief	The system should generate and propose schedules for grid operators to implement ad-hoc adjustments to relieve congestion. These schedules must adapt dynamically based on the real-time grid state and forecasted congestion scenarios.	Ge03
DT-O&M-04-GE-04	Historical Grid Data Analysis for Proactive Congestion Management	The platform must analyse historical grid performance data, including previous congestion instances and grid behaviour under different load conditions. Insights from historical analysis should inform proactive strategies for managing congestion.	Ge04
DT-O&M-04-GE-05	Real-Time Congestion Forecasting Using Current and Historical Data	The system must provide real-time forecasting of potential congestion in the grid based on current and historical data.	Ge04
DT-O&M-04-GE-06	Predictive Congestion Forecasting Logic for Low-Voltage Networks	The system must develop efficient calculation logic for forecasting grid congestion in low-voltage networks. It should rely on real-time user data, historical grid conditions, and advanced predictive models to anticipate potential congestion scenarios.	Ge04

Functional Requirement ID	Name	Description	Related Use case(s)
DT-O&M-04-GE-07	Multi-Source Data Integration for Congestion Forecasting	The system must collect and integrate data from various sources, including real-time sensor data, intelligent meters, and market-based aggregators, to ensure a comprehensive congestion forecast.	Ge04
DT-O&M-04-GE-08	Identification of Congestion-Prone Low-Voltage Grids	The system must identify critical low-voltage grids that are vulnerable to congestion based on load, user behaviour, and grid conditions. Only these critical grids should be actively monitored and managed for potential congestion.	Ge04
DT-O&M-04-GE-09	Demonstrator-Based System Validation in German Region	The system must be validated through a demonstrator setup, especially in the German region.	Ge04
DT-O&M-04-GE-10	Generation of Adaptive Proactive Control Schedules for Congestion Prevention	The system should generate actionable schedules and suggestions for grid operators to activate control measures that prevent congestion. Forecast schedules must be adaptable to real-time conditions and be proactive rather than reactive.	Ge04
DT-O&M-04-GE-11	Dynamic Load Shifting Based on Grid Constraints	The system must enable shifting of charging loads (e.g., electric vehicle charging) based on grid constraints to prevent congestion and comply with grid limits. It should allow households to shift loads based on network restrictions provided by the envelope curve	Ge05
DT-O&M-04-GE-12	HEMS Integration for Optimized Consumption Scheduling	The system must integrate with the household's HEMS, enabling it to calculate optimized consumption schedules for flexible loads, such as EVs and other controllable units.	Ge05
DT-O&M-04-GE-13	Aggregation of Flexibility Potential via HEMS	The system must aggregate flexibility potential from various household assets, such as Wallboxes or heat pumps, and renewable energy sources, using Home Energy Management Systems (HEMS).	Ge05
DT-O&M-04-GE-14	Real-Time Load Scheduling Based on Market and Network Data	The HEMS must be capable of adjusting load schedules based on real-time data, such as spot market prices and network restrictions.	Ge05

Functional Requirement ID	Name	Description	Related Use case(s)
DT-O&M-04-GE-15	Optimization of Flexible Asset Utilization for Load Management	The system must optimize the utilization of aggregated flexible assets to ensure efficient load management and congestion prevention in the network feeder.	Ge05
DT-O&M-04-GE-16	Cost-Effective Charging Schedule Based on EV Data and Market Prices	The HEMS should collect data such as the current charging level of the EV, customer preferences for the desired charge level, and ~~spot~~ market prices to generate the most cost-effective charging schedule.	Ge05
DT-O&M-04-GE-17	Network-Constrained Load Management with User Preferences	The system must adhere to network restrictions, such as the envelope curve, to prevent overloading the local grid with considering user preferences.	Ge05
DT-O&M-04-GE-18	Aggregation of Household Flexible Assets for Energy Optimization	The system must allow the aggregation of flexible assets within the household to optimize total energy consumption and load shifting for the grid feeder.	Ge05
DT-O&M-04-GE-19	Real-Time Load Control Scheduling for Flexible Assets	The system must generate real-time, 15-minute interval schedules for executing load control measures, ensuring that flexible assets comply with network conditions. The charging schedule must be executed via the Wallbox for EVs and controllable units in the household.	Ge05
DT-O&M-04-GE-20	Collection of Customer and Asset Flexibility Data for Regional Allocation	The system must collect customer-specific data, including regional allocation for balancing groups, redispatch regions, controllable assets (e.g., EVs, heat pumps), power values, and relevant contractual details. It must also record the flexibility characteristics of each asset, such as power capacity, operational limits, and constraints. (Only concept, not implemented in demonstrator)	Ge06
DT-O&M-04-GE-21	Forecasting Customer Flexibility Based on Historical Data and LV Grid Constraints	The system should be able to forecast the available flexibility for each customer or for a portfolio of customers based on historical consumption data, which include the regional low-voltage (LV) grid constraints.	Ge06
DT-O&M-04-GE-22	Dynamic Aggregation of Regional Flexibility for Secured Power Delivery	The system must aggregate the flexibility of multiple customers across a region (e.g., balancing groups or redispatch regions) to determine the total available secured power that can be offered to the TSO. This aggregation must be dynamic and scalable, capable of adjusting to varying numbers of customers and different asset types.	Ge06

Functional Requirement ID	Name	Description	Related Use case(s)
DT-O&M-04-GE-23	Aggregation and Analysis of Flexibility Data for Congestion Prediction	The system must aggregate and analyse data from flexible assets to predict potential congestion scenarios.	Ge04
DT-O&M-04-GE-31	Preventive Congestion Management Using Regional Flexibility	The system must support preventive measures for congestion management, utilizing flexibility from regional assets.	Ge05
DT-O&M-04-GE-24	Calculation of Secured Power for Grid Services from Aggregated Flexibility	The system must calculate the total secured power that can be offered for grid services, such as redispatch, based on aggregated flexibility. It must be able to identify the amount of secured power to ensure accurate and reliable grid service delivery.	Ge06
DT-O&M-04-GE-25	Disaggregation and Control of Flexibility via HEMS	Upon acceptance of an offer from the TSO, the system must disaggregate the flexibility, enabling control of individual assets at the customer level. It must send control signals to customer devices, such as Wallboxes, through the Home Energy Management System (HEMS) to activate or adjust their operations.	Ge06
DT-O&M-04-GE-26	TSO-Driven Control of Flexible Assets via HEMS	The system must be able to steer and control flexible assets (e.g., EV chargers) in response to TSO requests. Control must be executed through HEMS as in UC05, allowing for fine-grained control of customer devices.	Ge06
DT-O&M-04-GE-27	Regional Flexibility Management for Grid Alignment and TSO Coordination	The system must manage flexibility at the regional level, ensuring that flexibility is offered and activated in alignment with regional grid constraints and TSO requirements. It should incorporate regional aggregation principles, focusing on balancing group or redispatch region requirements.	Ge06
DT-O&M-04-GE-32	Seamless Real-Time Data Exchange for Micro-Flexibility Usage	The system must support seamless data exchange between TSOs and DSOs to facilitate real-time sharing of flexibility data. It should support the exchange of critical real-time or regular data to facilitate micro-flexibility usage.	Ge07
DT-O&M-04-GE-28	Real-Time Data Exchange for Critical Grid Parameter Access	The platform must facilitate real-time data exchange for critical grid parameters, ensuring both TSO and DSO have timely access to relevant data for operational decisions.	Ge07

Functional Requirement ID	Name	Description	Related Use case(s)
DT-O&M-04-GE-29	Aggregation and Exchange of Small-Scale Flexibility Data for TSO Integration	The system must enable the collection, aggregation, and exchange of data regarding small flexibility sources (e.g., residential storage, EVs) for TSO purposes. It should support the role of market aggregators in facilitating the exchange of control power between TSOs, DSOs, and small-scale flexibility providers.	Ge07
DT-O&M-04-GE-30	Control Power Management and Communication for Grid Stability	The system must allow DSOs and TSOs to request and manage control power from aggregated flexibility. It should provide a mechanism for the TSO to communicate control power requests to aggregators and DSOs, who ensure grid stability during activation.	Ge07
DT-O&M-07-SLO01-01	Dynamic RMS and Offline Analysis for Network Stability and Reliability	One separate system's tool should perform dynamic RMS analysis with an upgraded transmission system model to ensure network stability and reliability, while the second tool should conduct offline analysis.	SLO-BUC-1
DT-O&M-07-SLO01-02	Dynamic Behaviour Impact Assessment for Network Scenarios	The system must assess the impact of various scenarios on the network's dynamic behaviour.	SLO-BUC-1
DT-O&M-07-SLO01-03	Operational Impact Analysis for Network Improvement	The system's indirect results of the operations should allow improvements in the network.	SLO-BUC-1
DT-O&M-07-SLO01-04	Real-Time Integration of DSO and TSO Data for Network Condition Assessment	The system must continuously integrate data from the DSO and TSO environments to assess current network operating conditions. Integration is per request using standardized CIM format	SLO-BUC-1
DT-O&M-07-SLO01-05	AI-Driven Static and Dynamic Security Assessment for Vulnerability Detection	The system must utilize AI-driven tools to conduct both static and dynamic security assessments, identifying potential vulnerabilities under various operating scenarios.	SLO-BUC-1
DT-O&M-07-SLO01-06	Scenario-Based Modelling for Predicting Network Conditions with Distributed Generation Data	The system must support scenario-based modelling to predict future network conditions, incorporating data from distributed generation (DG) connected to the distribution grid.	SLO-BUC-1

Functional Requirement ID	Name	Description	Related Use case(s)
DT-O&M-07-SLO01-07	Enhanced Transmission Model with Dynamic Integration of Distributed Generation and Consumption	The system must enhance the existing transmission system model by integrating an upgraded dynamic model that includes distributed generation, representing different types of generation and aggregated dynamic consumption models.	SLO-BUC-1
DT-O&M-07-SLO01-08	Standardized Network Model Exchange between DSOs and TSO	The system must facilitate the exchange of network models between DSOs and TSO in a standardized and interoperable manner.	SLO-BUC-1
DT-O&M-07-SLO01-09	Generation of Detailed Outcome Reports	The system must generate detailed reports on all important outcomes.	SLO-BUC-1
DT-O&M-07-SLO01-10	Bottleneck and Critical Grid State Alerting System	The system must provide alerts and notifications when potential bottlenecks or critical grid states are detected.	SLO-BUC-1
DT-O&M-07-SLOSUC01-11	SCADA/EMS export capabilities regarding snapshots of the current state	The SCADA/EMS system should periodically generate a snapshot of the current operational state of the power system.	SLO-BUC-3
DT-O&M-07-SLOBUC03-12	Data exchange through NAS regarding storing	The SCADA/EMS system should store generated snapshots on a shared disk accessible by authorized systems.	SLO-BUC-3
DT-O&M-07-SLOBUC03-13	Data exchange through NAS regarding read access	The system should grant read access to the power system analysis tool for the shared disk containing SCADA/EMS snapshot files.	SLO-BUC-3
DT-O&M-07-SLOBUC03-14	Interoperability between tools and systems regarding shared disk	The power system analysis tool must retrieve the latest snapshot file(s) from the shared disk. In this particular case, data interoperability is achieved through CIM CGMES.	SLO-BUC-3
DT-O&M-07-SLOBUC03-15	SCADA/EMS export capabilities regarding file formats	The SCADA/EMS system must generate snapshots in at least the following formats: CIM, PSS/E, and TXT. Export capabilities should enable interoperability between tools and systems.	SLO-BUC-3
DT-O&M-07-SLOBUC03-16	Interoperability between tools and systems with given file formats	The power system analysis tool must support retrieval of files in CIM, PSS/E, and TXT formats.	SLO-BUC-3

Functional Requirement ID	Name	Description	Related Use case(s)
DT-O&M-07-SLOBUC03-17	Interoperability between tools and systems regarding snapshots	The power system analysis tool should allow the user to select a snapshot to use for a simulation or analysis task.	SLO-BUC-3
DT-O&M-07-SLOBUC03-18	Simulation tool validation capability	The tool should validate the imported data before launching simulations. This functional request is closely correlated with the request on interoperability.	SLO-BUC-3
DT-O&M-07-SLOBUC03-19	SCADA/EMS export capabilities regarding automatic snapshots	The SCADA/EMS system could automatically create and save snapshots at configurable time intervals.	SLO-BUC-3
DT-O&M-08-HU01-01	ANN-Based Digital Twins for Power Line Thermal Behaviour Simulation	The system must develop ANN-based digital twins for power line monitoring, capable of simulating the thermal behaviour of conductors.	Hu01
DT-O&M-08-HU01-02	Integration of Sensor and Weather Data for Accurate Power Line Thermal Modelling	The system must integrate data from physical sensors and weather datasets to accurately model the thermal behaviour of power lines.	Hu01
DT-O&M-08-HU01-03	DLR Calculation and Bottleneck Identification Using Digital Twin Data	The system must support DLR calculations using the data provided by the digital twins, facilitating the identification of potential bottlenecks in the high-voltage network.	Hu01
DT-O&M-08-HU01-04	Cost-Effective Operations through Advanced Digital Twin Technology	The system must reduce the dependency on physical monitoring devices by implementing advanced digital twin technology, thereby decreasing maintenance and operational costs.	Hu01
DT-O&M-08-HU01-05	Real-Time Monitoring and Alerting for Maximum Operating Temperature Exceedance	The system must provide real-time monitoring and alerting if maximum operating temperature (MOT) is exceeded, enabling proactive management of the grid	Hu01
DT-O&M-08-HU01-06	Scalable System for Future Expansion and Integration of Monitoring Devices	The system must be scalable to accommodate future expansion and integration of additional monitoring devices and data sources.	Hu01

Functional Requirement ID	Name	Description	Related Use case(s)
DT-O&M-08-HU01-07	System Operation Documentation and Insights for Stakeholder Evaluation	In the system, documentation of the system operation should be prepared that includes critical results, their evaluation, and findings. Based on these, insights can be provided that can be used during system operation and are useful outputs for stakeholders.	Hu01

C.3 DEMO 7: Demonstrations of digital twinning for forecasting and optimal grid and market actions

This section shows which FURs are defined for each specific UC that belongs to the DEMO 7.

Table 30 - DEMO 7: Demonstrations of digital twinning for forecasting and optimal grid and market actions

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-01-EM-GR-01-01	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-F&OG-01-EM-GR-01-02	Real-Time DER Monitoring and Control for Energy Balancing	The system should enable close to real-time monitoring and control of DERs for balancing energy supply and demand.	EM-GR-01
DT-F&OG-01-EM-GR-01-03	Congestion Management through DERs and Demand Response Optimization	The system must facilitate congestion management in both distribution and transmission grids by optimizing the use of DERs and industrial demand response.	EM-GR-01
DT-F&OG-01-EM-GR-01-04	Voltage and Thermal Limit Violation Prevention	The system should provide mechanisms for avoiding voltage and thermal limit violations.	EM-GR-01
DT-F&OG-01-EM-GR-01-05	Industrial Demand Response Support	The system must support industrial demand response programs, allowing large industrial consumers to adjust their electricity usage during peak periods.	EM-GR-01
DT-F&OG-01-EM-GR-01-06	DER Coordination for Grid Stress Flexibility	The system should coordinate with DERs to provide additional flexibility during times of grid stress.	EM-GR-01

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-01-EM-GR-01-07	Digital Twin Framework for Grid Simulation and Optimization	The system should include a digital twin framework for simulating and optimizing grid operations. The system must model various scenarios, including peak demand periods and grid stress conditions, to enhance grid stability and efficiency.	EM-GR-01
DT-F&OG-01-EM-GR-01-08	DER and Industrial Participation in Balancing Market	The system should enable DERs and industrial participants to engage in the balancing market, offering flexibility services. DERs and industrial participants can provide mFRR and congestion management.	EM-GR-01
DT-F&OG-01-EM-GR-01-09	Balancing Energy and Reserves Market Clearing Support	The system must support the clearing of balancing energy and reserves markets, including FCR, aFRR, and mFRR.	EM-GR-01
DT-F&OG-01-EM-GR-01-10	Comprehensive Grid View through TSO, DSO, and Market Operator Integration	The system must integrate data from TSOs, DSOs, and market operators to provide a comprehensive view of grid conditions.	EM-GR-01
DT-F&OG-01-EM-GR-02-01	Integration and Operation of FFR Capabilities with Energy Storage Systems	The system must support the integration and operation of FFR capabilities, particularly focusing on technologies such as energy storage systems.	EM-GR-02
DT-F&OG-01-EM-GR-02-02	Advanced Analytics for Decision-Making and Real-Time Optimization	The system should utilize advanced analytics for decision-making, forecasting, and close to real-time optimization.	EM-GR-02
DT-F&OG-01-EM-GR-02-03	Real-Time Activation and Deployment of FFR Resources	The system should enable close to real-time activation and deployment of FFR resources to address frequency deviations quickly.	EM-GR-02
DT-F&OG-01-EM-GR-02-04	Continuous Frequency Monitoring and Stability Alerts	The system must continuously monitor grid frequency and stability, providing close to real-time data and alerts on deviations.	EM-GR-02
DT-F&OG-01-EM-GR-02-05	Optimal FFR Scheduling and Deployment Algorithms Inclusion	The system must include algorithms for the optimal scheduling and deployment of FFR resources, balancing system requirements, grid conditions, and economic considerations.	EM-GR-02
DT-F&OG-01-EM-GR-02-06	FFR Deployment Scenario Modelling and Simulation	It should support the modelling and simulation of various FFR deployment scenarios to optimize resource allocation.	EM-GR-02

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-01-EM-GR-02-07	Facilitated FFR Market Participation	The system partially facilitates the participation of various entities, including DERs and energy storage operators, in the balancing market for FFR services.	EM-GR-02
DT-F&OG-01-EM-GR-02-08	FFR Bidding and Capability Modelling	The system should provide mechanisms for accurately modelling and bidding FFR capabilities and characteristics in the market.	EM-GR-02
DT-F&OG-01-EM-GR-02-09	Integrated FFR and Grid Condition Visualization	The system must integrate data from TSOs, DSOs, and other market participants to provide a comprehensive view of grid conditions and FFR availability.	EM-GR-02
DT-F&OG-01-EM-GR-02-10	Advanced Analytics and Optimization Framework	The system should utilize advanced analytics for decision-making, forecasting, and close to real-time optimization.	EM-GR-02
DT-F&OG-03&04-BG-01	Energy Grid Digital Twin Verification and SubDT Validation	The created Digital Twins (DTs) for the transmission grid, distribution grid, and cross-border energy exchange should be verified by the partners in the pilot. SubDTs related to the wind turbines, solar modules and OHLs (for ampacity forecasts) will be developed and validated by partners/system.	BG01
DT-F&OG-03&04-BG-02	Digital Twin Simulation and Performance Validation	The system should simulate real-life scenarios using the DT models and compare predefined performance indicators against historical or expected values.	BG01
DT-F&OG-03&04-BG-03	Digital Twin Model Performance Reporting and Discrepancy Management	The detailed reports on performed operations must be drafted by the partners in the pilot. A report must be generated detailing the accuracy and reliability of the DT models. Any discrepancies between simulated and real-world data must be logged and addressed. For the SubDTs related to the wind turbines, solar modules and OHLs (for ampacity forecasts) results will be automatically generated and presented by the system.	BG01
DT-F&OG-03&04-BG-04	Digital Twin Communication and Integration for Bulgarian Grid Systems and cross-border exchange	Seamless communication between the Digital Twins, particularly between DTs for the Bulgarian transmission system, distribution system, and cross-border exchange must be established. The communication must support the data formats and protocols defined in the PSS/E network models used by the Bulgarian grid operators. For the SubDTs related to the wind turbines, solar modules and OHLs (for ampacity forecasts) system will establish communication with the network DTs through Python scripts.	BG01

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-03&04-BG-05	Automated Data Flow Integration for CBME and Grid Operators	Automated information flow from DT CBME (Cross-Border Market Exchange) to the TSO (Transmission System Operator) and DSO (Distribution System Operator) DTs will be ensured through Python scripts (for PSS/E and SubDTs).	BG01
DT-F&OG-03&04-BG-06	Bidirectional Data Exchange and Integration for DTs and SubDTs	Bidirectional data exchange between DTs and DTs and SubDTs using appropriate programming codes and languages compatible with PSS/E network models must be ensured and supported.	BG01
DT-F&OG-03&04-BG-07	Data Exchange Validation and Discrepancy Resolution	Data exchange testing where random data sets are tracked to ensure accuracy and reliability throughout the exchange process must be conducted. If discrepancies are detected, the errors must be logged and handled to mitigate any inconsistencies in data flow.	BG01
DT-F&OG-03&04-BG-09	Predictive Analysis Integration for Grid Management and Stability	The system must integrate artificial neural networks and numerical weather prediction models into the SubDT and DT framework to support predictive analysis for energy and power system state forecasting. These predictive models should be fed into the DTs to assist in grid management, frequency control, voltage stability, and optimal use of grid flexibility.	BG01
DT-F&OG-03&04-BG-10	Authorized Access and Simulation Environment for DTs/SubDTs	The system should allow authorized users (e.g., TSO, DSO, grid operators) to access the SubDTs/DTs in the simulation environment and simulate data exchanges and actions foreseen within the UCs of the pilot.	BG01
DT-F&OG-03&04-BG-11	Grid Model Integration for RES and VRES Forecasting	The DTs should integrate grid models with high levels of RES (Renewable Energy Sources) production and consumption predictions, specifically considering the technical and geographical constraints of VRES (Variable Renewable Energy Sources) and battery systems.	BG01
DT-F&OG-03&04-BG-12	Grid Upgrade Evaluation for VRES and Battery Integration	The system's DTs could be capable of evaluating potential grid upgrade needs to accommodate increased hosting capacity for VRES and batteries.	BG01
DT-F&OG-03&04-BG-13	Weather Data Collection and Preprocessing for ANN Integration	The system must collect and preprocess weather data (such as wind speed, temperature, pressure, and other relevant climatic parameters) from high-resolution sources to use as input for the ANN (Artificial Neural Network).	BG02

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-03&04-BG-14	Confidential Data Delivery and Anonymization for WPP Production	To ensure confidentiality, all collected data will be delivered with necessary confidentiality measures (such as the aggregation or anonymization of the WPP production) already pre-taken.	BG02
DT-F&OG-03&04-BG-15	Integration of External Data Sources for Accurate Forecasting	The system could support integration with existing data sources like weather stations and historical production datasets for accurate forecasting.	BG02
DT-F&OG-03&04-BG-16	ANN Training for WPP Production Forecasting	The system must use the collected data (historical WPP production and weather data) to train an ANN model specifically designed to forecast WPP production power. It should support iterative training processes where the model adjusts parameters until the desired accuracy is achieved. The system must allow for ANN training using historical production and weather data.	BG02
DT-F&OG-03&04-BG-17	WPP Production Forecasting using ANN Model	The system must generate WPP production forecasts using the trained ANN model. Forecasts should be based on input weather data and technical characteristics of the WPP.	BG02
DT-F&OG-03&04-BG-18	ANN Forecast Validation and Accuracy Monitoring	The system must compare ANN-generated forecasts against actual production values and log any deviations for continuous improvement. The system must compare forecasted WPP production data against actual production to measure the accuracy.	BG02
DT-F&OG-03&04-BG-19	Grid Congestion and Voltage Issue Detection with WPP Forecasts	The system could help in identifying potential grid congestions and voltage issues by implementing forecasted WPP production in the created Digital Twins in the simulation environment.	BG02
DT-F&OG-03&04-BG-20	Continuous ANN Model Improvement through Data Integration	In the system, the ANN model must continuously improve by integrating new production and weather data, refining its predictions over time.	BG02
DT-F&OG-03&04-BG-21	Automated ANN Re-training for Forecast Deviation Management	The system could allow operators to trigger re-training of the model if significant deviations between forecasts and actuals are detected. The system must be capable of retraining if the forecast deviation exceeds predefined thresholds, ensuring continuous improvement.	BG02

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-03&04-BG-22	FSP Identification and Evaluation using Improved WPP Forecasts	The system could help the system operators identify potential Flexibility Service Providers (FSPs) by using improved forecasts and evaluate offers for services made by FSPs based on improved WPP production forecasts. This will be tested in the simulation environment in the scope of the pilot.	BG02
DT-F&OG-03&04-BG-23	Outage Prediction and Management for WPPs Using Weather Data	The system could assist in improving outage management by predicting WPP production outages or reduced output due to adverse weather conditions. In the scope of the pilot, this will only be tested in the simulation environment, based on the available historical datasets.	BG02
DT-F&OG-03&04-BG-24	Cost-Efficient Grid Operation through FSP Optimization	The system could contribute to the cost-efficient operation of the grid by helping system operators optimize the management of FSPs, minimize unnecessary activations, and avoid operational costs related to grid congestion. This will only be tested in the simulation environment in the scope of the pilot.	BG02
DT-F&OG-03&04-BG-25	FSP Identification and Management Optimization	The system could help the system operators improve the identification and management of FSPs (Flexible Service Providers) in the grid. This will only be tested in the simulation environment in the scope of the pilot.	BG02
DT-F&OG-03&04-BG-26	WPP Production Forecasting for Grid Congestion and Voltage Stability	The system must help avoid grid congestions and voltage issues by improving WPP production forecasts.	BG02
DT-F&OG-03&04-BG-27	AI-Driven Decision Support for Outage Management and Grid Optimization	The AI system could support enhanced decision-making for outage management and grid operation optimization. This will only be tested in the simulation environment in the scope of the pilot.	BG02
DT-F&OG-03&04-BG-28	High-Resolution Weather and SPP Data Collection and Preprocessing for AI Integration	The system must collect high-resolution weather data and SPP production data from selected capacities. The collected data must be verified and converted into a format that can be processed by the AI/ANN algorithm.	BG03
DT-F&OG-03&04-BG-29	Confidential Data Delivery with Anonymization for SPP Production	To ensure confidentiality, all collected data will be delivered with necessary confidentiality measures (such as the aggregation or anonymization of the SPP production) already pre-taken.	BG03

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-03&04-BG-30	ANN-Based Pattern Recognition for SPP Production Forecasting	The system must utilize Artificial Neural Networks (ANN) to identify patterns between weather conditions and SPP production data. The system must support the training of the ANN model using historical SPP production data and weather forecasts.	BG03
DT-F&OG-03&04-BG-31	AI-Enhanced SPP Production Forecasting	The AI model must be designed to improve the accuracy of SPP production forecasting compared to current methodologies.	BG03
DT-F&OG-03&04-BG-32	Continuous AI Training for SPP Production Forecasting	The system must train the AI model using historical SPP production data and corresponding weather data to establish accurate forecasting patterns. The model must be capable of continuously learning from new data and refining predictions.	BG03
DT-F&OG-03&04-BG-33	Model Validation and Iterative Retraining for Accuracy	The system must support the testing of trained models using separate data (testing data) to validate accuracy. The models must undergo multiple iterations of testing and retraining until a predefined accuracy threshold is met.	all
DT-F&OG-03&04-BG-34	AI Model Calibration through Forecast and Actual Production Comparison	The system's AI models must compare forecasted production values with historical actual production values and adjust parameters as needed.	BG03
DT-F&OG-03&04-BG-35	FSP Identification and Service Evaluation using Improved SPP production Forecasts	The system could help the system operators identify potential Flexibility Service Providers (FSPs) by using improved forecasts and evaluate offers for services made by FSPs based on improved SPP production forecasts. This will be tested in the simulation environment in the scope of the pilot.	BG03
DT-F&OG-03&04-BG-36	FSP Management and Outage Mitigation for Grid Stability	The system could support grid operators in managing FSPs, improving outage management, and enhancing overall system stability by allowing them to estimate if and when some FSP will be able to provide a service. This will only be tested in the simulation environment in the scope of the pilot.	BG03

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-03&04-BG-37	Forecast-Based Outage Prediction and Grid Stability Enhancement	The system could enhance grid stability by providing early warnings of potential outages or production variability based on forecasted SPP production. This will only be tested in the simulation environment in the scope of the pilot by using available historical datasets.	BG03
DT-F&OG-03&04-BG-38	Digital Twin Integration for DER, VRES, and Battery Storage Optimization	The system must integrate with a digital twin of the Bulgarian electricity grid to simulate and analyse optimal points of connection for Distributed Energy Resources (DER), Variable Renewable Energy Sources (VRES), and battery storage systems.	BG03
DT-F&OG-03&04-BG-39	Weather and Real-Time Loading Data Collection for OHL Monitoring	The system must gather weather data, including temperature, wind speed, humidity, and solar radiation, for the areas through which the Overhead Lines (OHL) pass. The system must collect real-time loading data for OHLs that are highly loaded or passing through regions with significant wind exposure.	BG04
DT-F&OG-03&04-BG-40	Ampacity Forecast Optimization for OHLs Based on Load and Weather Conditions	The system must identify which OHLs can benefit from ampacity forecasts based on operator interviews, line load percentage, and weather conditions in the region. The system must prioritize lines where seasonal ratings are conservative, especially in windy areas. System operator feedback will be of high relevance for the proper selection of lines.	BG04
DT-F&OG-03&04-BG-41	Operator-Driven Prioritization for OHL Ampacity Forecasting	The lines will be prioritized mostly based on operator input, but also taking into account percentage of loading and geographic areas with significant wind cooling potential.	BG04
DT-F&OG-03&04-BG-42	AI-Driven Ampacity Forecasting for OHLs Based on Weather Conditions	The system must implement an AI-driven algorithm capable of forecasting ampacity for selected OHLs based on weather conditions. The algorithm must improve upon existing line rating methods and provide accurate, dynamic ampacity forecasts. This will only be tested in the simulation environment and based on the available datasets.	BG04

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-03&04-BG-43	AI-Boosted Ampacity Forecast Validation and Benchmarking	The system must validate the AI-boosted ampacity forecast method through multiple tests, comparing forecasted ampacity to seasonal line ratings and benchmark data.	BG04
DT-F&OG-03&04-BG-44	Digital Twin Integration for OHL Ampacity and Grid Parameter Simulation	The system must integrate with the digital twin of the Bulgarian electricity grid for the simulation of OHL ampacity and other grid parameters in the defined environment.	BG04
DT-F&OG-03&04-BG-45	Ampacity Forecast Impact Assessment on Congestion, Voltage, and Flexibility	The system must use the digital twin to assess how ampacity forecasts impact congestion management, voltage control, and system flexibility.	BG04
DT-F&OG-03&04-BG-46	Load Flow Analysis for Ampacity Forecast Impact on Line Loading	The system must conduct load flow analyses for selected time periods to demonstrate the impact of forecasted ampacity ratings on line loading.	BG04
DT-F&OG-03&04-BG-47	Seasonal vs. Forecasted Ampacity Comparison for Grid Reinforcement Optimization	The system must provide clear comparisons between seasonal and forecasted ampacity, showing how the updated ratings reduce the need for grid reinforcements.	BG04
DT-F&OG-03&04-BG-48	Ampacity Forecasting for Power Flow Optimization and Congestion Management	The system could provide ampacity forecasts to grid operators, enabling them to make informed decisions regarding power flow and congestion management. Forecasts could be implemented in the Digital Twins in the simulation environment to test their potential in optimizing grid usage and reducing the investments.	BG04
DT-F&OG-03&04-BG-49	Ampacity Forecast Insights for Infrastructure Optimization	The system could provide system operators with the insights into how forecasted ampacity could minimize the need for new infrastructure investments by maximizing existing line capacities, allowing them to make informed decisions on that.	BG04
DT-F&OG-03&04-BG-50	Data Collection for Cross-Border Transmission and Flexibility Exchange	The system must collect relevant technical data and high-resolution climate data (e.g., wind speed, temperature) for cross-border transmission lines and those near borders. It must gather real-time operational data on line loading, energy flow, and flexibility exchange between neighbouring grids.	BG05

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-03&04-BG-51	Prioritization and Monitoring of Cross-Border Transmission Lines for Energy and Flexibility Optimization	The system must identify and prioritize cross-border transmission lines with the highest potential for improved energy and flexibility exchange using ampacity forecasts. Lines with significant cross-border exchange constraints (e.g., energy flow limits) must be flagged for enhanced monitoring and analysis. System operator feedback will be of high relevance for the proper selection of lines.	BG05
DT-F&OG-03&04-BG-52	AI-Driven Ampacity Forecasting for Cross-Border Transmission Lines	The system must utilize an AI algorithm to forecast ampacity for cross-border lines, integrating high-resolution weather forecasts to predict potential transmission capacity. This will only be tested in the simulation environment, by using the available historical datasets.	BG05
DT-F&OG-03&04-BG-53	Adaptation of AI Algorithm for Cross-Border Transmission Ampacity Forecasting	The system must adapt the AI algorithm developed in BG04 for cross-border transmission lines, ensuring that the same forecasting principles can be applied and adjusted for cross-border specificities.	BG05
DT-F&OG-03&04-BG-54	Cross-Border Condition Adaptation for Ampacity Forecasting	In the system, enhancements or modifications must be implemented if unique cross-border conditions (e.g., specific climate patterns or infrastructure constraints) require additional considerations.	BG05
DT-F&OG-03&04-BG-55	Load Flow Simulation for Cross-Border Ampacity Optimization	The system must conduct load flow simulations for specific hours where cross-border line loading is high, comparing forecasted ampacity to seasonal ratings to assess potential improvements.	BG05
DT-F&OG-03&04-BG-56	Impact Evaluation of Ampacity Forecasting on Cross-Border Energy Exchange	The system must use the simulations to evaluate the impact of ampacity forecasting on cross-border energy and flexibility exchange.	BG05
DT-F&OG-03&04-BG-57	Forecast Comparison for Cross-Border Energy Transfer Optimization	The system must compare hourly forecasted line ratings to seasonal ratings, focusing on percentual growth in line capacity and identifying opportunities for greater cross-border energy transfer. Forecasts must be used to identify times when cross-border energy exchange is limited by line capacity, and how ampacity forecasts could alleviate these constraints.	BG05

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-03&04-BG-58	Ampacity Forecasting and Load Flow Optimization for Cross-Border Exchange	The system could provide system operators with ampacity forecasts and load flow simulation results, supporting them in optimizing cross-border energy and flexibility exchange.	BG05
DT-F&OG-03&04-BG-59	AI-Driven Decision Support for Cross-Border Grid Stability and Security	The system could support decision-making for grid stability and security by giving the system operators needed information to achieve optimal utilization of cross-border transmission lines. This will be done based on AI forecasts.	BG05
DT-F&OG-03&04-BG-60	Ampacity Forecast-Driven Decision Support for Infrastructure Optimization	The system could support decision-making of the system operators by indicating areas where the ampacity forecasts could delay or prevent new infrastructure construction. This could help them in optimizing available budget and resources.	BG05
DT-F&OG-03&04-BG-61	RES Connection Selection Based on Grid Characteristics and Risk Assessment	The system must allow for the selection of regions for RES (Renewable Energy Sources) connection based on technical grid characteristics, investor interest, and risk assessment for grid reliability. Feedback of the system operator in charge of that part of the system will also play a major role in the selection process. The input data for geographic regions will include technical characteristics of the grid, weather conditions, and anonymized RES capacity data. No preprocessing of data is foreseen, and the collection will be done manually, in the beginning of the pilot practical activities.	BG06
DT-F&OG-03&04-BG-62	Time-Series Generation for RES Production Based on Weather Parameters	The system must generate realistic time-series of RES production based on weather parameters (e.g., wind speeds for WPPs, irradiance and temperature for SPPs).	BG06
DT-F&OG-03&04-BG-63	Ampacity Calculation for RES Integration Based on Climatic Parameters	The system must calculate ampacities of lines using climatic parameters to ensure the grid can support the RES under characteristic operational regimes.	BG06
DT-F&OG-03&04-BG-64	Optimization of RES Connection Points Using Advanced Algorithms	The system must implement optimization algorithms (e.g., genetic algorithm) to determine optimal connection points for RES.	BG06

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-03&04-BG-65	Optimal Power Flow Calculation for RES Connection and Grid Stability	The system must perform optimal power flow calculations to identify connection points that maximize RES generation without causing voltage or overloading issues in the grid. This should be done in the simulation environment.	BG06
DT-F&OG-03&04-BG-66	Simulation of Operational Scenarios for Grid Reliability	The system must simulate characteristic operational hours (high demand or high-RES generation) to ensure reliability under various scenarios.	BG06
DT-F&OG-03&04-BG-67	Load Flow Analysis for RES Integration and Grid Security	The load flow calculations based on the forecasts will be done in the simulation environment to guarantee that RES integration does not compromise grid stability. This does not refer to the dynamic analyses for which term stability is usually used, but for the security and flexibility analyses.	BG06
DT-F&OG-03&04-BG-68	Digital Twin Integration for Grid Evaluation and Technical Capability Assessment	The system must integrate with a digital twin of the Bulgarian electricity grid, enabling the evaluation of grid models and technical capabilities of the grid. This will be done in the simulation environment in the scope of the pilot.	BG06
DT-F&OG-03&04-BG-69	Simulation of Grid Upgrades for RES and Battery Integration to improve grid models	The system could allow for the simulation of grid upgrades to host additional capacity, including new RES and battery installations. This will be done in the simulation environment. The type of capacity that will be considered for connection will depend on input data from SOs. Operators will define necessary inputs for every foreseen simulation and prepare necessary grid models accordingly. Scope of the BG pilot is to improve grid models already developed by the SOs and prove those improvements through the foreseen simulations.	BG06
DT-F&OG-03&04-BG-70	Extreme System Regime Integration for Grid Analysis using Digital Twin	The system must collect input data from the Bulgarian TSO for handpicking extreme system regimes, such as high demand, high RES (Renewable Energy Sources) production, or low line loading. The system must integrate these system regimes into the digital twin (DT) model of the Bulgarian transmission grid for further analysis. The selection of hours should be made based on feedback from SOs and system will incorporate them using appropriate python scripts developed for this purpose.	BG07

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-03&04-BG-71	N-1 Outage Simulation for Grid Impact Assessment	The system must perform N-1 simulations for each single element outage in the transmission grid to assess the impact on system operation. This should be done in the simulation environment.	BG07
DT-F&OG-03&04-BG-72	Load Flow and Voltage Estimation for Outage Scenario Analysis	The system must run load flow calculations and voltage estimation for every outage scenario, identifying critical points such as overloaded branches or buses with voltages out of defined boundaries. This should be done in the simulation environment.	BG07
DT-F&OG-03&04-BG-73	Simulated Critical Event Detection	The system must monitor and detect critical issues like branch overloading and bus voltage deviations resulting from element outages. This should be done in the simulation environment.	BG07
DT-F&OG-03&04-BG-74	Criticality Report Export for Simulation Analysis	Report exporting detailing the criticalities seen in the simulations could be implemented in the solution in order to allow SOs to further process that data.	BG07
DT-F&OG-03&04-BG-75	Mitigation Measure Evaluation and Coordination with TSO	The system could provide information for the evaluation of the mitigation measures, such as switching operations or unit re-dispatch, in close coordination with the TSO.	BG07
DT-F&OG-03&04-BG-76	Ampacity Forecast-Based Critical Issue Resolution in Simulation	The system could assess whether critical issues can be resolved by applying realistic ampacity forecasts for transmission lines. This can only be done in the simulation environment and for the predefined reasonable number of elements of the grid.	BG07
DT-F&OG-03&04-BG-77	Grid Modification and Investment Prioritization Based on N-1 Risk Analysis	The system could help SOs in underlining situations where grid modifications (e.g., upgrades, new transmission lines) are required to resolve ongoing risks detected during the N-1 analysis. The system could also aid in prioritization of the investments for grid development based on identified hotspots.	BG07
DT-F&OG-03&04-BG-78	Integration with Digital Twin for Enhanced Grid Decision-Making	The system must integrate with a digital twin of the Bulgarian grid, incorporating grid models, high-RES production forecasts, and consumption predictions for enhanced decision-making.	BG07

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-03&04-BG-79	Operational Regime Data Collection for Maintenance Season Planning	The system must collect relevant data from the Bulgarian TSO on operational regimes for maintenance season periods (spring, summer, and autumn) based on high demand, high-RES production, or low line loading.	BG08
DT-F&OG-03&04-BG-80	Simulation of Grid Behavior During Maintenance Periods Using Digital Twin Integration	The system must integrate this data into the digital twin (DT) to simulate realistic grid behaviour during planned maintenance periods. This should be done in the simulation environment.	BG08
DT-F&OG-03&04-BG-81	N-1 Scenario Simulation for Maintenance Periods in Operational Conditions	The system must simulate N-1 scenarios for each element undergoing maintenance, ensuring that the maintenance season's operational conditions are accurately modelled. This should be done in the simulation environment.	BG08
DT-F&OG-03&04-BG-82	N-1 Reliability Assessment for Maintenance Scenarios in Simulation	For every maintenance scenario, the system must switch off the element under maintenance and run N-1 reliability assessments on the modified grid topology. This should be done in the simulation environment.	BG08
DT-F&OG-03&04-BG-83	Critical Issue Detection and Flagging in Maintenance Scenarios	The system must detect critical points, such as overloaded branches or buses with voltages out of defined boundaries, for each maintenance scenario. The system must flag the most critical maintenance actions that are likely to cause operational issues in the grid. This should be done in the simulation environment.	BG08
DT-F&OG-03&04-BG-84	Risk Assessment and Mitigation Recommendations for Critical Points During Maintenance	The system could help the SOs assess the risks for each identified critical point during maintenance. It could also help them in providing mitigation recommendations based on prior N-1 analysis results (e.g., from Bg07).	BG08
DT-F&OG-03&04-BG-85	Collaborative Mitigation Strategy Development for Criticalities During Maintenance	The mitigation measures for the criticalities should be determined by the partners in the pilot, with feedback from the relevant SO having the highest impact. The measures could include switching operations, activation of flexibility service providers (FSPs), or rescheduling of maintenance to minimize operational risks.	BG08

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-03&04-BG-86	Expanded Mitigation Measures and Maintenance Plan Adjustment for Critical Issues	If critical issues persist despite applying the mitigation strategies, the set of mitigation measures can be expanded to include changes in the maintenance plan, ensuring that risky maintenance periods do not coincide with extreme operational regimes (e.g., peak demand or high-RES generation).	BG08
DT-F&OG-03&04-BG-87	Data-Driven Maintenance Planning with Expert Collaboration and Historical Analysis	The system must utilize historical data and expert evaluations to select critical elements for maintenance and ensure that maintenance planning accounts for past operational issues and trends. This must be done in cooperation with the system operators in charge of maintaining the selected part of grid.	BG08
DT-F&OG-03&04-BG-88	Congestion Point Detection in Distribution Grid Using Digital Twin Simulation	The system could detect congestion points in the distribution grid using data from the digital twin (DT) model, specifically targeting critical elements prone to overload under extreme operational regimes. This shall be done in the simulation environment by the partners in the pilot. No automated preprocessing of the input data is foreseen.	BG09
DT-F&OG-03&04-BG-89	Collection of Flexibility Service Provider Data for Congested Area Assessment	The data on the available flexibility service providers (FSPs), including renewable energy sources (WPPs, SPPs) and controllable demand (all connected to the distribution grid in the congested area) will be collected in the beginning of the activities. No automated preprocessing of data is foreseen.	BG09
DT-F&OG-03&04-BG-90	Collection of Environmental Data for FSP Performance Assessment	The relevant weather data and other environmental parameters that impact the performance of FSPs, such as wind speed for WPPs and solar irradiance for SPPs, will need to be collected in the beginning of the activities. No automated preprocessing of the input data is foreseen.	BG09
DT-F&OG-03&04-BG-91	Load Flow Simulation with Flexibility Measures for Congestion Impact Assessment	The system must simulate load flow scenarios based on the modified DT model, with congestion conditions imposed, to assess the impact of potential flexibility measures on grid stability. This should be done in the simulation environment.	BG09

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-03&04-BG-92	ANN-Based Flexibility Potential Calculation for FSPs in Simulation	The system could calculate the power reduction potential for controllable demand and the production increase potential for WPPs and SPPs using ANN-based algorithms that predict their flexibility capabilities. This should be done in the simulation environment. The type of the FSP should be determined in coordination with the SO in charge of the observed part of the system.	BG09
DT-F&OG-03&04-BG-93	Simulation of FSP Response and Optimal System Condition Estimation	The system must simulate the FSP response in the critical situation and help in estimating if the optimal system condition is reached once the FSP becomes active. The type of the FSP should be determined in coordination with the SO in charge of the observed part of the system.	BG09
DT-F&OG-03&04-BG-94	FSP Power Reduction Simulation for Surplus Generation Management	The system could support a scenario where FSP power production can be reduced to zero, especially for renewable energy sources (e.g., WPPs or SPPs) during periods of surplus generation. The type of the FSP should be determined in coordination with the SO in charge of the observed part of the system.	BG09
DT-F&OG-03&04-BG-95	FSP Intervention Analysis for Grid Congestion Mitigation Effectiveness	The system could provide detailed analysis and conclusions on whether FSP interventions can effectively mitigate grid congestion. This can be particularly relevant for the situations in which the congestion cannot be fully resolved by FSP management.	BG09
DT-F&OG-03&04-BG-96	Transmission Grid Congestion Detection and FSP Integration for issue Resolution	The system must detect congestion in the transmission grid and identify areas where flexibility services (FSPs) in the distribution grid can help resolve the issue. This should be done in the simulation environment.	BG10
DT-F&OG-03&04-BG-97	Identification of Relevant FSPs for Transmission Grid Congestion Mitigation	The system must identify relevant flexibility service providers (FSPs) in the distribution grid, such as Wind Power Plants (WPPs), Solar Power Plants (SPPs), and controllable demand sources, that can be leveraged to mitigate transmission grid congestion. This should be done in the simulation environment.	BG10

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-03&04-BG-98	Simulation of Transmission Grid Congestion and FSP Activation Impact	The system must simulate various grid congestion scenarios at the transmission level and determine the effect of activating FSPs in the distribution grid on resolving the congestion. This should be done in the simulation environment.	BG10
DT-F&OG-03&04-BG-98	Load Flow Simulation to Verify FSP Effectiveness in Congestion Resolution	The system must conduct load flow calculations to simulate and verify the effectiveness of the FSPs in resolving congestion within specified parameters. This should be done in the simulation environment.	BG10
DT-F&OG-03&04-BG-99	TSO-DSO Coordination Simulation for Flexibility Measure Application	The system could simulate communication and coordination between the Transmission System Operator (TSO) and the Distribution System Operator (DSO) to ensure that flexibility measures in the distribution grid are correctly applied to address transmission grid issues. This will only be done in the simulation environment.	BG10
DT-F&OG-03&04-BG-100	FSP Flexibility Management and Grid Load Balancing in Simulation	The system must manage the level of flexibility provided by each FSP and ensure that the solution is implemented effectively without overloading other parts of the grid. This should be done in the simulation environment.	BG10
DT-F&OG-05-EM-CY-02-01	Coordination of Frequency Support Services Across HVDC Link (Cyprus-Greece)	The system must enable the coordination of frequency support services across the HVDC link in a region (between Cyprus and Greece).	EM-CY-02
DT-F&OG-05-EM-CY-02-02	Real-Time Monitoring and Control for Frequency Stability Management	The system must support real-time monitoring and control to manage frequency stability at both ends of the interconnection.	EM-CY-02
DT-F&OG-05-EM-CY-02-03	Digital Twin Simulation for Cyprus-Greece Interconnection and Operational Scenarios	The system should implement a digital twin environment that replicates in a realistic manner the future interconnection between Cyprus and Greece. The system must simulate various operational scenarios, including power imbalances, to assess the impact on system stability.	EM-CY-02
DT-F&OG-05-EM-CY-02-04	Regional Coordination Framework for Frequency Support Services Management	The system must provide a regional coordination framework for managing frequency support services.	EM-CY-02

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-05-EM-CY-02-05	Simulation and Analysis of Cyber-Attack Impact on HVDC Link	The system should simulate and analyse the potential impact of cyber-attacks on the HVDC link.	EM-CY-02
DT-F&OG-05-EM-CY-02-06 DT-CYB-02-EM-CY-01-09	Creation and Analysis of Operational Scenarios for Power Imbalances and Cyber-Attacks	The system should support the creation and analysis of various operational scenarios, such as intense power imbalances and cyber-attacks.	EM-CY-01, EM-CY-02
DT-F&OG-06-SLO02-01	Unified Observability through TSO Network Model Integration	The system must integrate the TSO's internal dynamic RMS network model with the dynamic RMS models of neighbouring TSOs to create a unified observability area for accurate analysis.	SLO-BUC-2
DT-F&OG-06-SLO02-02	Real-Time Network Data Retrieval for Dynamic Stability	The system must retrieve real-time data on network operational states from SCADA/EMS, including voltages, power flows, and generator setpoints, to maintain an up-to-date model for dynamic stability assessments.	SLO-BUC-2
DT-F&OG-06-SLO02-03	Secure Exchange of Dynamic Generator Data	The system must facilitate the secure exchange of dynamic generator parameters and controller models between TSOs via the TwinEU federated data exchange, ensuring compatibility and interoperability of exchanged data.	SLO-BUC-2
DT-F&OG-06-SLO02-04	Real-Time RMS Simulations for Dynamic Stability Assessment	The system must perform real-time RMS simulations to assess dynamic stability using the combined TSO and neighbouring TSO models, detecting transient state influences from the rest of the interconnected system.	SLO-BUC-2
DT-F&OG-06-SLO02-05	Network Model Validation for RMS Simulation Accuracy	Before running dynamic RMS simulations, the system must validate the combined network model by comparing simulated power flows and voltages against actual measurements from SCADA/EMS.	SLO-BUC-2
DT-F&OG-06-SLO02-06	Dynamic RMS Simulations for Contingency Analysis	Once validation is successful, the system must run a predefined list of dynamic RMS simulations to evaluate system stability under various contingency scenarios.	SLO-BUC-2

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-06-SLO02-07	Calculation of Network Stability Indices from RMS Simulations	The system must calculate network stability indices based on RMS simulation results, providing quantifiable insights into the system's dynamic security and resilience.	SLO-BUC-2
DT-F&OG-06-SLO02-08	Real-Time Display of Stability Indices with Risk Indicators	The system must display calculated stability indices, enabling operators to monitor and interpret network stability in real-time, with visual indicators for alerting operators to potential stability risks.	SLO-BUC-2
DT-F&OG-06-SLO02-09	Static Network Model Import/Export for SCADA/EMS Integration	The system must support import and export functions for static network models, enabling SCADA/EMS data to be seamlessly loaded into the analysis tool and facilitating interoperability with other tools.	SLO-BUC-2
DT-F&OG-02-HU-01	Scheduled DLR Calculation for Market Gate Closures	In the system, the DLR calculations should be deployed 4 times per day, aligning with the gate closures of the DA, IDA1, IDA2 and IDA3 markets.	Hu02
DT-F&OG-02-HU-02	Co-Optimization of Energy and Balancing Capacity with DLR and Flow-Based Constraints	The system should support co-optimization of energy and balancing capacity products within the spot market auction process, considering flow-based transmission constraints and DLR-enhanced capacities.	Hu03
DT-F&OG-02-HU-03	Timely and Realistic DLR Calculation Using Forecast Punctuality	In the system, the DLR data is calculated closer in time to the gate closures and should provide more and more realistic inputs for the capacity calculation. Weather data is assessed through the punctuality of the weather forecast used for the DLR calculations.	Hu02
DT-F&OG-02-HU-04	Web-Based Visualization of Market, Grid, and DLR Data	The system must provide a web-based platform that visualizes real-time and historical market and grid data, including DLR and auction outcomes, to support informed decision-making by market participants.	Hu03
DT-F&OG-02-HU-05	Market Data Query Interface for Participant Interaction	The system must enable market participants to query market-relevant data (e.g., transmission limits, auction prices, balancing capacity availability) through a user-friendly interface to support participation in market transactions.	Hu03

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-02-HU-06	Flow-Based Transmission Constraint Modelling in Auctions	The system must model and apply flow-based transmission network constraints in the auction process to reflect realistic power flow limitations across borders and critical network elements.	Hu02
DT-F&OG-02-HU-07	Enhanced Price Coupling with Integrated Energy and Balancing Capacity	The system must enable enhanced price coupling for the day-ahead market by integrating energy and balancing capacity in a unified auction, maximizing cross-zonal exchange and price convergence.	Hu03
DT-F&OG-02-HU-08	DLR-Based Congestion Management for Enhanced Capacity Utilization	The system should utilize DLR data to refine congestion management strategies, increasing the availability of network capacity for energy transfer without compromising grid security.	Hu02
DT-F&OG-02-HU-09	Unified Bidding Interface for Energy and Balancing Markets	The system should provide a unified platform interface for market participants to submit bids for both day-ahead and intraday energy markets, as well as for balancing capacity markets.	Hu03
DT-F&OG-02-HU-10	Pre-Processing of Bid Data for Time-Aligned Optimization	The system should support pre-processing of historical and real-time bid data to enable structured, time-aligned optimization input.	Hu03
DT-F&OG-02-HU-11	Single-Run Auction Engine for Integrated Energy and Balancing Market Clearing	The system should implement a single-run auction engine that simultaneously optimizes both energy and balancing market clearing for all time periods and constraints.	Hu03
DT-F&OG-02-HU-12	Support for Linked Capacity Offers Across Market Timeframes	The system should allow the definition and processing of linked capacity offers, enabling participants to offer capacity across multiple market timeframes (DA, ID, BC).	Hu03
DT-F&OG-02-HU-13	Inclusion of Worst-Case Activation Scenarios in Balancing Optimization	The system should incorporate worst-case activation scenarios in the optimization to ensure system security and reliability across balancing capacity procurements.	Hu03
DT-F&OG-02-HU-14	Compliance with SDAC and SIDC for Cross-Border Market Coupling	The system should be compliant with SDAC and SIDC methodologies, supporting harmonized processes for cross-border market coupling and capacity allocation.	Hu03

Functional Requirement ID	Name	Description	Related Use case(s)
DT-F&OG-02-HU-15	Dynamic Transmission Capacity Updates Based on DLR for Market Clearing	The system should provide dynamically updated transmission capacities to the energy and balancing market clearing mechanisms based on DLR adjustments.	Hu02
DT-F&OG-02-HU-16	Optimization of DLR-Enhanced Transmission Capacity for Cross-Zonal Trading	The system should optimize the allocation of increased transmission capacity resulting from DLR to support efficient cross-zonal electricity trading	Hu02
DT-F&OG-02-HU-17	Utilization of DLR-Enhanced Capacity to Increase Tradable Market Volumes	The system should use the DLR-enhanced transmission capacity data to increase the volume of tradable energy and balancing products in the day-ahead and intraday markets.	Hu02
DT-F&OG-02-HU-18	Logging and Reporting of Congestion Events Pre- and Post-DLR Application	The system should log and report congestion events before and after DLR application, enabling comparison of grid utilization efficiency.	Hu02
DT-F&OG-02-HU-19	Enabling Renewable Integration via DLR-Based Transmission Margin Gains	The system should facilitate greater integration of variable renewable energy by unlocking transmission constraints through DLR-based margin gains.	Hu02

C.4 DEMO 8: Demonstrations of digital twinning for smart coordinated planning of the grid

This section shows which FURs are defined for each specific UC that belongs to the DEMO 8.

Table 31 - DEMO 8: Demonstrations of digital twinning for smart coordinated planning of the grid

Functional Requirement ID	Name	Description	Related Use case(s)
DT-SC&PG-02-NL02-01	Verification of System Predictive Accuracy Using Synthetic Models and Expert Validation	The investigated system should be verified against data resembling real-world events and system responses reported in existing accessible literature to check its predictive accuracy. Verification done by using signals generated from synthetic models. The suitability of the synthetic models will be discussed with experts of the TSO and DSOs.	NL02
DT-SC&PG-02-NL02-02	Simulation-Based Coordination of Control Measures for Enhanced System Resilience	The performed simulations used to suggest possible coordinated control measures between DSOs and TSOs to enhance system resilience during disturbances.	NL02
DT-SC&PG-02-NL02-03	Real-Time Data Integration and Validation with Synthetic Model Testing	The system should be capable of integrating real-time data from various sources but will be tested against synthetic data generated from models validated by the operators.	NL02
DT-SC&PG-02-NL02-04	Secure Data Management and Accurate Time-Stamping for Real-Time Decision Support	The system must ensure data is accurately time-stamped to support real-time analysis and decision-making.	NL02
DT-SC&PG-02-NL02-05	Simulate Operation Scenarios	The system must simulate the impact of selected interesting operation scenarios.	all
DT-SC&PG-03&04-IB-01	Probabilistic Grid Forecasting and Remedial Action Planning	The system must forecast probabilistic grid status for system operation purposes, for example, from 3 to 24-hour, using probabilistic models. This probabilistic grid status will be used as an input for the calculations of the remedial grid actions.	Ib01

Functional Requirement ID	Name	Description	Related Use case(s)
DT-SC&PG-03&04-IB-02	AI-Driven Operational Parameter Management	The AI algorithms will recommend actions to ensure the system operation within grid operational parameters (e.g., power, voltage) remain within acceptable limits.	Ib01
DT-SC&PG-03&04-IB-03	Transmission Risk Mitigation and Remedial Actions	The system must suggest a remedial action or set of remedial actions for mitigating transmission system risks. For example, limitation of generation, grid topological actions, definition of controllable devices setpoints.	Ib01
DT-SC&PG-03&04-IB-04	Control Centre Data Integration and Power Forecasting	The system will use control centre data and power generations status & forecasts as main inputs.	Ib01
DT-SC&PG-03&04-IB-05	AI-Driven Grid Event Learning and Forecast Optimization	The AI algorithms must utilize machine learning (ML) models to learn from past grid events and actions and improve the accuracy of the forecasts and remedial actions recommendations.	Ib01
DT-SC&PG-03&04-IB-06	Synthetic Renewable Resource Generation	The system must generate synthetic series of renewable resources such as solar, wind and hydro.	Ib02
DT-SC&PG-03&04-IB-07	Renewable Resource Correlation and Variability Model	The system must model correlations of the renewable resources (e.g., wind) to capture their interdependency and time-variability in real-world conditions. Variability and correlation of renewable resource should be determined based on geographic locations.	Ib02
DT-SC&PG-03&04-IB-08	Long-Term Grid Planning and Use Case Exploration	The system must allow long-term grid planning. Applicability to different use cases such as real-time operation (short-term) will be also explored	Ib02
DT-SC&PG-03&04-IB-09	Flexibility strategies for EV chargers to maintain voltage quality in planning and operational phases	The system must analyze and determine the flexibility needs for EV chargers to maintain voltage quality in both planning and operational phases. It should identify the optimal times for increasing consumption or decreasing generation based on grid conditions, load demands, and voltage levels.	Ib10
DT-SC&PG-03&04-IB-10	Machine Learning for Trend Detection and Synthetic Resource Forecasting	Application of Machine learning (ML) algorithms to detect trends in historical data and generate more accurate synthetic series for future resource forecasts will be explored	Ib02

Functional Requirement ID	Name	Description	Related Use case(s)
DT-SC&PG-03&04-IB-11	Strategic Operational and Grid Planning	The system shall provide strategic planning of its operations, grid conditions, maintenance, or future states.	Ib01, Ib02, Ib07
DT-SC&PG-03&04-IB-12	Dynamic Robustness Assessment for Iberian Grid Control Area	The DT must assess the dynamic robustness in one control area of the power grid (Iberia) and provide system frequency behaviour following a loss of generation	Ib03
DT-SC&PG-03&04-IB-13	Grid Dynamic Behaviour and Interconnection Simulation	The digital twin (DT) must simulate the dynamic behaviour of the Iberian system and its interconnection with the central European system under various operational conditions for large disturbances like sudden generation loss.	Ib03
DT-SC&PG-03&04-IB-14	Real-Time Simulation of Large Generation Disconnection	The DT must allow real-time simulation of-sudden disconnection of large generation units.	Ib03
DT-SC&PG-03&04-IB-15	Frequency Stability Assessment with Reduced Synchronous Inertia	The DT must assess the frequency stability of the Iberian grid, simulating the impact of reduced synchronous inertia due to increased electronic converter-based renewable energy sources.	Ib03
DT-SC&PG-03&04-IB-16	System Frequency Response Analysis with Selected Settings	It should allow operators to analyse system frequency response under different scenarios of inertia, damping, and generator droop settings.	Ib03
DT-SC&PG-03&04-IB-17	Frequency Ancillary Services Identification and Proposal, Including FFR and Virtual Inertia	The DT must identify and propose suitable frequency ancillary services, including new services like Fast Frequency Response (FFR) and virtual inertia.	Ib03
DT-SC&PG-03&04-IB-18	Generation and Technology Response Modelling for Grid Stability	The system should model responses from both traditional generation units and modern technologies like batteries, hydro-pumping units, and power converters.	Ib03
DT-SC&PG-03&04-IB-19	Modelling of Renewable Energy and Storage Impact on Frequency Stability	The DT must model and include electronic power converters and renewable energy sources (e.g., wind, solar) and/or storage devices, and assess their impact on frequency stability. It should account for their dynamic behaviour, including their contribution to frequency ancillary services.	Ib03

Functional Requirement ID	Name	Description	Related Use case(s)
DT-SC&PG-03&04-IB-20	Future Grid Scenarios with Low Synchronous Generation and High Converter-Based Penetration	The DT must allow simulation of future scenarios (e.g., 2030 and 2040) with lower levels of synchronous generation and higher penetration of converter-based generation.	Ib03
DT-SC&PG-03&04-IB-21	Ancillary Services Sensitivity Analysis for Future Grid Conditions	The system enables sensitivity studies regarding the required ancillary services, including the volume and types needed for future grid conditions.	Ib03
DT-SC&PG-03&04-IB-22	AGC Integration for Secondary Frequency Regulation Evaluation	The DT could be integrated with Automatic Generation Control (AGC) systems to evaluate the interaction between the grid and control loops for secondary frequency regulation (aFRR).	Ib03
DT-SC&PG-03&04-IB-23	Demand-Side Technology Integration in DT	The DT must include demand-side technologies like electric mobility (EV charging), electrolysers, and thermal loads.	Ib03
DT-SC&PG-03&04-IB-24	Historical Calibration and Real-Time Data Integration	The system must support calibration using real historical disturbance data, such as system frequency response after the loss of significant generation (e.g., Almaraz II Nuclear plant incident). It should continuously improve its accuracy by incorporating real-time data from system operators.	Ib03
DT-CYB-03-IB04-01	Abnormal Market	The system must detect and identify abnormal market participation patterns based on pre-defined thresholds and criteria for wholesale and local flexibility markets. (The system must detect abnormal market participation activities.)	Ib04
DT-CYB-03-IB04-02	Real-Time Cybersecurity Monitoring for Digital Twin Operations	The system's RT operational modules of the involved DTs must continuously monitor transactions in real-time for signs of cyber-attacks or irregular behaviour from market participants.	Ib04
DT-CYB-03-IB04-03	Flag Suspicious Market Activities	The system should flag suspicious market activities, such as unusual bidding patterns.	Ib04

Functional Requirement ID	Name	Description	Related Use case(s)
DT-CYB-03-IB04-04	Risk Identification and Management with AI-Driven Threat Analysis	The system must identify and manage potential risks (propose remedial actions to mitigate identified risks) and could classify them by severity. The AI agent should identify potential risks related to system stability, overloads, or other critical issues in the power grid. The system must flag high-risk conditions and provide detailed risk analysis. The system must evaluate and identify potential cybersecurity threats across both wholesale and local flexibility markets by analysing data & communication between stakeholders (TSO, DSO, and MO).	Ib04
DT-CYB-03-IB04-05	Rapid Threat Information Sharing and Response Activation	The system should facilitate the swift sharing of threat detection information between all levels of the electricity system, ensuring that countermeasures are activated without delay.	Ib04
DT-CYB-03-IB04-06	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-CYB-03-IB04-07	Real-Time Threat Response and Market Transaction Security	The system must enable real-time protocol activation, allowing immediate response to identified threats to prevent the escalation of market disruptions. The DT should automatically execute pre-configured actions to secure market transactions based on the severity and type of abnormal market behaviour.	Ib04
DT-SC&PG-03&04-IB-25	Real-Time SCADA Data Integration	The system must collect and integrate real-time data from SCADA sensors throughout the distribution network for dynamic analysis of current grid conditions.	Ib05
DT-SC&PG-03&04-IB-26	N-1 Contingency Analysis and Simulation	The system must perform N-1 contingency analysis for grid stability by means of a power flow (evaluate the network's ability to handle the failure of single risk components). The system must simulate N-1 contingency scenarios by selectively disconnecting critical elements (e.g., lines, transformers) from the network. For each disconnection, the DT must evaluate whether the network remains stable and operational under this scenario.	Ib05

Functional Requirement ID	Name	Description	Related Use case(s)
DT-SC&PG-03&04-IB-27	Real-Time Power Flow Monitoring and Updates	The Digital Twin (DT) must be able to continuously monitor and update power flow simulations based on real-time measurements.	Ib05
DT-SC&PG-03&04-IB-28	Optimal Power Flow (OPF) Simulation and Optimization	The system must perform optimal power flow (OPF) simulations under normal operating conditions to verify system stability. OPF should optimize both generation and consumption loads, ensuring the most efficient use of resources while preventing overloads.	Ib05
DT-SC&PG-03&04-IB-29	Grid Bottleneck and Weak Point Identification	The system must identify potential bottlenecks or weak points in the grid, especially under different boundary conditions scenarios or after the failure of a critical element. These critical points should be highlighted for further analysis and potential infrastructure upgrades.	Ib05
DT-SC&PG-03&04-IB-30	Integration with Renewable Energy Source (RES) Digital Twin Models	The Digital Twin (DT) of the distribution grid must be integrated with DT-based models of Renewable Energy Sources (RES) power plants to perform detailed analyses of the network's capacity for integrating new RES.	Ib06
DT-SC&PG-03&04-IB-31	Renewable Energy Source (RES) Integration Validation	The system must validate plans for integrating new renewable energy sources (RES) in the MV grid.	Ib06
DT-SC&PG-03&04-IB-32	RES Integration Impact Simulation on Grid Stability	The system must simulate the impact of RES integration on grid stability and performance.	Ib06
DT-SC&PG-03&04-IB-33	RES Connection Point Pre-Validation and Feasibility Analysis	The system must provide a pre-validation process for connection points of proposed RES power plants, analysing their potential impact on the distribution network at different grid nodes. The pre-validation process must assess whether these connections are technically feasible and recommend modifications or alternatives where necessary.	Ib06
DT-SC&PG-03&04-IB-34	Dynamic MV Grid Behaviour Simulation with Real-Time Data	The DT must simulate the dynamic behaviour of the MV grid, considering real-time data inputs like load profiles, generation patterns, and RES outputs over a defined period of time.	Ib06

Functional Requirement ID	Name	Description	Related Use case(s)
DT-SC&PG-03&04-IB-35	Simultaneous RES Integration Scenario Simulation and Bottleneck Identification	~~It~~ The DSO's DT must simulate scenarios in which multiple RES plants connect simultaneously, identifying critical combinations that may cause network bottlenecks or failures. The system must analyze and identify critical points in the network where RES integration may overload capacity or cause stability issues.	Ib06
DT-SC&PG-03&04-IB-36	Multi-Time Scale Simulation for Grid Planning	The system must handle simulations of various time scales (short, medium, and long-term) to help with grid planning for different future scenarios.	Ib06
DT-SC&PG-03&04-IB-37	RES Integration Scenario Simulation and Comparative Analysis	The system must simulate multiple scenarios of RES integration and provide comparative analysis, identifying the best configurations for grid stability and reliability.	Ib06
DT-SC&PG-03&04-IB-38	Optimization Suggestions for RES Integration and Grid Management	The system should offer optimization suggestions, such as ideal connection points, load management strategies, and necessary grid upgrades.	Ib06
		The system must deliver actionable insights for grid planning purposes, helping utilities and operators understand the short-, medium-, and long-term impacts of RES deployment. It should provide reports that detail grid capacity, necessary infrastructure improvements, and risk mitigation strategies.	Ib06
DT-SC&PG-03&04-IB-39	Planned Maintenance Impact Simulation on Grid Operations	The system must simulate the impact of planned maintenance activities on the distribution grid by running dynamic simulations based on grid data, generation and consumption forecasts and real-time conditions.	Ib07
DT-SC&PG-03&04-IB-40	Grid Issue Identification During Maintenance Simulations	Simulations must identify potential grid issues (e.g., load imbalance, voltage drops) that may arise during maintenance works.	Ib07
DT-SC&PG-03&04-IB-41	Real-Time Grid Monitoring During Maintenance Works	The system must monitor the real-time state of the grid throughout the maintenance works, comparing real-time data to the expected behavior from simulations.	Ib07
DT-SC&PG-03&04-IB-42	Real-Time Model Updates for Enhanced Maintenance Planning	The DT must update its models based on real-time operational data, improving the accuracy of future maintenance planning.	Ib07

Functional Requirement ID	Name	Description	Related Use case(s)
DT-SC&PG-03&04-IB-43	Forecasting Grid Performance During Planned Maintenance	The system must forecast grid performance during the entire period of planned maintenance, simulating various scenarios (based on probabilistic forecasting results) to minimize risks such as service interruptions or overloading critical nodes. The system should incorporate different operational constraints, such as peak loads or variable renewable generation	Ib07
DT-SC&PG-03&04-IB-44	Continuous Real-Time Data Ingestion for Operational Insights	The DT should continuously ingest real-time data from SCADA systems, sensors, and other data sources to provide updated operational insights throughout the maintenance works.	Ib07
DT-SC&PG-03&04-IB-45	Long-Term Flexibility Requirements Identification for Grid Congestion	The system must identify long-term flexibility requirements in both the planning and operational phases to address grid congestion, considering demand growth, DER integration, and consumption patterns.	Ib08
DT-SC&PG-03&04-IB-46	Long-Term Flexibility Planning for MV Grid	The system must support long-term planning for flexibility in the MV grid.	Ib08
DT-SC&PG-03&04-IB-47	Grid Constraint Analysis and Congestion Forecasting for DER Integration	The system should analyze grid constraints and forecast potential congestions that could arise from an increased share of renewable energy sources and other DERs.	Ib08
DT-SC&PG-03&04-IB-48	DR mechanism to manage load balancing	The system must integrate demand response (DR) mechanisms to increase consumption during periods of low demand, thereby managing load imbalances effectively.	Ib08
DT-SC&PG-03&04-IB-49	Generation Curtailment Recommendations for Grid Stability	The system must be able to recommend generation curtailment when excess energy is being produced (e.g., from renewable sources), ensuring grid stability and preventing congestion.	Ib08
DT-SC&PG-03&04-IB-50	Operational Scenario Impact Simulation	The system must simulate the impact of various operation scenarios	Ib03, Ib06, Ib07, IB13
DT-SC&PG-03&04-IB-51	Detailed Operation Report Generation	The system must generate detailed reports on performed operation.	Ib06, Ib07, IB13

Functional Requirement ID	Name	Description	Related Use case(s)
DT-SC&PG-03&04-IB-52	Real-Time Critical Risk Alerts and Notifications	The system must provide real-time alerts for critical risks and notifications to operators.	Ib07
DT-SC&PG-03&04-IB-53	Probabilistic Analysis of Cross-Border Capacity Allocation	The system must support probabilistic analysis of cross-border capacity allocation.	Ib10
DT-SC&PG-03&04-IB-54	Day-Ahead and Intraday ATC Calculation with Probabilistic Scenarios	The system must calculate the day-ahead and intraday Available Transfer Capacity (ATC) between bidding zones (e.g., Portugal and Spain) using probabilistic scenarios.	Ib10
DT-SC&PG-03&04-IB-55	Simulation of System Behaviour with Variability in Demand, Renewable Generation, and Weather	The system must incorporate variability in demand, renewable energy generation, and weather conditions to simulate different system behaviours.	Ib10
DT-SC&PG-03&04-IB-56	Probabilistic Grid Congestion Risk Assessment and Operational Adjustment Suggestions	The system could assess potential grid congestion risks based probabilistic forecasts. It should automatically suggest operational changes to prevent overload on the transmission system, safeguarding interconnection capacity.	Ib10
DT-SC&PG-03&04-IB-57	Risk-Based Decision Support for Cross-Border Trading with Uncertainty Considerations	The system must enable TSOs and RCCs to make risk-based decisions on cross-border trading, considering uncertainties like weather-dependent generation and equipment outages.	Ib10
DT-SC&PG-03&04-IB-58	Historical Data Integration and Continuous Model Update for Probabilistic Forecasting	The system must incorporate historical data on load profiles, renewable energy generation, and grid performance to inform the probabilistic models. It should continuously update these models with new data to improve forecast accuracy over time.	Ib10
DT-SC&PG-03&04-IB-59	Data-Driven Robust Optimization for Optimal Trade Capacity Determination	The system must leverage data-driven robust optimization algorithms to determine the optimal trade capacity under multiple scenarios.	Ib10

Functional Requirement ID	Name	Description	Related Use case(s)
DT-SC&PG-03&04-IB-60	Comparison of Probabilistic ATC Outcomes with Traditional Congestion Management Approaches	The system should compare probabilistic ATC outcomes with traditional approaches to assess eventual improvements in congestion management.	Ib10
DT-SC&PG-03&04-IB-61	Dynamic Grid Performance Monitoring and Contingency Simulation	The system could dynamically monitor grid performance and simulate contingencies (e.g., equipment outages or extreme weather events).	Ib10
DT-SC&PG-03&04-IB-62	Contingency Planning Recommendations for Grid Reconfiguration and Reserve Activation	The system should offer recommendations for contingency planning, such as grid reconfiguration or reserve activation.	Ib10
DT-SC&PG-03&04-IB-63	Flexibility Service Provider (FSP) Prequalification for Neighbouring System Operators (SOs)	The system must facilitate the prequalification of Flexibility Service Providers (FSPs) to provide flexibility to neighbouring System Operators (SOs) where they have no direct connection.	Ib11
DT-SC&PG-03&04-IB-64	Streamlined Prequalification Process for Cross-Border Flexibility Service Providers (FSPs)	The system could implement a streamlined prequalification process for cross-border participation, enabling FSPs to qualify for flexibility products in different markets.	Ib11
DT-SC&PG-03&04-IB-65	FSP Evaluation for Neighbouring System Operator (SO) Flexibility Product Requirements	The system must evaluate FSPs to ensure they meet the requirements set by the neighbouring SO for the specific flexibility product.	Ib11
DT-SC&PG-03&04-IB-66	FSP Validation for Load Management and Generation Flexibility Delivery	The system must validate the FSP's ability to deliver services like load management or generation flexibility without causing disruptions.	Ib11
DT-SC&PG-03&04-IB-67	Seamless Communication and Standardized Data Exchange for Cross-Border SOs	The system must enable seamless communication between SOs of different countries using standardized data exchange protocols, providing a common data framework for exchanging grid prequalification data between different SOs.	Ib11

Functional Requirement ID	Name	Description	Related Use case(s)
DT-SC&PG-03&04-IB-68	Market Coordination and Real-Time Communication for Grid Actors	The system must facilitate market coordination among TSO, DSO, MO, prosumers and all other grid actors. The system should support seamless, (near to) real-time communication and data exchange between Transmission System Operators (TSOs), Distribution System Operators (DSOs), Market Operators (MOs), and prosumers.	Ib12
DT-SC&PG-03&04-IB-69	Grid Data Sharing and Operational Planning for Improved Management	The system must enable sharing of grid data, operational status, flexibility offers, and consumption/generation forecasts to improve grid management and operational planning.	Ib12
DT-SC&PG-03&04-IB-70	Prosumers' Participation in Energy, Balancing, and Flexibility Markets	The system must allow prosumers to participate in energy, balancing, and flexibility markets, enabling them to offer surplus energy and flexibility services to the grid.	Ib12
DT-SC&PG-03&04-IB-71	Prosumers' Active Engagement in Wholesale and Local Markets	The system must provide mechanisms for prosumers to actively engage in wholesale and local markets (day-ahead, intraday, balancing, and ancillary services).	Ib12
DT-SC&PG-03&04-IB-72	Market-Based Flexibility Service Procurement from FSPs	The system must support market-based mechanisms for procuring flexibility services from Flexibility Service Providers (FSPs) to address local grid needs and requirements.	Ib12
DT-SC&PG-03&04-IB-73	DSO Acquisition of System Services from Prosumers and FSPs	The system must allow DSOs to acquire system services effectively from prosumers and FSPs while ensuring alignment with broader TSO operations and market participation.	Ib12
DT-SC&PG-03&04-IB-74	Federated Coordination Framework for TSO-DSO-MO-Prosumers Market Alignment	The system must implement a federated coordination framework to align market activities among TSOs, DSOs, MOs, and prosumers to optimize system operations and grid stability. It must coordinate between TSO-DSO market interactions to ensure synergies and efficient service provision.	Ib12
DT-SC&PG-03&04-IB-75	Digital Twin Simulation for Real-Time Grid Conditions and Market Coordination	The system must use the DT to simulate real-time grid conditions and assess market coordination, flexibility procurement, and grid operations	Ib12

Functional Requirement ID	Name	Description	Related Use case(s)
DT-SC&PG-03&04-IB-76	Grid Qualification Optimization for FSPs and Resource Allocation	The system must optimize grid qualification for FSPs by assessing their capability to provide flexibility without causing grid instability or congestion. It must allocate resources optimally based on available flexibility and market demand, balancing TSO-DSO operational needs.	Ib12
DT-SC&PG-03&04-IB-77	Collaboration-Enabling Architectural Features for Digital Twins (DTs) of Market and System Operators	In the system, all digital twins (DTs), including the market operator and the system operators (TSOs and DSOs), must implement the necessary architectural features to enable their collaboration.	Ib all
DT-SC&PG-03&04-IB-78	User-Friendly Interface for Data Visualization, Action Proposals, and Configuration	The system should have a user-friendly interface for operators to view chosen data and proposed actions, as well as allow user configuration of parameters and reporting.	Ib06, Ib07
DT-SC&PG-03&04-IB-79	Enhanced Short-Circuit Modelling for RES in EHV/HV Substations	The system must enhance TSO short-circuit models for renewable energy sources (RES) to provide accurate estimates of short-circuit currents in EHV/HV substations.	Ib13
DT-SC&PG-03&04-IB-80	Incorporation of RES Impact in Short-Circuit Calculations	The system must incorporate the impact of RES generators in short-circuit calculations	Ib13
DT-SC&PG-03&04-IB-81	Data Exchange Between TSOs and DSOs for Short-Circuit Contributions and Planning	The system must facilitate data exchange between TSOs and DSOs to share short-circuit contributions and planning data.	Ib13
DT-SC&PG-03&04-IB-82	Exchange of Short-Circuit Forecasts for Coordinated Grid Planning	The system must support the exchange of short-circuit forecasts to enable coordinated grid planning.	Ib13
DT-SC&PG-03&04-IB-83	Short-Circuit Current Validation Post-Wholesale Market Results	The system must allow for short-circuit current validation after the wholesale market results are available, ensuring short-term operational planning incorporates market conditions.	Ib13

Functional Requirement ID	Name	Description	Related Use case(s)
DT-SC&PG-03&04-IB-84	Comparison of Forecasted Short-Circuit Currents with TSO Planning Values	The system must compare forecasted short-circuit currents with the TSO planning values for EHV/HV substations, providing a computation of deviations.	Ib13
DT-SC&PG-03&04-IB-85	Comparison of Forecasted Short-Circuit Currents with Circuit Breaker Capacity	The system must compare forecasted short-circuit currents with the rated short-circuit capacity of circuit breakers to identify potential operational risks.	Ib13
DT-SC&PG-03&04-IB-86	Short-Circuit Current Validation and Estimation for Operational Planning	The system must support the validation and estimation of short-circuit currents for short-term operational planning, focusing on improving grid reliability and resilience.	Ib13
DT-SC&PG-03&04-IB-87	Integration with TSO Operational Planning for Short-Circuit Contributions	The system must be prepared to integrate with TSO operational planning processes, ensuring short-circuit contributions from both TSO and DSO grids are factored into planning decisions.	Ib13
DT-SC&PG-03&04-IB-88	Validation of Flexible Connection Points for RES Power Plants Based on DT Simulations	The system must validate the viability of granting flexible connection points to Renewable Energy Sources (RES) power plant developers, based on simulation results from the Digital Twin (DT).	Ib14
DT-SC&PG-03&04-IB-89	Real-Time and Historical Data Analysis for Distribution Network Capacity and Power Surge Management	The system must incorporate real-time and historical data from the DT to analyze the capacity of the distribution network and evaluate its ability to handle power surges without congestion.	Ib14
DT-SC&PG-03&04-IB-90	Interaction Between DT of Distribution System and NEMO's LFM for Surplus Energy Absorption Optimization	The system must support the interaction between the DT of the distribution system and the DT of the NEMO's LFM to optimize the grid's ability to absorb surplus energy during congestion scenarios.	Ib14
DT-SC&PG-03&04-IB-91	Power Exchange Simulation and Validation through Local Flexibility Market for Congestion Management	The system must simulate and validate power exchange through a Local Flexibility Market to assess its impact on congestion management.	Ib14

Functional Requirement ID	Name	Description	Related Use case(s)
DT-SC&PG-03&04-IB-92	RES Installation Impact Simulation and Validation at Connection Points	The system must simulate the effects of RES installations with peak power capacities in relation to the maximum allowable power at the connection points and validate these with DT-based forecasts.	Ib14
DT-SC&PG-03&04-IB-93	Continuous Modelling of RES for Grid Capacity Management	The system must continuously model the behavior of renewable energy systems to ensure that grid capacity is not exceeded.	Ib14
DT-SC&PG-03&04-IB-94	Data Exchange Between DT, RES, and LFM	The system must facilitate the exchange of data between the DT of the distribution network, RES power plants, and the LFM.	Ib14
DT-SC&PG-03&04-IB-95	Real-Time On-Demand Load and Capacity Forecast Updates	The system must support on-demand updates on load and capacity forecasts, ensuring timely validation and decision-making for new connection points.	Ib14
DT-SC&PG-03&04-IB-96	Dynamic Forecasting for Power Generation and Congestion in LFM Flexibility Settlement	The system must integrate dynamic forecasting models to predict power generation and congestion scenarios and assist in flexibility settlement within the LFM.	Ib14
DT-SC&PG-03&04-IB-97	Surplus Power Management Feedback Based on Grid Forecasting Models	The system must provide feedback on whether surplus power can be managed without creating congestion based on grid forecasting models.	Ib14
DT-SC&PG-03&04-IB-98	Prequalification of New Flexibility Resources in LFM	The system could include functionality for the prequalification of new flexibility resources (e.g., battery storage, virtual inertia, dynamic loads) within the LFM.	Ib14
DT-SC&PG-03&04-IB-99	Assessment of New Resource Capabilities for Ancillary Services Integration	The system could assess the technical capabilities of new resources for providing ancillary services and their integration into the grid.	Ib14
DT-SC&PG-03&04-IB-100	Identify critical EV impact nodes and suggest flexibility	The system should identify critical nodes where EV chargers might affect voltage quality and suggest proactive flexibility measures.	Ib09
DT-SC&PG-03&04-IB-101	Compare Flexibility vs Infrastructure Investment	The system should offer comparative analysis for decision-making regarding investment in new infrastructure versus flexibility mechanisms.	Ib09

Functional Requirement ID	Name	Description	Related Use case(s)
DT-SC&PG-03&04-IB-102	Assess EV Flexibility Potential in Planning	The system must determine the flexibility potential of the connection of EV chargers during the planning phases.	Ib09
DT-SC&PG-03&04-IB-103	Assess Voltage Deviation	The system must study grid voltage levels and assess deviations from acceptable thresholds.	Ib09
DT-SC&PG-03&04-IB-104	Integrate with Grid Planning for EV Flexibility	The system should integrate with distribution grid planning tools to estimate long-term flexibility requirements for EV chargers (consumers) .	Ib09
DT-SC&PG-03&04-IB-105	Simulate and Forecast Grid Flexibility Scenarios	The system should support simulation and forecasting functionalities to evaluate grid behavior under different connections and flexibility strategies.	Ib09
DT-SC&PG-03&04-IB-106	Reports for validation and auditing	The system must provide reports for validation and auditing.	Ib09
DT-SC&PG-03&04-IB-107	Enforce Flexibility Constraints Compliance	The system must ensure that flexibility actions do not violate technical or safety constraints of end-user settings.	Ib09

C.5 Functional requirements mapping to Use Cases

This section presents the tabular mapping between UCs and defined FURs. FURs are derived for each UCs, specifying the main functionalities that need to be implemented within each UC. In the first column is shown the pilot site of the UC, which is provided in the second column of the mapping table. The third column outlines the FURs that have been developed for each UC.

Table 32 - German pilot's mapping table/matrix

Pilot	Related Use case(s)	FUR ID
German pilot	Ge08 - Visualizing hosting capacities within Connection request and online connection check applications	DT-O&M-05-GE-01
		DT-O&M-06-GE-01
		DT-O&M-05-GE-02
		DT-O&M-05-GE-03
		DT-O&M-05-GE-04
		DT-O&M-05-GE-05
		DT-O&M-05-GE-06
	Ge01 - Utilization monitoring on LV-/MV-level	DT-O&M-06-GE-27
		DT-O&M-06-GE-05
		DT-O&M-06-GE-06
		DT-O&M-06-GE-07
		DT-O&M-06-GE-09
		DT-O&M-06-GE-02
		DT-O&M-06-GE-23
		DT-O&M-06-GE-10
		DT-O&M-06-GE-12
		DT-O&M-06-GE-13
		DT-O&M-06-GE-14
		DT-O&M-06-GE-16
	Ge02 - State estimation under changing topology on LV-level	DT-O&M-06-GE-27
		DT-O&M-04-GE-03
		DT-O&M-06-GE-05
		DT-O&M-06-GE-06
		DT-O&M-06-GE-07
		DT-O&M-06-GE-08
		DT-O&M-06-GE-11
		DT-O&M-06-GE-09
		DT-O&M-06-GE-17
		DT-O&M-06-GE-18
		DT-O&M-06-GE-19
		DT-O&M-06-GE-20
		DT-O&M-06-GE-21
		DT-O&M-06-GE-22
	Ge03 - Development of advanced monitoring & control tools for congestion management	DT-O&M-04-GE-03
		DT-O&M-06-GE-15
		DT-O&M-06-GE-03
		DT-O&M-06-GE-04

		DT-O&M-06-GE-27
		DT-O&M-06-GE-05
		DT-O&M-06-GE-06
		DT-O&M-06-GE-07
		DT-O&M-06-GE-24
		DT-O&M-06-GE-25
		DT-O&M-06-GE-26
	Ge04 - Development of a concept for a preventive congestion management	DT-O&M-04-GE-02
		DT-O&M-06-GE-01
		DT-O&M-04-GE-01
		DT-O&M-04-GE-03
		DT-O&M-04-GE-04
		DT-O&M-04-GE-05
		DT-O&M-04-GE-23
		DT-O&M-04-GE-06
		DT-O&M-04-GE-07
		DT-O&M-04-GE-08
		DT-O&M-04-GE-09
		DT-O&M-04-GE-10
	Ge05 - Optimal utilization of the flexibility potential in the network feeder by aggregation of flexible assets within the household via HEMS	DT-O&M-04-GE-02
		DT-O&M-04-GE-01
		DT-O&M-04-GE-03
		DT-O&M-04-GE-11
		DT-O&M-04-GE-12
		DT-O&M-04-GE-13
		DT-O&M-04-GE-14
		DT-O&M-04-GE-15
		DT-O&M-04-GE-16
		DT-O&M-04-GE-17
		DT-O&M-04-GE-18
		DT-O&M-04-GE-19
		DT-O&M-04-GE-31
	Ge06 - Development of advanced tools for preventive congestion management through regional aggregation of flexible assets	DT-O&M-04-GE-02
		DT-O&M-04-GE-01
		DT-O&M-04-GE-03
		DT-O&M-04-GE-20
		DT-O&M-04-GE-21
		DT-O&M-04-GE-22
		DT-O&M-04-GE-24
		DT-O&M-04-GE-25
		DT-O&M-04-GE-26
		DT-O&M-04-GE-27
	Ge07 - Conceptual description of interoperable solutions that support an efficient TSO-DSO	DT-O&M-04-GE-02
		DT-O&M-04-GE-01
		DT-O&M-06-GE-01
		DT-O&M-04-GE-28

	data exchange on the interface level.	DT-O&M-04-GE-29
		DT-O&M-04-GE-32
		DT-O&M-04-GE-30

Table 33 - Iberian pilot's mapping table/matrix

Pilot	Related Use case(s)	FUR ID
Iberian pilot	Ib01 - AI Agent for probabilistic grid status forecast and remedial actions identification for the TSO's Control Center Operator	DT-SC&PG-03&04-IB-77
		DT-SC&PG-03&04-IB-11
		DT-SC&PG-03&04-IB-01
		DT-SC&PG-03&04-IB-02
		DT-SC&PG-03&04-IB-03
		DT-SC&PG-03&04-IB-04
		DT-SC&PG-03&04-IB-05
	Ib02 - DT for generation of synthetic series of renewable resources	DT-SC&PG-03&04-IB-77
		DT-SC&PG-03&04-IB-06
		DT-SC&PG-03&04-IB-07
		DT-SC&PG-03&04-IB-08
		DT-SC&PG-03&04-IB-10
		DT-SC&PG-03&04-IB-11
	Ib03 - DT-enabled multi-area system dynamic behaviour assessment	DT-SC&PG-03&04-IB-77
		DT-SC&PG-03&04-IB-50
		DT-SC&PG-03&04-IB-51
		DT-SC&PG-03&04-IB-12
		DT-SC&PG-03&04-IB-13
		DT-SC&PG-03&04-IB-14
		DT-SC&PG-03&04-IB-15
		DT-SC&PG-03&04-IB-16
		DT-SC&PG-03&04-IB-17
		DT-SC&PG-03&04-IB-18
		DT-SC&PG-03&04-IB-19
		DT-SC&PG-03&04-IB-20
		DT-SC&PG-03&04-IB-21
		DT-SC&PG-03&04-IB-22
		DT-SC&PG-03&04-IB-23
		DT-SC&PG-03&04-IB-24
	Ib04 - Abnormal market participation detection and protocol activation for mitigating the risk and consequences	DT-SC&PG-03&04-IB-77
		DT-CYB-03-IB04-01
		DT-CYB-03-IB04-02
		DT-CYB-03-IB04-03
		DT-CYB-03-IB04-04
		DT-CYB-03-IB04-05
		DT-CYB-03-IB04-06
		DT-CYB-03-IB04-07

	Ib05 - DT-based N-1 contingency analysis	DT-SC&PG-03&04-IB-77
		DT-SC&PG-03&04-IB-25
		DT-SC&PG-03&04-IB-26
		DT-SC&PG-03&04-IB-27
		DT-SC&PG-03&04-IB-28
		DT-SC&PG-03&04-IB-29
	Ib06 - DT-enabled new RES integration validated plan in the MV grid	DT-SC&PG-03&04-IB-77
		DT-SC&PG-03&04-IB-78
		DT-SC&PG-03&04-IB-50
		DT-SC&PG-03&04-IB-30
		DT-SC&PG-03&04-IB-31
		DT-SC&PG-03&04-IB-32
		DT-SC&PG-03&04-IB-33
		DT-SC&PG-03&04-IB-34
		DT-SC&PG-03&04-IB-35
		DT-SC&PG-03&04-IB-36
		DT-SC&PG-03&04-IB-37
		DT-SC&PG-03&04-IB-38
	Ib07 - DT-based grid maintenance planning activities	DT-SC&PG-03&04-IB-77
		DT-SC&PG-03&04-IB-78
		DT-SC&PG-03&04-IB-50
		DT-SC&PG-03&04-IB-11
		DT-SC&PG-03&04-IB-39
		DT-SC&PG-03&04-IB-40
		DT-SC&PG-03&04-IB-41
		DT-SC&PG-03&04-IB-42
		DT-SC&PG-03&04-IB-43
		DT-SC&PG-03&04-IB-44
		DT-SC&PG-03&04-IB-52
	Ib08 - Long term flexibility in MV	DT-SC&PG-03&04-IB-77
		DT-SC&PG-03&04-IB-45
		DT-SC&PG-03&04-IB-46
		DT-SC&PG-03&04-IB-47
		DT-SC&PG-03&04-IB-48
		DT-SC&PG-03&04-IB-49
	Ib10 - Probabilistic cross-border capacity allocation	DT-SC&PG-03&04-IB-09
		DT-SC&PG-03&04-IB-77
		DT-SC&PG-03&04-IB-50
		DT-SC&PG-03&04-IB-53
		DT-SC&PG-03&04-IB-54
		DT-SC&PG-03&04-IB-55
		DT-SC&PG-03&04-IB-56
		DT-SC&PG-03&04-IB-57
		DT-SC&PG-03&04-IB-58
		DT-SC&PG-03&04-IB-59

		DT-SC&PG-03&04-IB-60
		DT-SC&PG-03&04-IB-61
		DT-SC&PG-03&04-IB-62
	Ib11 - Cross-border assessment of flexibility and pre-qualification	DT-SC&PG-03&04-IB-77
		DT-SC&PG-03&04-IB-63
		DT-SC&PG-03&04-IB-64
		DT-SC&PG-03&04-IB-65
		DT-SC&PG-03&04-IB-66
		DT-SC&PG-03&04-IB-67
	Ib12 - Integration of TSO-DSO-MO-Prosumer market coordination	DT-SC&PG-03&04-IB-77
		DT-SC&PG-03&04-IB-68
		DT-SC&PG-03&04-IB-69
		DT-SC&PG-03&04-IB-70
		DT-SC&PG-03&04-IB-71
		DT-SC&PG-03&04-IB-72
		DT-SC&PG-03&04-IB-73
		DT-SC&PG-03&04-IB-74
		DT-SC&PG-03&04-IB-75
		DT-SC&PG-03&04-IB-76
	Ib13 - Enhancement of short-circuit models and TSO/DSO information exchange for operational planning	DT-SC&PG-03&04-IB-77
		DT-SC&PG-03&04-IB-79
		DT-SC&PG-03&04-IB-80
		DT-SC&PG-03&04-IB-81
		DT-SC&PG-03&04-IB-82
		DT-SC&PG-03&04-IB-83
		DT-SC&PG-03&04-IB-84
		DT-SC&PG-03&04-IB-85
		DT-SC&PG-03&04-IB-86
		DT-SC&PG-03&04-IB-87
	Ib14 - DT-endorsed flexible connection grant through the settlement of a Local Flexibility Market to internally balance the production surplus in congestion-creation hours/scenarios.	DT-SC&PG-03&04-IB-77
		DT-SC&PG-03&04-IB-88
		DT-SC&PG-03&04-IB-89
		DT-SC&PG-03&04-IB-90
		DT-SC&PG-03&04-IB-91
		DT-SC&PG-03&04-IB-92
		DT-SC&PG-03&04-IB-93
		DT-SC&PG-03&04-IB-94
		DT-SC&PG-03&04-IB-95
		DT-SC&PG-03&04-IB-96
		DT-SC&PG-03&04-IB-97
		DT-SC&PG-03&04-IB-98
		DT-SC&PG-03&04-IB-99
	Ib09 - Flex Connections	DT-SC&PG-03&04-IB-100
		DT-SC&PG-03&04-IB-101
		DT-SC&PG-03&04-IB-102

		DT-SC&PG-03&04-IB-103
		DT-SC&PG-03&04-IB-104
		DT-SC&PG-03&04-IB-105
		DT-SC&PG-03&04-IB-106
		DT-SC&PG-03&04-IB-107

Table 34 - Bulgarian pilot's mapping table/matrix

Pilot	Related Use case(s)		FUR ID
Bulgarian pilot	BG01 - Establishment of the data exchange between the Digital Twins	BG01 (T7.4)	DT-F&OG-03&04-BG-32
			DT-F&OG-03&04-BG-01
			DT-F&OG-03&04-BG-02
			DT-F&OG-03&04-BG-03
			DT-F&OG-03&04-BG-04
			DT-F&OG-03&04-BG-05
			DT-F&OG-03&04-BG-06
			DT-F&OG-03&04-BG-07
			DT-F&OG-03&04-BG-08
		BG01 (T7.5)	DT-F&OG-03&04-BG-32
			DT-F&OG-03&04-BG-01
			DT-F&OG-03&04-BG-02
			DT-F&OG-03&04-BG-03
			DT-F&OG-03&04-BG-09
			DT-F&OG-03&04-BG-04
			DT-F&OG-03&04-BG-06
			DT-F&OG-03&04-BG-07
			DT-F&OG-03&04-BG-09
			DT-F&OG-03&04-BG-10
			DT-F&OG-03&04-BG-11
	Bg02 - AI-Improved Forecast of WPP Production	BG02 (T7.4)	DT-F&OG-03&04-BG-32
			DT-F&OG-03&04-BG-12
			DT-F&OG-03&04-BG-13
			DT-F&OG-03&04-BG-14
			DT-F&OG-03&04-BG-15
			DT-F&OG-03&04-BG-17
			DT-F&OG-03&04-BG-16
			DT-F&OG-03&04-BG-18
			DT-F&OG-03&04-BG-19
			DT-F&OG-03&04-BG-20
			DT-F&OG-03&04-BG-21
			DT-F&OG-03&04-BG-22
			DT-F&OG-03&04-BG-23
		BG02 (T7.5)	DT-F&OG-03&04-BG-12
			DT-F&OG-03&04-BG-20

			DT-F&OG-03&04-BG-32
			DT-F&OG-03&04-BG-19
			DT-F&OG-03&04-BG-21
			DT-F&OG-03&04-BG-22
			DT-F&OG-03&04-BG-32
			DT-F&OG-03&04-BG-13
			DT-F&OG-03&04-BG-15
			DT-F&OG-03&04-BG-16
			DT-F&OG-03&04-BG-17
			DT-F&OG-03&04-BG-24
			DT-F&OG-03&04-BG-18
			DT-F&OG-03&04-BG-25
			DT-F&OG-03&04-BG-26
	Bg03 - AI-Improved Forecast of SPP Production	BG03 (T7.4)	DT-F&OG-03&04-BG-27
			DT-F&OG-03&04-BG-28
			DT-F&OG-03&04-BG-29
			DT-F&OG-03&04-BG-32
			DT-F&OG-03&04-BG-30
			DT-F&OG-03&04-BG-31
			DT-F&OG-03&04-BG-32
			DT-F&OG-03&04-BG-33
			DT-F&OG-03&04-BG-34
			DT-F&OG-03&04-BG-35
		BG03 (T7.5)	DT-F&OG-03&04-BG-27
			DT-F&OG-03&04-BG-28
			DT-F&OG-03&04-BG-29
			DT-F&OG-03&04-BG-30
			DT-F&OG-03&04-BG-31
			DT-F&OG-03&04-BG-33
			DT-F&OG-03&04-BG-34
			DT-F&OG-03&04-BG-35
			DT-F&OG-03&04-BG-32
			DT-F&OG-03&04-BG-32
			DT-F&OG-03&04-BG-36
			DT-F&OG-03&04-BG-37
	Bg04 - AI-Improved Forecast of OHL Ampacity	BG04 (T7.4)	DT-F&OG-03&04-BG-38
			DT-F&OG-03&04-BG-32
			DT-F&OG-03&04-BG-39
			DT-F&OG-03&04-BG-40
			DT-F&OG-03&04-BG-41
			DT-F&OG-03&04-BG-42
			DT-F&OG-03&04-BG-43
			DT-F&OG-03&04-BG-44
			DT-F&OG-03&04-BG-45
			DT-F&OG-03&04-BG-46
			DT-F&OG-03&04-BG-47

		BG04 (T7.5)	DT-F&OG-03&04-BG-38
			DT-F&OG-03&04-BG-39
			DT-F&OG-03&04-BG-41
			DT-F&OG-03&04-BG-42
			DT-F&OG-03&04-BG-43
			DT-F&OG-03&04-BG-44
			DT-F&OG-03&04-BG-45
			DT-F&OG-03&04-BG-46
			DT-F&OG-03&04-BG-47
			DT-F&OG-03&04-BG-48
	BG05 - Increase of power flow on cross border transmission lines		DT-F&OG-03&04-BG-49
			DT-F&OG-03&04-BG-32
			DT-F&OG-03&04-BG-50
			DT-F&OG-03&04-BG-51
			DT-F&OG-03&04-BG-52
			DT-F&OG-03&04-BG-53
			DT-F&OG-03&04-BG-54
			DT-F&OG-03&04-BG-55
			DT-F&OG-03&04-BG-56
			DT-F&OG-03&04-BG-57
			DT-F&OG-03&04-BG-58
			DT-F&OG-03&04-BG-59
	BG06 - Determination of optimal locations for RES connection		DT-F&OG-03&04-BG-60
			DT-F&OG-03&04-BG-32
			DT-F&OG-03&04-BG-61
			DT-F&OG-03&04-BG-62
			DT-F&OG-03&04-BG-63
			DT-F&OG-03&04-BG-64
			DT-F&OG-03&04-BG-65
			DT-F&OG-03&04-BG-66
			DT-F&OG-03&04-BG-67
			DT-F&OG-03&04-BG-68
	BG07 - N-1 assessment on the DT level		DT-F&OG-03&04-BG-32
			DT-F&OG-03&04-BG-69
			DT-F&OG-03&04-BG-70
			DT-F&OG-03&04-BG-71
			DT-F&OG-03&04-BG-72
			DT-F&OG-03&04-BG-73
			DT-F&OG-03&04-BG-74
			DT-F&OG-03&04-BG-75
			DT-F&OG-03&04-BG-76
			DT-F&OG-03&04-BG-77
	BG08 - DT-based Maintenance plan of TSO grid		DT-F&OG-03&04-BG-78
			DT-F&OG-03&04-BG-79
			DT-F&OG-03&04-BG-32
			DT-F&OG-03&04-BG-80

		DT-F&OG-03&04-BG-81
		DT-F&OG-03&04-BG-82
		DT-F&OG-03&04-BG-83
		DT-F&OG-03&04-BG-84
		DT-F&OG-03&04-BG-85
		DT-F&OG-03&04-BG-86
	BG09 - Flexibility Requirements to Avoid Congestions	DT-F&OG-03&04-BG-87
		DT-F&OG-03&04-BG-88
		DT-F&OG-03&04-BG-89
		DT-F&OG-03&04-BG-90
		DT-F&OG-03&04-BG-32
		DT-F&OG-03&04-BG-91
		DT-F&OG-03&04-BG-92
		DT-F&OG-03&04-BG-93
		DT-F&OG-03&04-BG-94
	BG10 - Inter-SO Flexibility Exchange	DT-F&OG-03&04-BG-95
		DT-F&OG-03&04-BG-96
		DT-F&OG-03&04-BG-97
		DT-F&OG-03&04-BG-98
		DT-F&OG-03&04-BG-99
		DT-F&OG-03&04-BG-100
		DT-F&OG-03&04-BG-32

Table 35 - Italian pilot's mapping table/matrix

Pilot	Related Use case(s)		FUR ID
Italian pilot	IT01 - Analysis through DT of the TSO defense system		DT-O&M-03-IT01-01
			DT-O&M-03-IT01-02
			DT-O&M-03-IT01-03
			DT-O&M-03-IT01-04
			DT-O&M-03-IT01-05
			DT-O&M-03-IT01-06
			DT-O&M-03-IT01-07
			DT-O&M-03-IT01-08
			DT-O&M-03-IT01-09
			DT-O&M-03-IT01-10
	EACL-IT-01 - Digital Twin for definition of data model		DT-O&M-01-EACL-IT-01-01

		DT-O&M-01-EACL-IT-01-02
		DT-O&M-01-EACL-IT-01-03
		DT-O&M-01-EACL-IT-01-04
		DT-O&M-01-EACL-IT-01-05
		DT-O&M-01-EACL-IT-01-06
	EACL-IT-02 - Digital Twin for design validation	DT-O&M-01-EACL-IT-02-01
		DT-O&M-01-EACL-IT-02-02
		DT-O&M-01-EACL-IT-02-03
		DT-O&M-01-EACL-IT-02-04
		DT-O&M-01-EACL-IT-02-05
	IT02 - Analysis through DT of the behaviour of aggregated distributed resources during a grid event in the TSO system	DT-O&M-03-IT02-01
		DT-O&M-03-IT02-02
		DT-O&M-03-IT02-03
		DT-O&M-03-IT02-04
		DT-O&M-03-IT02-05
		DT-O&M-03-IT02-06
		DT-O&M-03-IT02-07
		DT-O&M-03-IT02-08
		DT-O&M-03-IT02-09
		DT-O&M-03-IT02-10
		DT-O&M-03-IT02-11
		DT-O&M-03-IT02-12
	EACL-IT-03 - Scalability of Digital twin for design validation	DT-O&M-01-EACL-IT-03-02

		DT-O&M-01-EACL-IT-03-03
		DT-O&M-01-EACL-IT-03-04

Table 36 - Dutch-French pilot's mapping table/matrix

Pilot	Related Use case(s)	FUR ID
Dutch-French pilot	NL01 - DT-enabled real-time cyberattack detection and impact analysis on the operation of integrated power grid	DT-CYB-01-NL01-01
		DT-CYB-01-NL01-02
		DT-CYB-01-NL01-03
		DT-CYB-01-NL01-04
		DT-CYB-01-NL01-05
		DT-CYB-01-NL01-08
		DT-CYB-01-NL01-06
		DT-CYB-01-NL01-07
	NL02 - DT-based dynamic stability assessment under active power flow changing events.	DT-SC&PG-02-NL02-01
		DT-SC&PG-02-NL02-02
		DT-SC&PG-02-NL02-03
		DT-SC&PG-02-NL02-04
		DT-SC&PG-02-NL02-05
	FR01 - Power system training simulator for complex and critical situations	DT-CYB-04-FR01-01
		DT-CYB-04-FR01-02
		DT-CYB-04-FR01-03
		DT-CYB-04-FR01-04
		DT-CYB-04-FR01-05
		DT-CYB-04-FR01-06
		DT-CYB-04-FR01-07
		DT-CYB-04-FR01-08
		DT-CYB-04-FR01-09
		DT-CYB-04-FR01-10
		DT-CYB-04-FR01-11

Table 37 - Hungarian pilot's mapping table/matrix

Pilot	Related Use case(s)	FUR ID
Hungarian pilot	Hu01 - Digital twin for power line monitoring	DT-O&M-08-HU01-01
		DT-O&M-08-HU01-02
		DT-O&M-08-HU01-03
		DT-O&M-08-HU01-04
		DT-O&M-08-HU01-05
		DT-O&M-08-HU01-06
		DT-O&M-08-HU01-07
	Hu02 - Enhanced flow-based capacity calculation for market co-optimization using DLR data	DT-F&OG-02-HU-01
		DT-F&OG-02-HU-03
		DT-F&OG-02-HU-06
		DT-F&OG-02-HU-08
		DT-F&OG-02-HU-15
		DT-F&OG-02-HU-16
		DT-F&OG-02-HU-17
		DT-F&OG-02-HU-18
		DT-F&OG-02-HU-19
	Hu03 - Co-optimizing the energy and balancing capacity market coupling with dynamic flow-based auction	DT-F&OG-02-HU-02
		DT-F&OG-02-HU-04
		DT-F&OG-02-HU-05
		DT-F&OG-02-HU-07
		DT-F&OG-02-HU-09
		DT-F&OG-02-HU-10
		DT-F&OG-02-HU-11
		DT-F&OG-02-HU-12
		DT-F&OG-02-HU-13
		DT-F&OG-02-HU-14

Table 38 - Eastern-Mediterranean pilot's mapping table/matrix

Pilot	Related Use case(s)	FUR ID
Eastern-Mediterranean Pilot	EM-CY-01 - Congestion management in distribution grids through ancillary services	DT-CYB-02-EM-CY-01-01
		DT-CYB-02-EM-CY-01-02
		DT-CYB-02-EM-CY-01-03
		DT-CYB-02-EM-CY-01-04
		DT-CYB-02-EM-CY-01-05
		DT-CYB-02-EM-CY-01-06

		DT-CYB-02-EM-CY-01-07
		DT-CYB-02-EM-CY-01-08
		DT-CYB-02-EM-CY-01-09
	EM-CY-02 - Frequency support management of HVDC-interconnected systems in a regional level	DT-F&OG-05-EM-CY-02-01
		DT-F&OG-05-EM-CY-02-02
		DT-F&OG-05-EM-CY-02-03
		DT-F&OG-05-EM-CY-02-04
		DT-F&OG-05-EM-CY-02-05
		DT-F&OG-05-EM-CY-02-06
	EM-GR-01 - Congestion management in transmission and distribution grids through TSO-DSO coordination	DT-F&OG-01-EM-GR-01-01
		DT-F&OG-01-EM-GR-01-02
		DT-F&OG-01-EM-GR-01-03
		DT-F&OG-01-EM-GR-01-04
		DT-F&OG-01-EM-GR-01-05
		DT-F&OG-01-EM-GR-01-06
		DT-F&OG-01-EM-GR-01-07
		DT-F&OG-01-EM-GR-01-08
		DT-F&OG-01-EM-GR-01-09
		DT-F&OG-01-EM-GR-01-10
	EM-GR-02 - Fast Frequency Response for Effective Frequency Control through TSO-DSO coordination	DT-F&OG-01-EM-GR-02-01
		DT-F&OG-01-EM-GR-02-02
		DT-F&OG-01-EM-GR-02-03
		DT-F&OG-01-EM-GR-02-04
		DT-F&OG-01-EM-GR-02-05
		DT-F&OG-01-EM-GR-02-06
		DT-F&OG-01-EM-GR-02-07
		DT-F&OG-01-EM-GR-02-08
		DT-F&OG-01-EM-GR-02-09
		DT-F&OG-01-EM-GR-02-10

C.6 General Functional Requirements (GFURs)

In this section, the GFURs are presented for each GSUC, illustrating how they respond to the functional needs identified in the corresponding general system use cases.

Table 39 - General Functional Requirements for each GSUC

Requirement ID	Name	Description	Related UCs
TwinEU_GFUR_01	TwinEU system must be able to manage and certificate the identity of each TwinEU Participant	TwinEU system manage the identities of all the TwinEU participants offering an Identity Provider.	GSUC_02, GSUC_03
TwinEU_GFUR_02	TwinEU system must be able to register/unregister a Data Space connector	Data Space Connector need to register itself before starting any data exchange process.	GSUC_02, GSUC_03
TwinEU_GFUR_03	Each TwinEU Participant must be uniquely identified using certification	TwinEU Participants are uniquely identified within the TwinEU ecosystem, using certification process and establishing trust among all participants.	GSUC_02, GSUC_03
TwinEU_GFUR_04	Each Data Space Connector have a unique certificate and identifier		GSUC_02, GSUC_03
TwinEU_GFUR_05	Each Data Space Connector is able to verify the identity of the other Data Space Connectors		GSUC_02, GSUC_03
TwinEU_GFUR_06	TwinEU participant must be able to run the Data Space connector in its own environment	TwinEU Middleware leverage on the IDS decentralized approach. The Data Space Connector provided by TwinEU must be deployable in any environment.	GSUC_02, GSUC_03
TwinEU_GFUR_07	The TwinEU Participant must be able to configure its own Data Space Connector	Data Space connectors are configurable by the TwinEU participants using specific interfaces.	GSUC_02, GSUC_03
TwinEU_GFUR_08	The Data Space connector must be able to send metadata of a data source to one or more system components	Once the connector is configured it is able to provide and/or search metadata as well as discover for new data sources and participants.	GSUC_02, GSUC_03
TwinEU_GFUR_09	The Participant must be able to search and discover other TwinEU Participants		GSUC_02, GSUC_03

TwinEU_GFUR_10	The Data Space Connector must be able to search for metadata published within the data space.		GSUC_02, GSUC_03
TwinEU_GFUR_11	The Data Space Connector must be able to exchange data with other connectors using pull and/or push mechanisms	The data exchange process happens end-to-end exploiting pull or push mechanisms.	GSUC_02, GSUC_03
TwinEU_GFUR_12	The TwinEU system must be able to support the creation, management and usage of vocabularies	A feature provided by TwinEU system is the Vocabulary Provider. It manages and offers vocabularies (i.e., ontologies, reference data models, or metadata elements) that can be used to annotate and describe datasets.	GSUC_02, GSUC_03
TwinEU_GFUR_13	The TwinEU participant could use vocabularies for creating and structuring its metadata		GSUC_02, GSUC_03
TwinEU_GFUR_14	The TwinEU system should offer data services/apps for data processing and transformation	One of the main features of the TwinEU system is the possibility to enrich, transform, validate and harmonize the data processed. In addition, the TwinEU allow to log all the data transaction.	GSUC_02, GSUC_03
TwinEU_GFUR_15	The TwinEU system should be able to log any data transaction between any TwinEU participant		GSUC_02, GSUC_03
TwinEU_GFUR_16	The TwinEU system should be able to assess the quality of data processed		GSUC_02, GSUC_03
TwinEU_GFUR_17	The TwinEU system should be able to perform a semantic validation of the data processed		GSUC_02, GSUC_03
TwinEU_GFUR_18	The TwinEU system could use AI mechanism for empowering Data services	For improving the Data Services offered by the TwinEU system, some AI mechanism could be implemented.	GSUC_02, GSUC_03
TwinEU_GFUR_19	The TwinEU Orchestration Workbench must be able to manage data and service orchestration	The TwinEU Orchestration Workbench aims to support the data orchestration for the evaluation of the performance and scalability of the AI, IoT and Big Data cross-platform services for market and grid operations. The TwinEU Orchestration Workbench allows to integrate data coming from the TwinEU 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	GSUC_02
TwinEU_GFUR_20	The TwinEU Orchestration Workbench must be able to integrate data using the TwinEU Middleware		GSUC_02
TwinEU_GFUR_21	The Service Provider must be able to register its service in the TwinEU Orchestration Workbench		GSUC_02
TwinEU_GFUR_22	The Service Provider must be able to create a data workflow using the Orchestration Workbench		GSUC_02

TwinEU_GFUR_23	The Service Provider must be able to evaluate the performance of its own service	system should provide a centralized AI & Big Data marketplace for discovering, integrating, and utilizing AI-driven services and analytics tools. The system should support service registration and discovery through an IDSA-compliant Federated Catalogue.	GSUC_02
TwinEU_GFUR_24	The TwinEU Orchestration Workbench should provide a service catalogue to the TwinEU Participants		GSUC_02
TwinEU_GFUR_25	The TwinEU system should offer a UI dashboard to TwinEU Participants for monitoring and analytics	The TwinEU system should implement a GUI for facilitating the TwinEU Participants in the management, monitoring and analytics of the data transactions.	GSUC_02
TwinEU_GFUR_26	Digital Twin Federation Integration	The system must enable the creation of a Digital Twin Federation by integrating local Digital Twins into a system-of-systems.	GSUC_01
TwinEU_GFUR_27	Bidirectional Data Exchange for Physical and Virtual Entities	The system should provide bidirectional data flow between physical and virtual entities.	GSUC_01
TwinEU_GFUR_28	Seamless Interoperability Across Digital Twins	The system should ensure seamless interoperability between different Digital Twins, regardless of their underlying data structures and models.	GSUC_01
TwinEU_GFUR_29	Secure Digital Twin Data Exchange via Data Space Connector	The system should utilize the Data Space Connector to enable secure and controlled data sharing between Digital Twins.	GSUC_01
TwinEU_GFUR_30	Scalable Federated Computing Architecture Support	The system should support distributed and federated computing architectures to enhance scalability.	GSUC_01
TwinEU_GFUR_31	Federated Digital Twin Data Space Orchestration	The system should implement a Data Space Framework for orchestrating data sharing, model exchange, and real-world data integration across Digital Twin clusters.	GSUC_01
TwinEU_GFUR_32	Regulatory-Compliant Data Exchange Governance	The system should ensure that all data exchanges follow data governance policies and regulatory compliance requirements.	GSUC_01

TwinEU_GFUR_33	Integration of heterogeneous data sources	The system shall enable integration of heterogeneous data sources regardless of their structure or format.	GSUC_01
TwinEU_GFUR_34	Service Orchestration	The system should allow dynamic orchestration of services, enabling users to define and manage workflows.	GSUC_01
TwinEU_GFUR_35	Trusted and authorized Digital Twins	The system shall verify that only trusted and authorized Digital Twins are permitted to participate in data exchange	GSUC_01
TwinEU_GFUR_36	Data versioning and traceability	The system could enable data versioning and traceability to track data provenance and integrity.	GSUC_01
TwinEU_GFUR_37	Role-Based Access Control for Secure Data Exchange	The system should allow role-based access control (RBAC) for data exchange, ensuring that only authorized entities can access or modify data.	GSUC_01
TwinEU_GFUR_38	Error-handling mechanism	The system could include an error-handling mechanism that enables automatic retries and logs failures for further analysis.	GSUC_01
TwinEU_GFUR_39	Identity management	The system should implement a robust identity management framework to authenticate and authorize Digital Twin actors.	GSUC_01
TwinEU_GFUR_40	Governance model	The system should include a governance model to manage interactions and security policies across the Digital Twin Federation.	GSUC_01
TwinEU_GFUR_41	Validation of DT	The system could support real-world validation of Digital Twin interoperability through simulation environments.	GSUC_01
TwinEU_GFUR_42	Policy-driven optimizations	The system should allow policy-driven optimizations to ensure regulatory compliance and efficient energy market operations.	GSUC_01
TwinEU_GFUR_43	Enforced Data Retention Policy for Sensor Data	The system will not store raw sensor data indefinitely but will implement a data retention policy aligned with regulatory and operational needs.	GSUC_01

TwinEU_GFUR_44	AI & Big Data Marketplace for providers	The system should allow service providers to publish and manage AI models, services, and data assets.	GSUC_02
TwinEU_GFUR_45	AI & Big Data Marketplace for consumers	The system should enable data consumers to access and integrate available AI-driven services via standardized APIs.	GSUC_02
TwinEU_GFUR_46	Predictive Analytics and Data-Driven AI Solutions	The system could offer real-time anomaly detection to identify inconsistencies in energy data and prevent disruptions.	GSUC_02
TwinEU_GFUR_47	Data Streaming Consumption and Querying	The system should allow data consumers to retrieve data entities based on specific queries.	GSUC_03
TwinEU_GFUR_48	Data Streaming Provision	The system shall allow data providers to create, modify, and delete data entities.	GSUC_03
TwinEU_GFUR_49	IoT Indexing and Discovery	The system should enable registration and management of IoT devices as data entities. The system should maintain a catalogue of all registered entities and their associated providers.	GSUC_03
TwinEU_GFUR_50	IoT Device Integration	The system should support the registration of IoT devices. The system should map each registered IoT device to TwinEU data entity associated with a Data Provider.	GSUC_03
TwinEU_GFUR_51	Validation against regulatory standards, directives, laws, and codes	The system should validate all exchanged data against applicable regulatory standards, directives, laws, and codes.	GSUC_04
TwinEU_GFUR_52	Regulatory Compliance Enforcement	The system should enforce compliance validation before data is accepted or shared within the TwinEU system.	GSUC_04
TwinEU_GFUR_53	Secure and Transparent Data Exchange with CIM in two SGAM Layers	The system must enable secure and transparent data exchange using CIM standard definitions within the Communication and Information layers of SGAM.	GSUC_04
TwinEU_GFUR_54	CIM-Based Interoperability for SGAM Communication and Information Layers	The system should implement the CIM standard in the Communication and Information layers of the SGAM	GSUC_04

		communication model to ensure interoperability and standardized data exchange.	
TwinEU_GFUR_55	Compliance Validation	The system could provide compliance validation for all TwinEU components.	GSUC_04
TwinEU_GFUR_56	Monitoring of Regulatory Changes	The system must track regulatory changes at EU, national, and regional levels.	GSUC_04
TwinEU_GFUR_57	Secure and Transparent Data Exchange	The system must implement access control mechanisms for regulatory data, ensuring only authorized entities can access or modify it.	GSUC_04
TwinEU_GFUR_58	Allerts issuing	The system could issue alerts for any detected non-compliance in data exchanges.	GSUC_04
TwinEU_GFUR_59	Report Generation	The system could generate periodic compliance reports detailing regulatory adherence and potential violations. The system could allow authorized users to export compliance reports in standard formats (e.g., PDF, CSV, XML).	GSUC_04
TwinEU_GFUR_60	Logging Activity	The system could log all compliance validation activities for audit purposes. The system could ensure that all compliance-related data exchanges are logged and auditable.	GSUC_04
TwinEU_GFUR_61	Grid Resilience Simulation	The system should provide simulation tools to assess the resilience of the energy grid under normal and abnormal conditions.	GSUC_05
TwinEU_GFUR_62	Grid Stability Analysis for RES and DER Integration	The system must detect and analyse grid stability issues caused by the integration of RES and DER.	GSUC_05
TwinEU_GFUR_63	Proactive Grid Planning	The system should support decision-making by grid operators through predictive analytics for grid stability.	GSUC_05
TwinEU_GFUR_64	Scenario-Based Strategic Planning for Infrastructure Expansion	The system should enable scenario-based strategic planning for infrastructure expansion and adaptation.	GSUC_05

TwinEU_GFUR_65	Abnormal Conditions and Disruptions Modelling	The system should detect and model potential physical disruptions in the energy grid. The system should provide response strategies for mitigating abnormal conditions.	GSUC_05
TwinEU_GFUR_66	Infrastructure Bottleneck Identification	The system shall identify grid infrastructure bottlenecks that impact the efficient transmission and distribution of energy.	GSUC_05
TwinEU_GFUR_67	Large-Scale Integration of RES and DER	The system should evaluate the impact of RES and DER on grid stability and adjust control mechanisms accordingly.	GSUC_05
TwinEU_GFUR_68	Pan-European Energy Market Scenario Modelling	The system should model interconnected energy markets across Europe to simulate cross-border energy exchanges, market trends, and impact of regulatory frameworks.	GSUC_05
TwinEU_GFUR_69	Report Generation	The system could generate reports on potential vulnerabilities in the grid infrastructure. Furthermore, the system should generate dynamic reports to support real-time and historical analysis.	GSUC_05
TwinEU_GFUR_70	Wanning System	The system could provide early warnings for grid disturbances and potential failures.	GSUC_05
TwinEU_GFUR_71	High-quality Real-time Data Visualization	The system should support high-quality real-time visualization of Digital Twin (DT) data, allowing users to possibly view and analyze live grid performance.	GSUC_06
TwinEU_GFUR_72	Multiuser XR Collaboration	The system should allow multiple users to interact and collaborate within the same Extended Reality (XR) environment in real time.	GSUC_06
TwinEU_GFUR_73	Unity3D-Based Plugin Integration	The system must integrate a Unity3D-based plugin to streamline user interaction with DT data and enhance XR visualization capabilities.	GSUC_06
TwinEU_GFUR_74	Immersive XR Toolkit	The system should provide pre-built components and building blocks to facilitate rapid creation of XR applications	GSUC_06

		by developers in an easy way. The system should provide reusable building blocks to enable rapid development of XR applications	
TwinEU_GFUR_75	Advanced VR Visualization Features	The system could support Virtual Reality (VR) visualization for immersive energy infrastructure simulations and interactive visualization of grid anomalies, bottlenecks, and infrastructure risks.	GSUC_06
TwinEU_GFUR_76	Immersive User Interface (UI)	The system should provide an intuitive XR user interface with easy navigation, tooltips, and context-sensitive controls.	GSUC_06
TwinEU_GFUR_77	Security	The system should enforce secure authentication and authorization mechanisms to protect sensitive energy data and simulation parameters.	GSUC_06
TwinEU_GFUR_78	Full IoT Edge-Network Control	The system will not provide detailed edge device control	GSUC_06

Annex D SGAM architectural layers definition

This annex includes the contribution used to build the first version of the SGAM technical specifications presented in the first draft of the TwinEU reference architecture, which merged the input from the Iberian Pilot UCs and served as basis for the rest of the Pilots to define their owns. The second version includes the contribution of all Pilots, concluding with a final version that represents all UC in the project.

D.1 First generalised architecture version using Iberian Pilot

Use Case architectures

Component layer

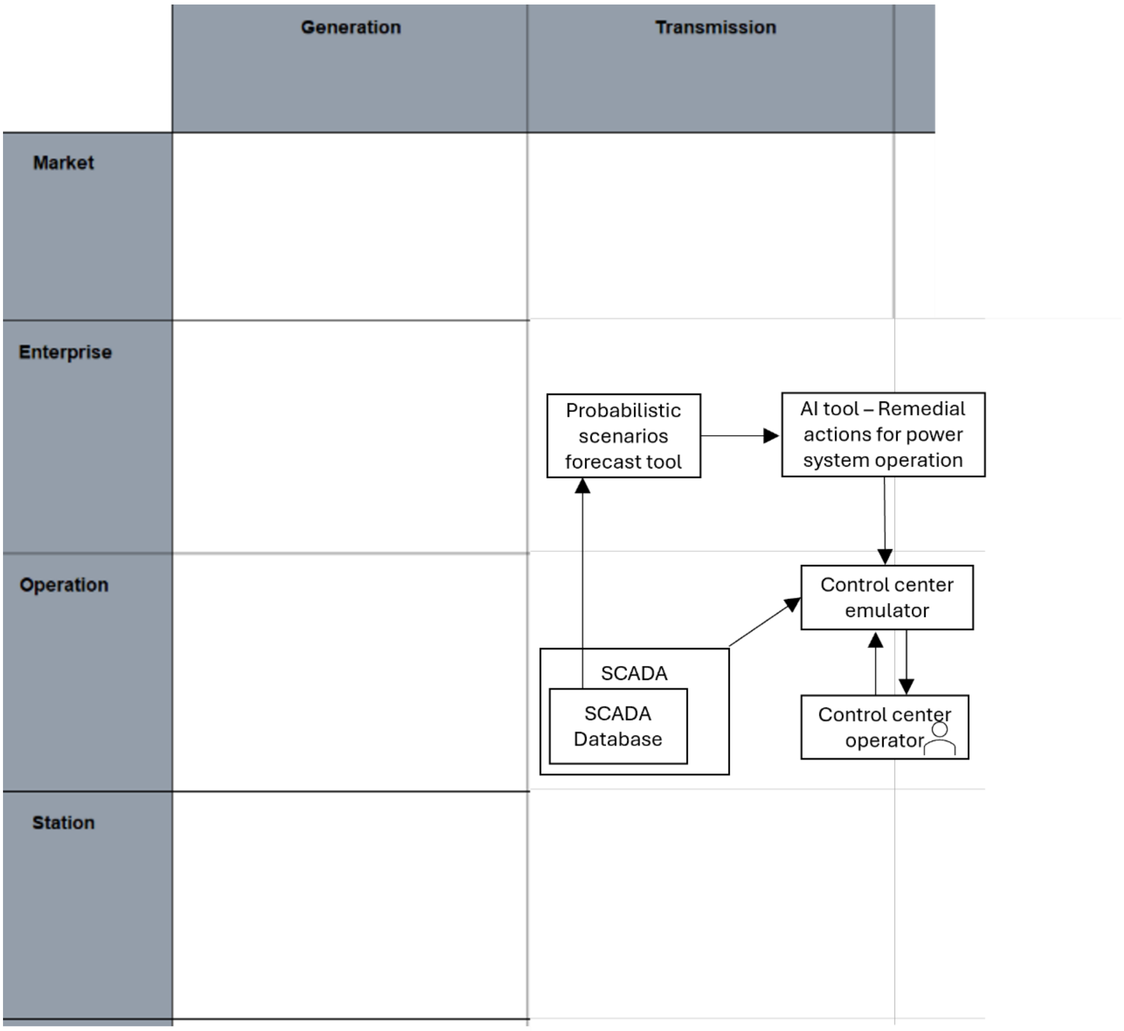


Figure 18 - Ib01 component layer

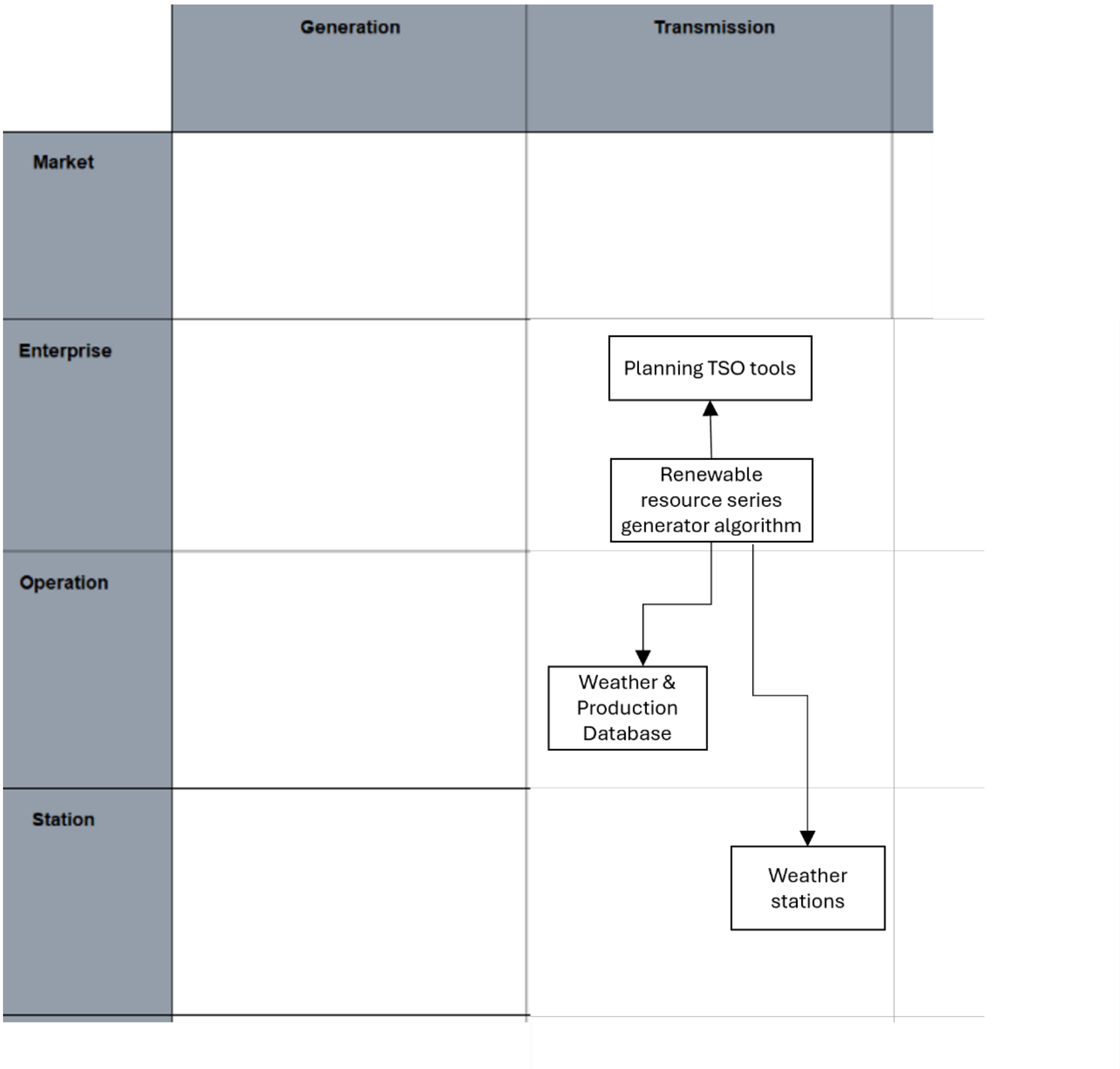


Figure 19 - Ib02 component layer

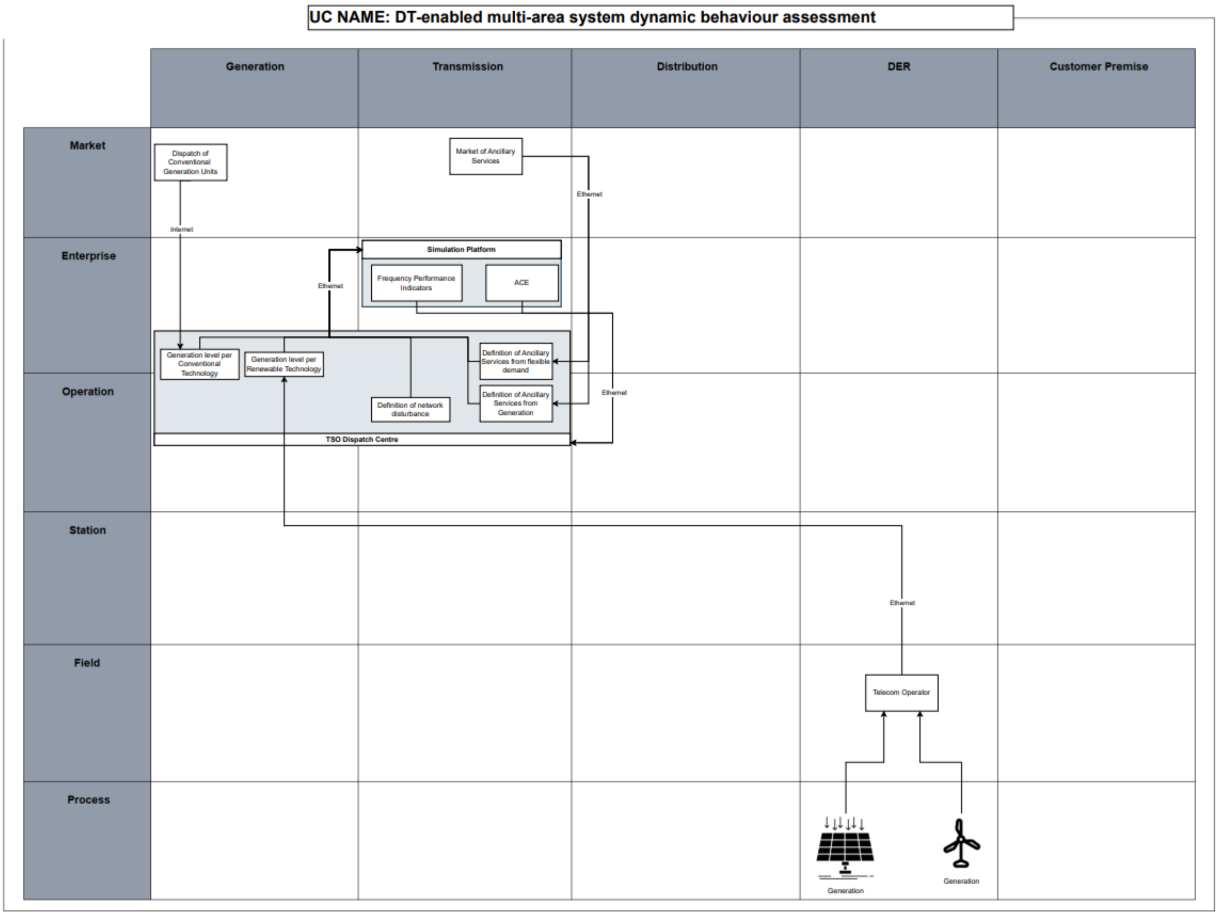


Figure 20 - Ib03 component layer

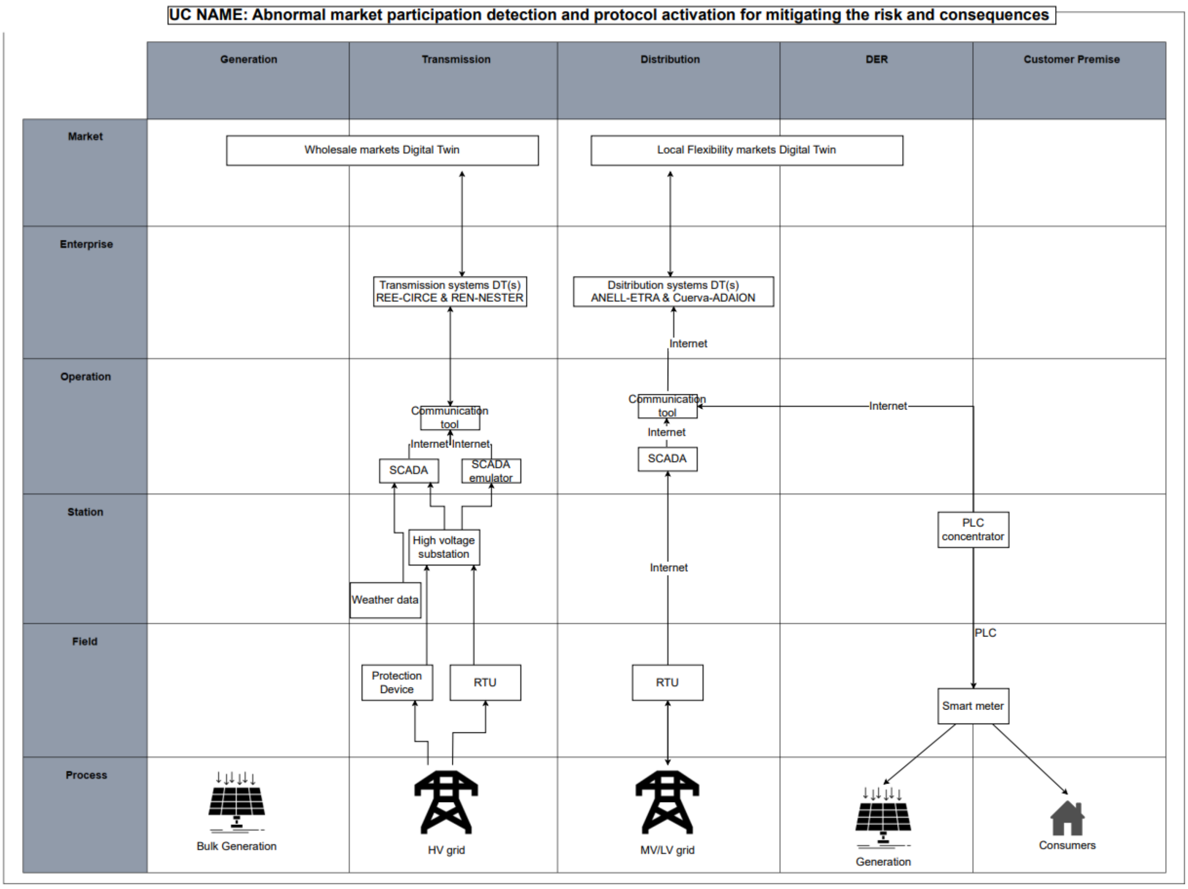


Figure 21 - Ib04 component layer

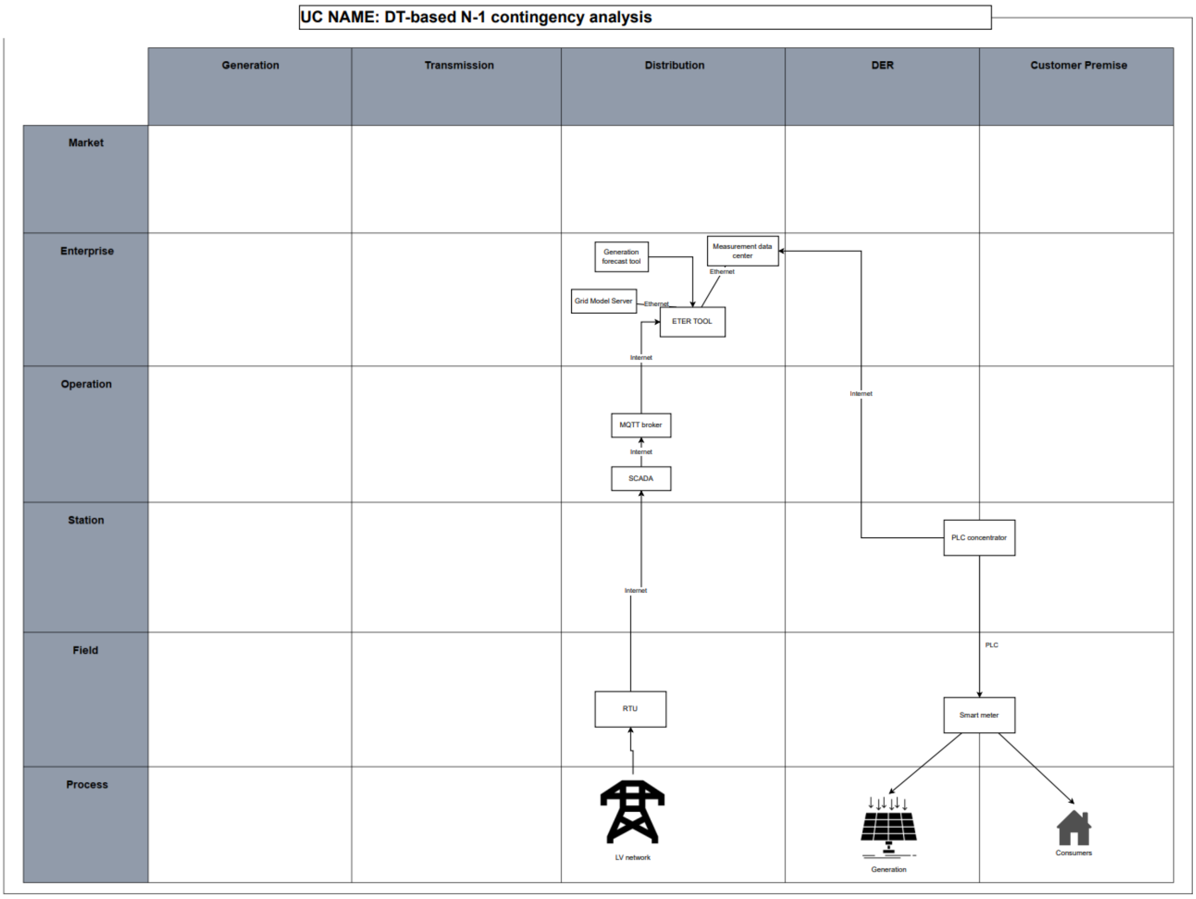


Figure 22 - Ib05, Ib06 and Ib07 component layer

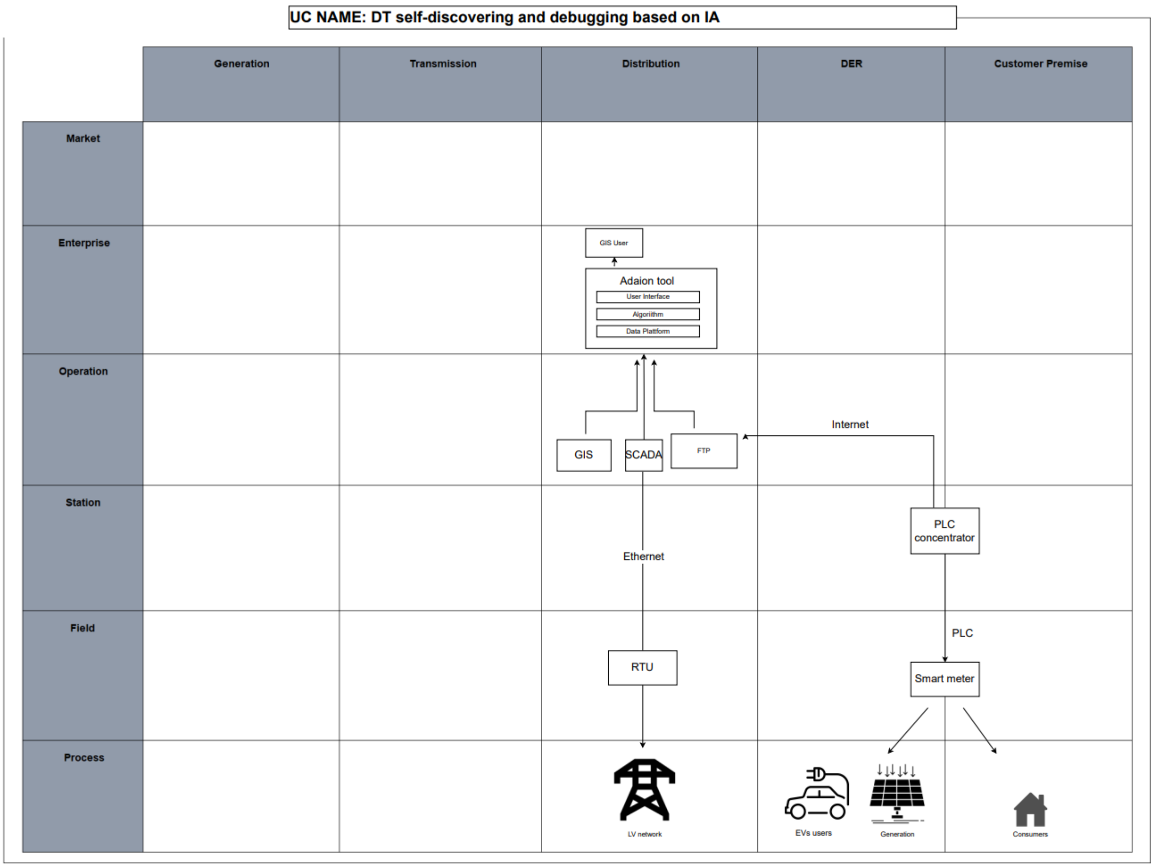


Figure 23 - Ib08 and Ib09 component layer

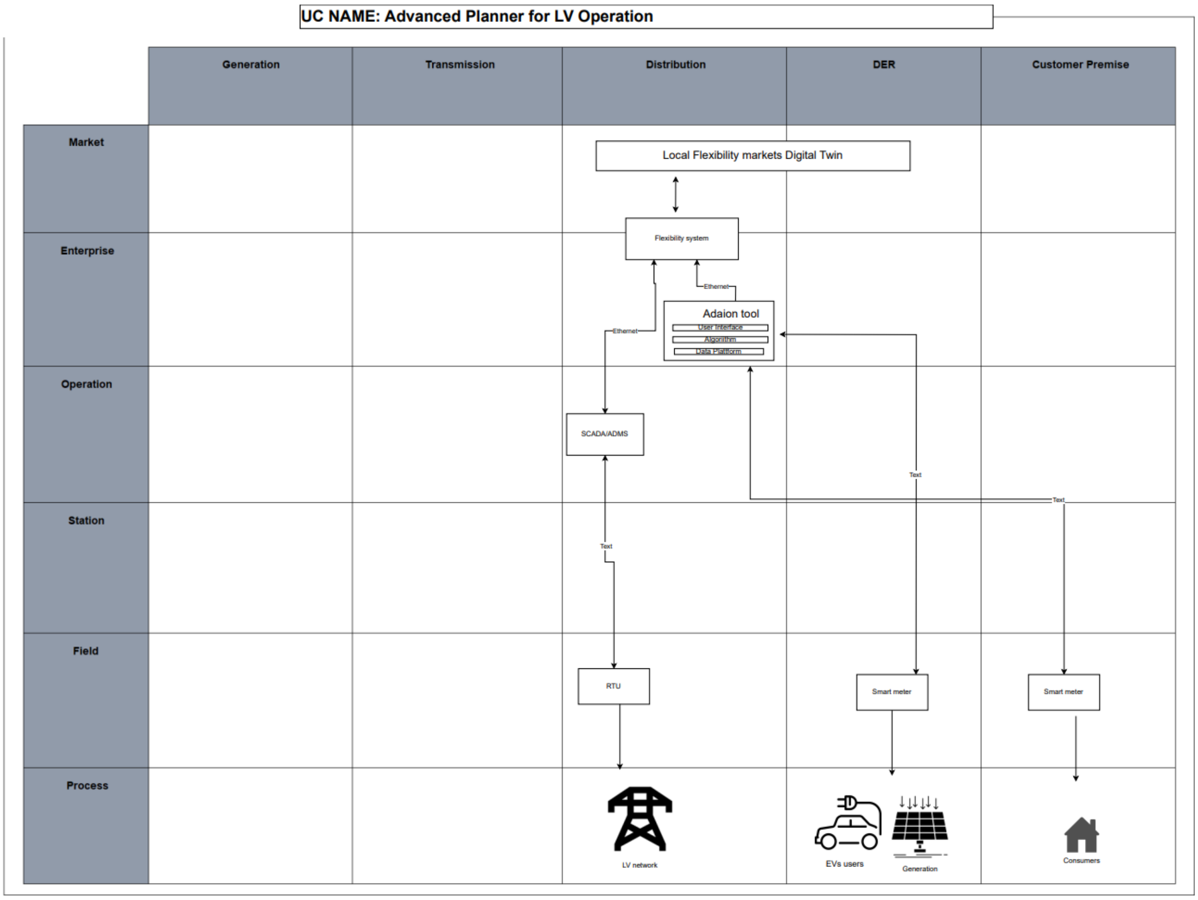


Figure 24 - Ib10 and Ib11 component layer (now Ib 10 discarded While Ib11 is now Ib8)

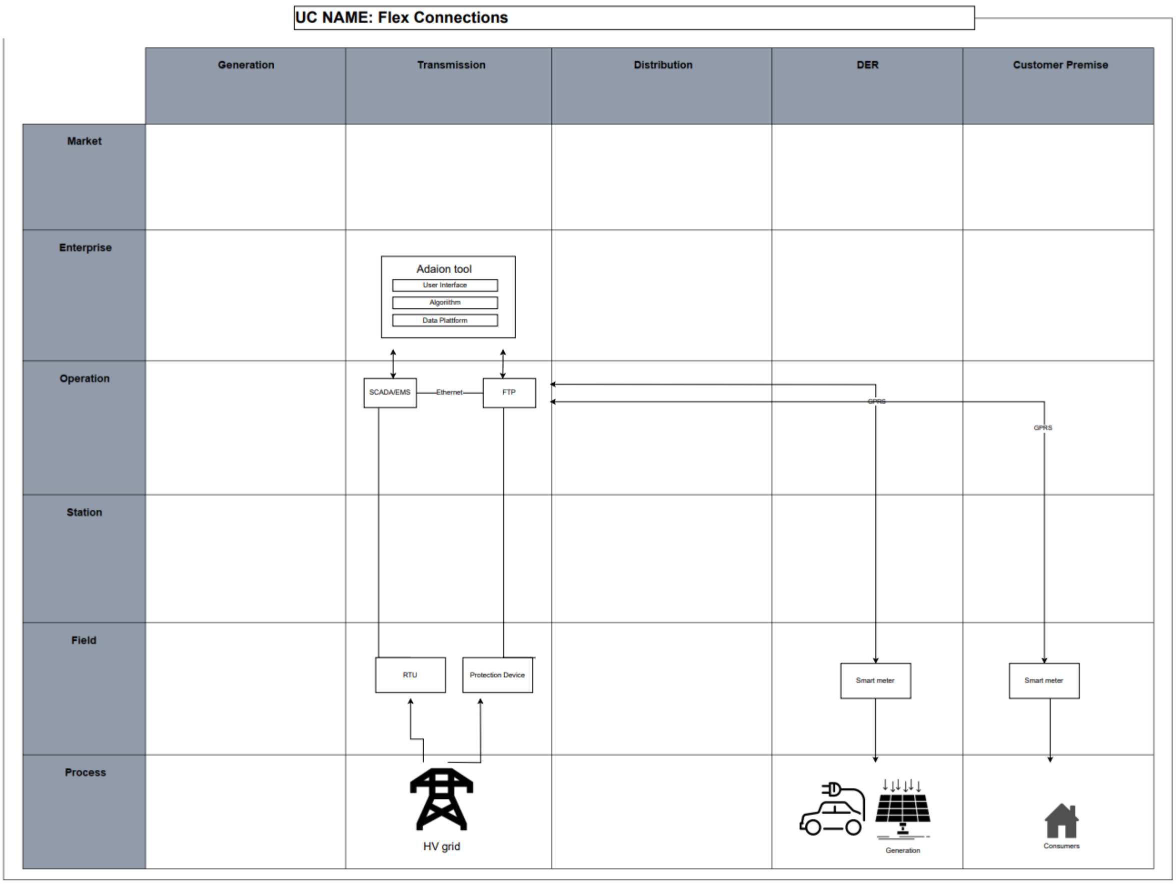


Figure 25 - Ib12 component layer (now Ib9)

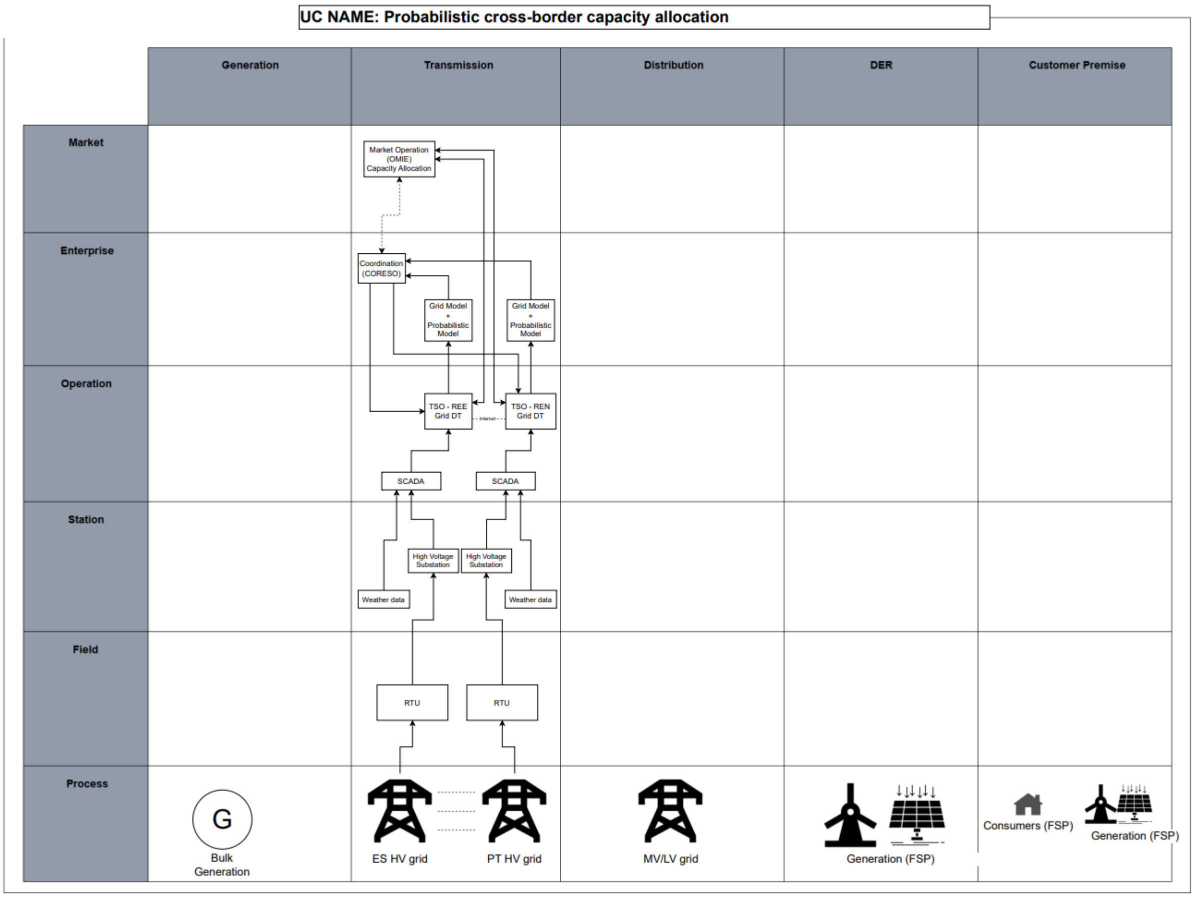


Figure 26 - Ib13 component layer (now Ib10)

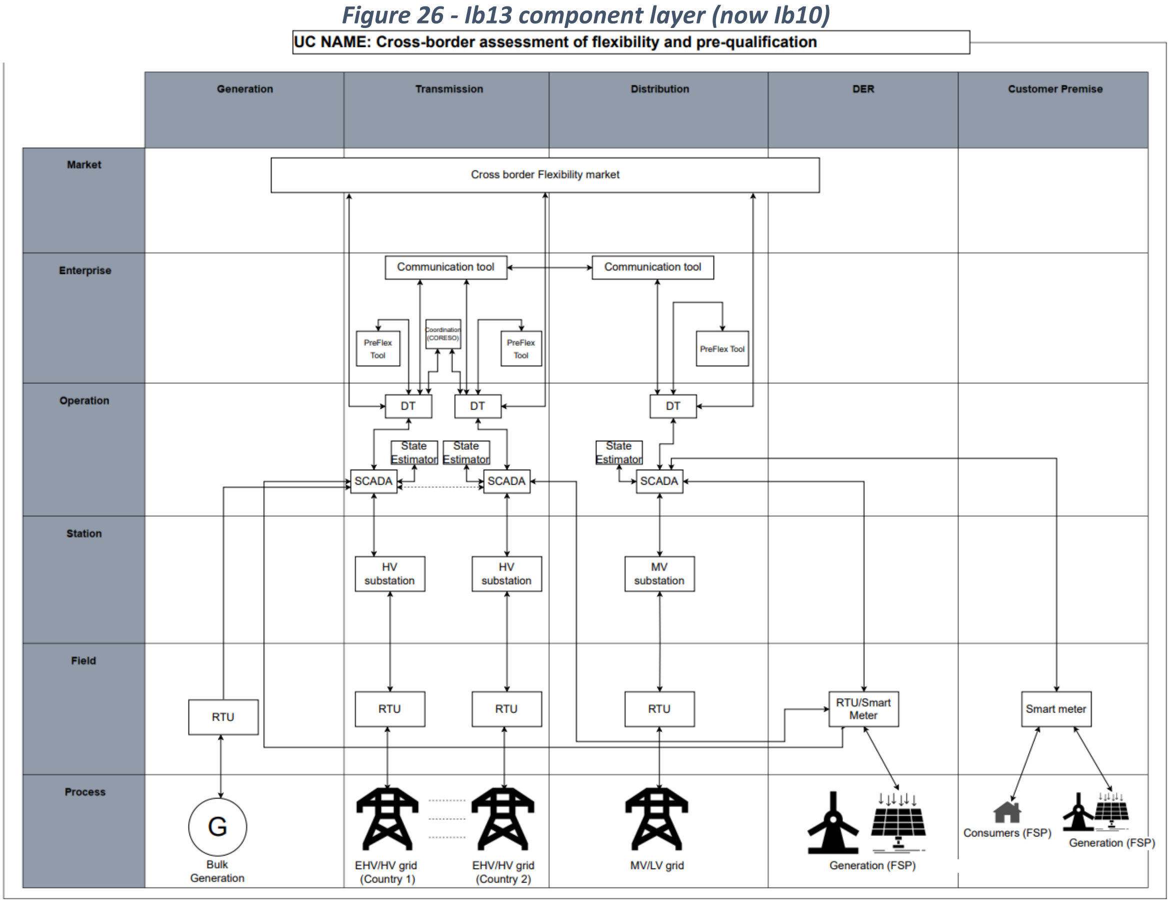


Figure 27 - Ib14 component layer (now Ib11)

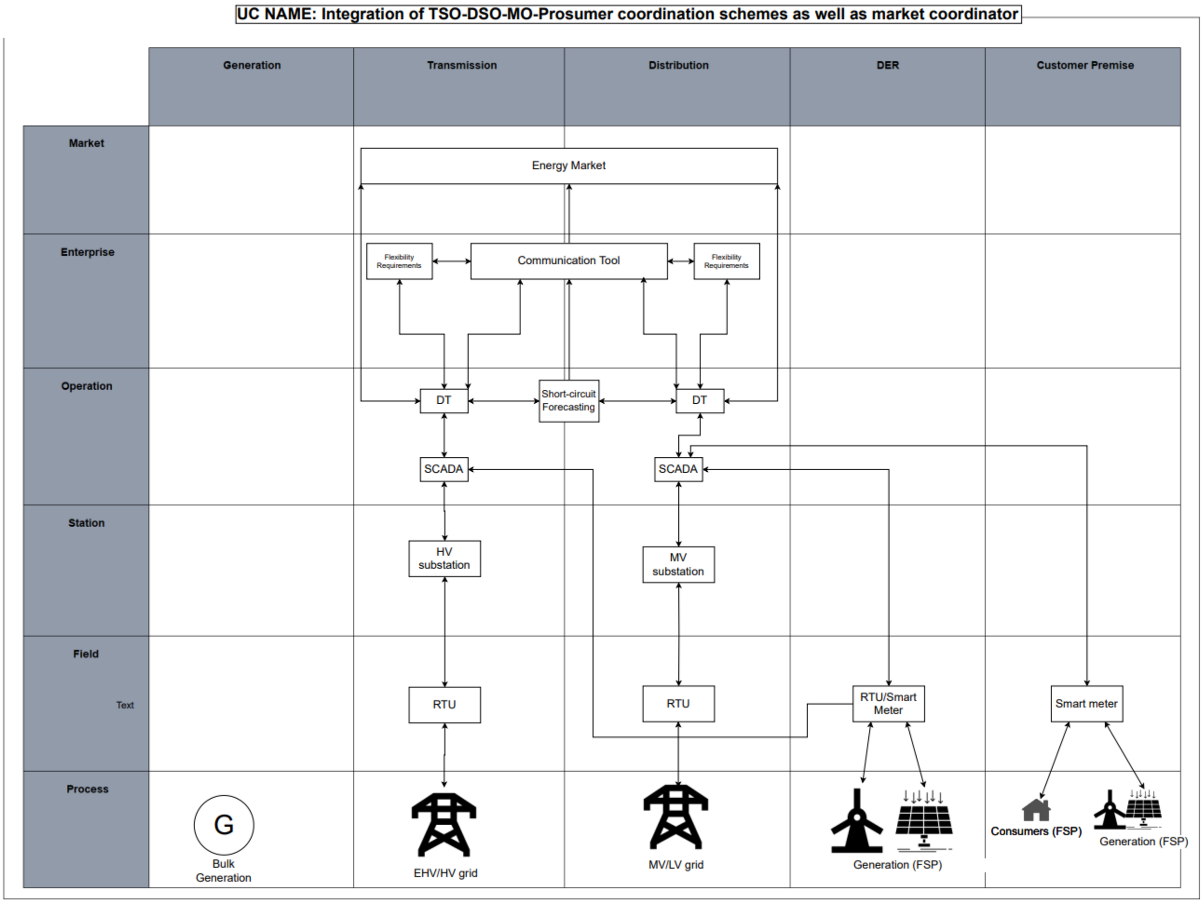


Figure 28 - Ib15 and 16 component layer (now Ib12 and 13)

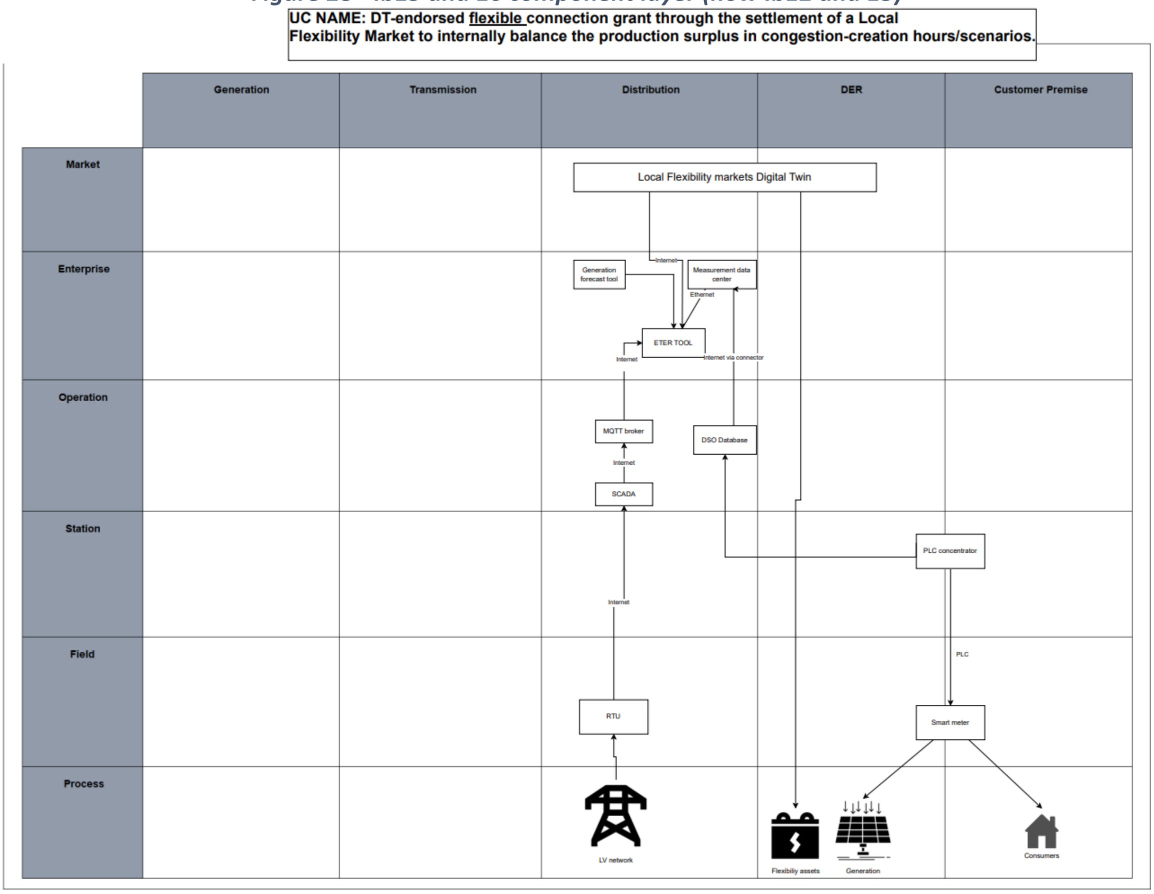


Figure 29 - Ib17 component layer (now Ib14).

Communication layer

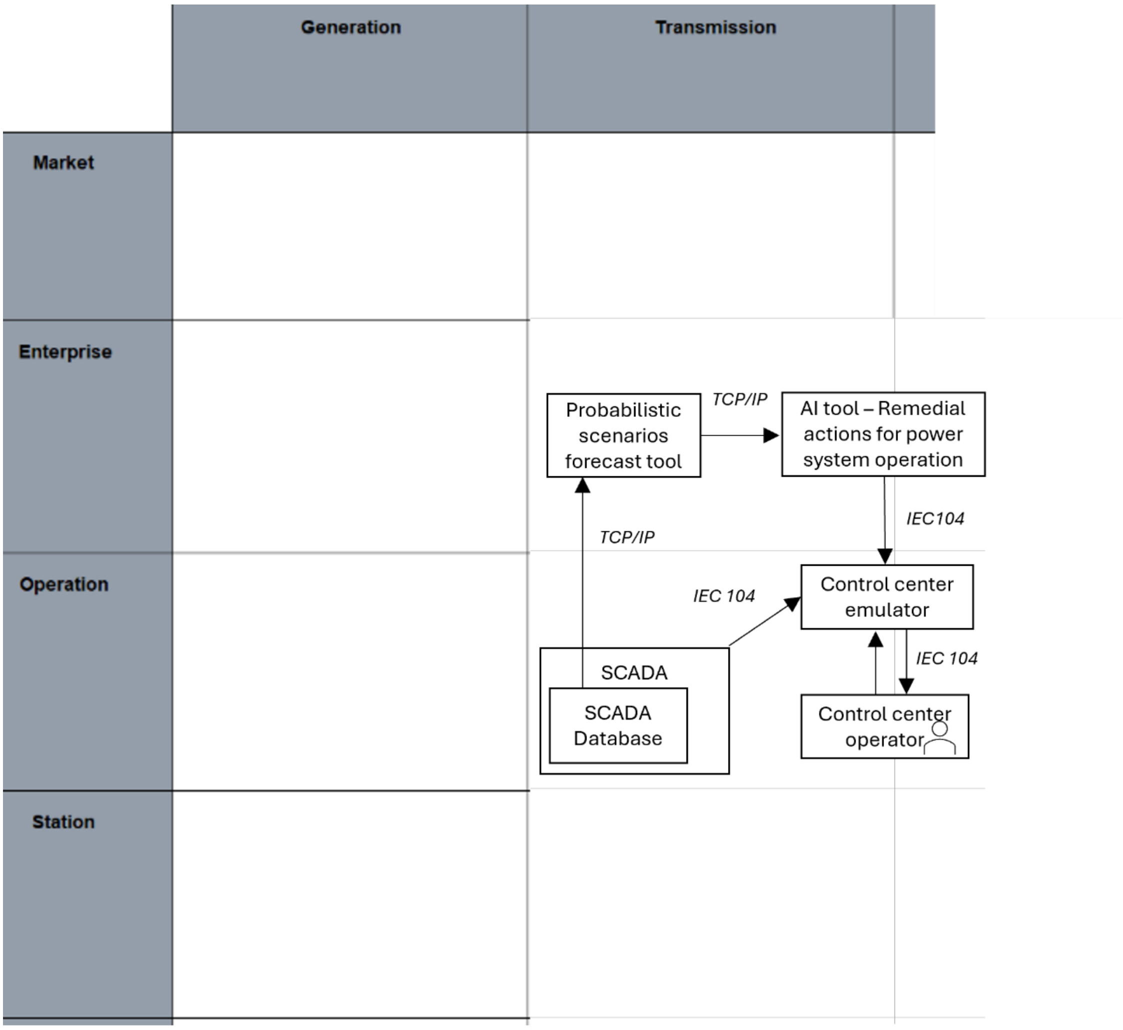


Figure 30 - Ib01 communication layer

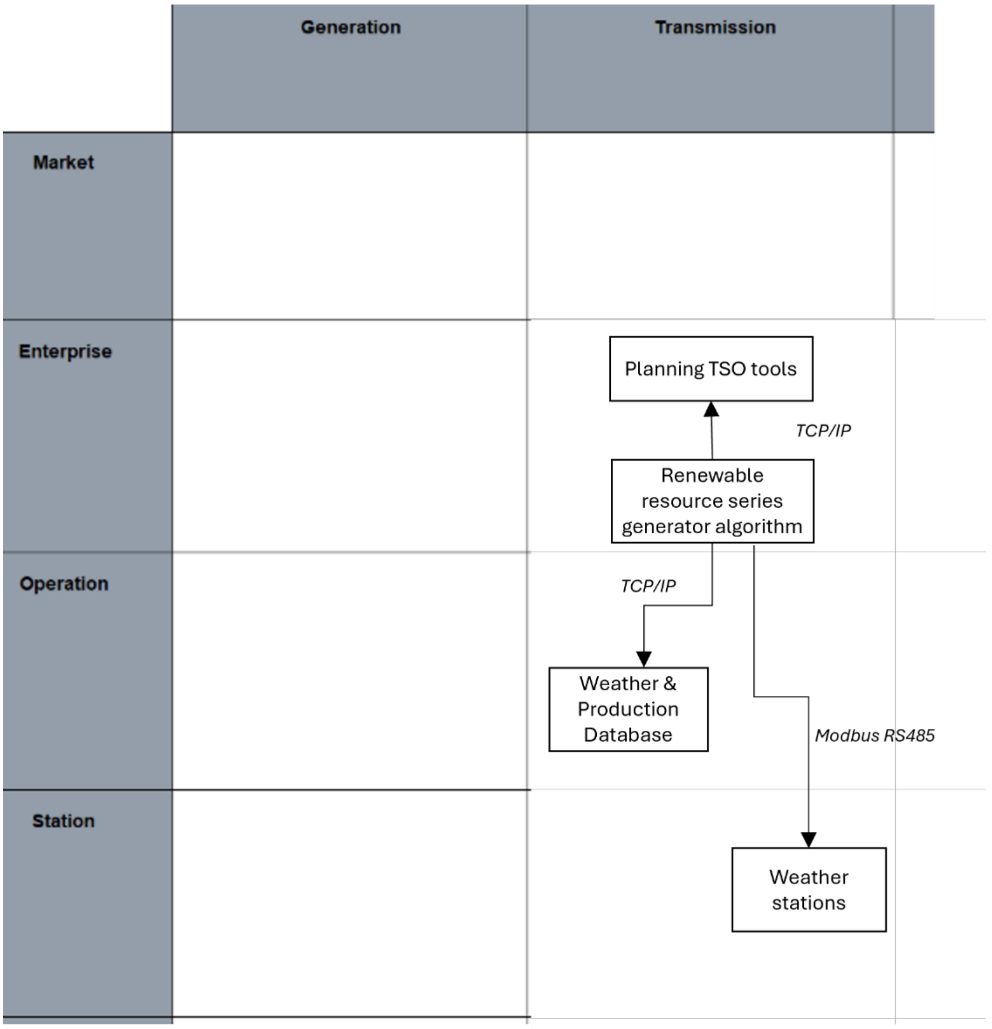


Figure 31 - Ib02 communication layer

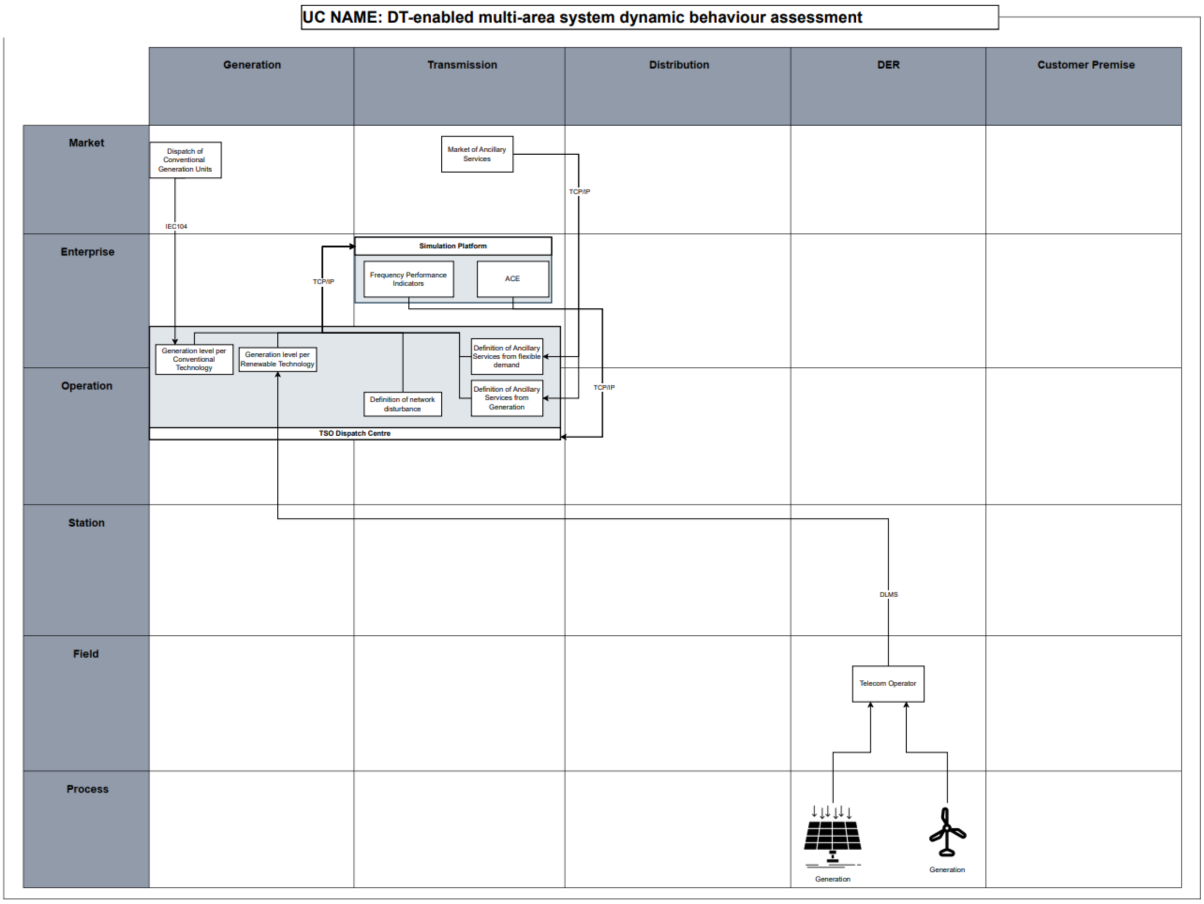


Figure 32 - Ib03 communication layer

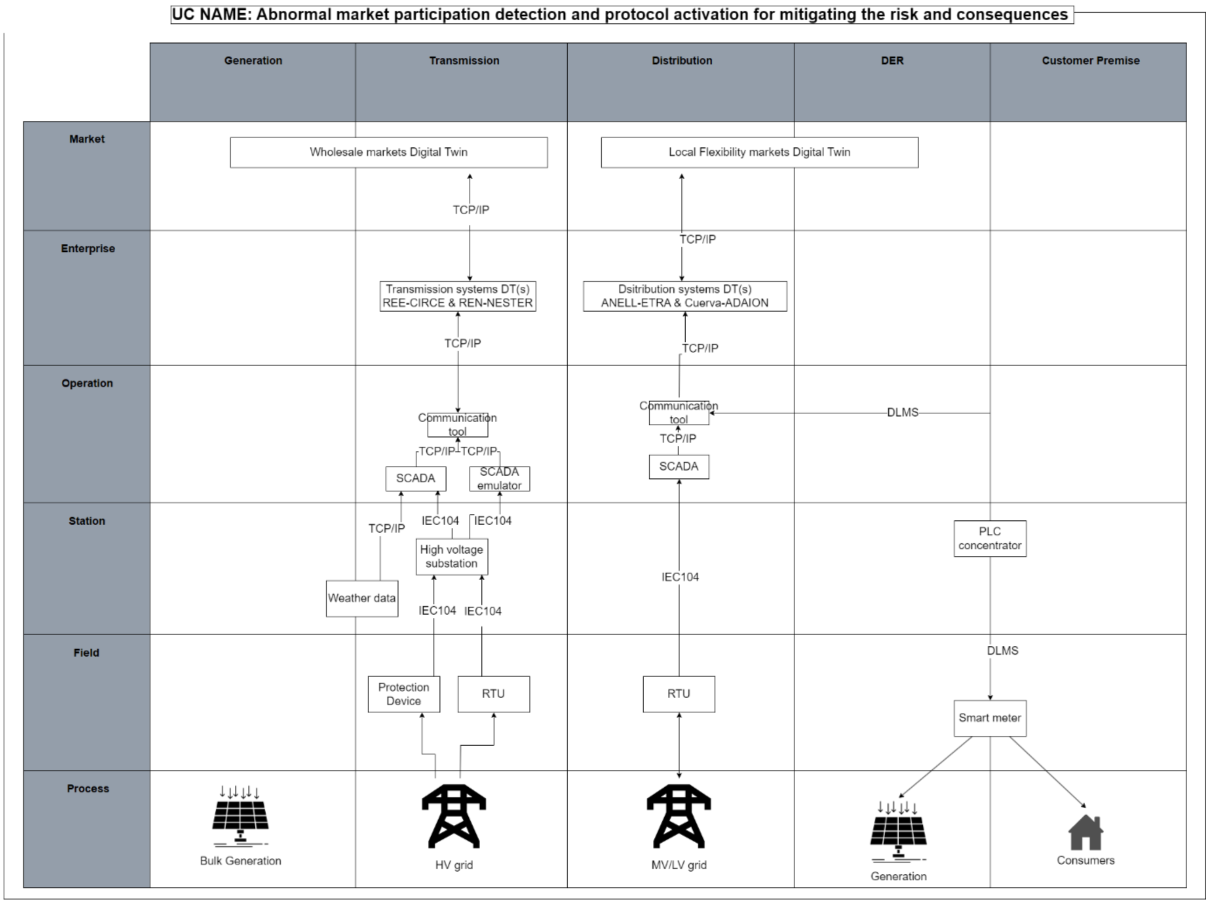


Figure 33 - Ib04 communication layer

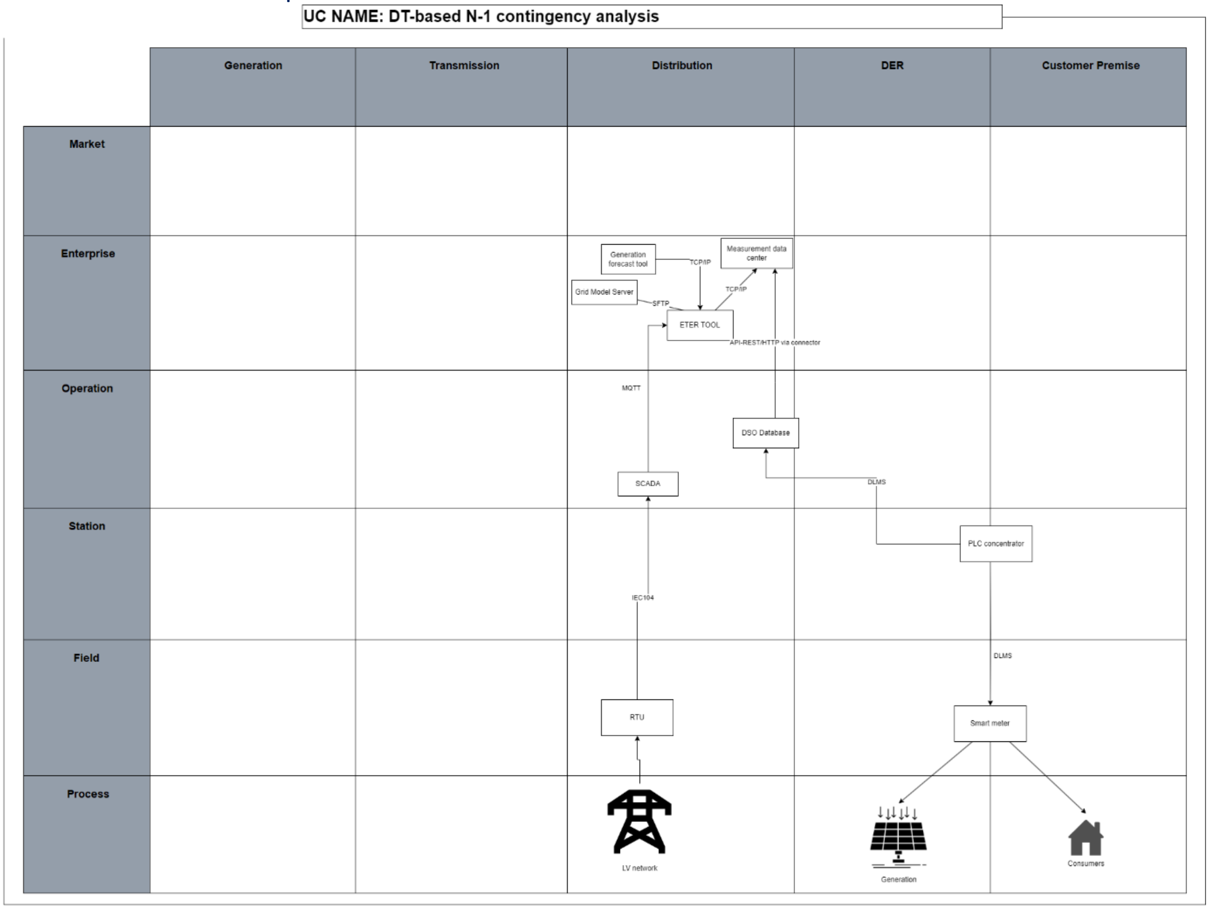


Figure 34 - Ib05, Ib06 and Ib07 communication layers

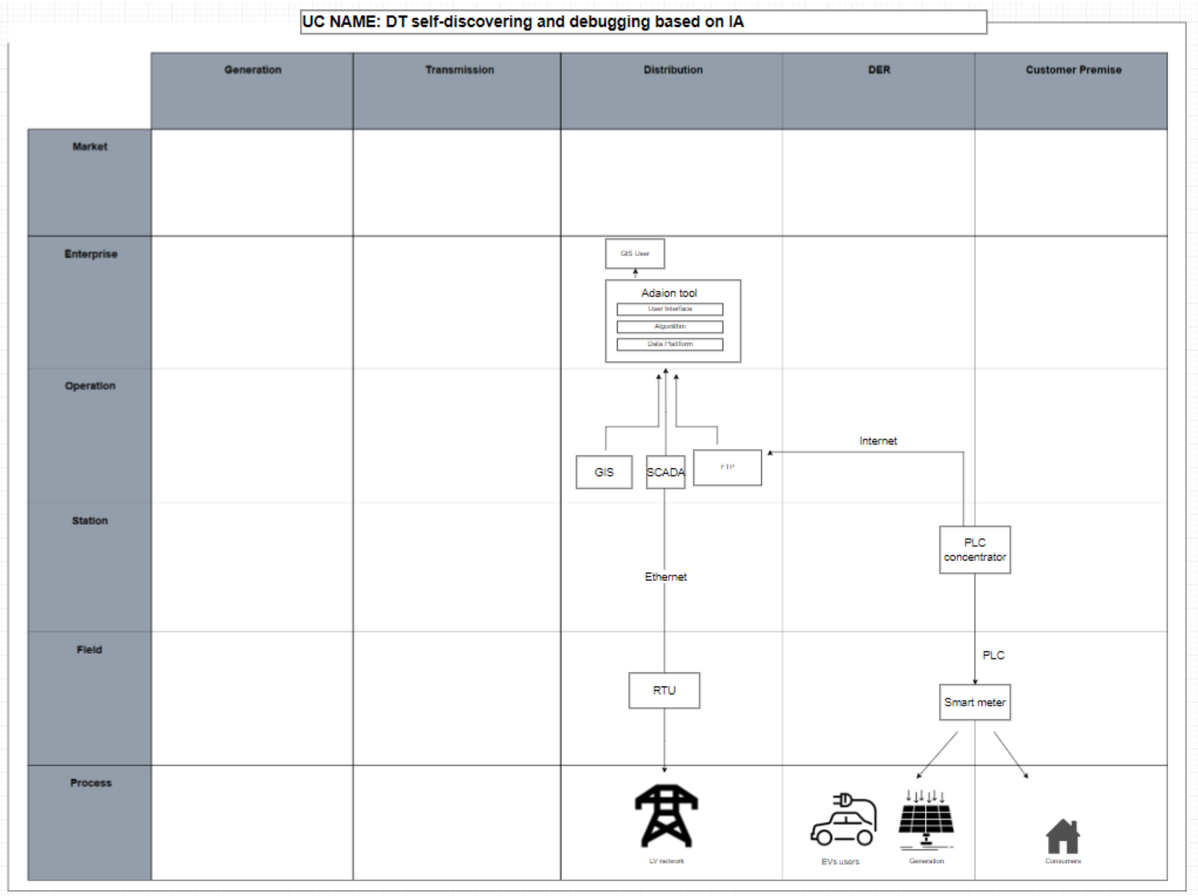


Figure 35 - Ib08 and Ib09 communication layers

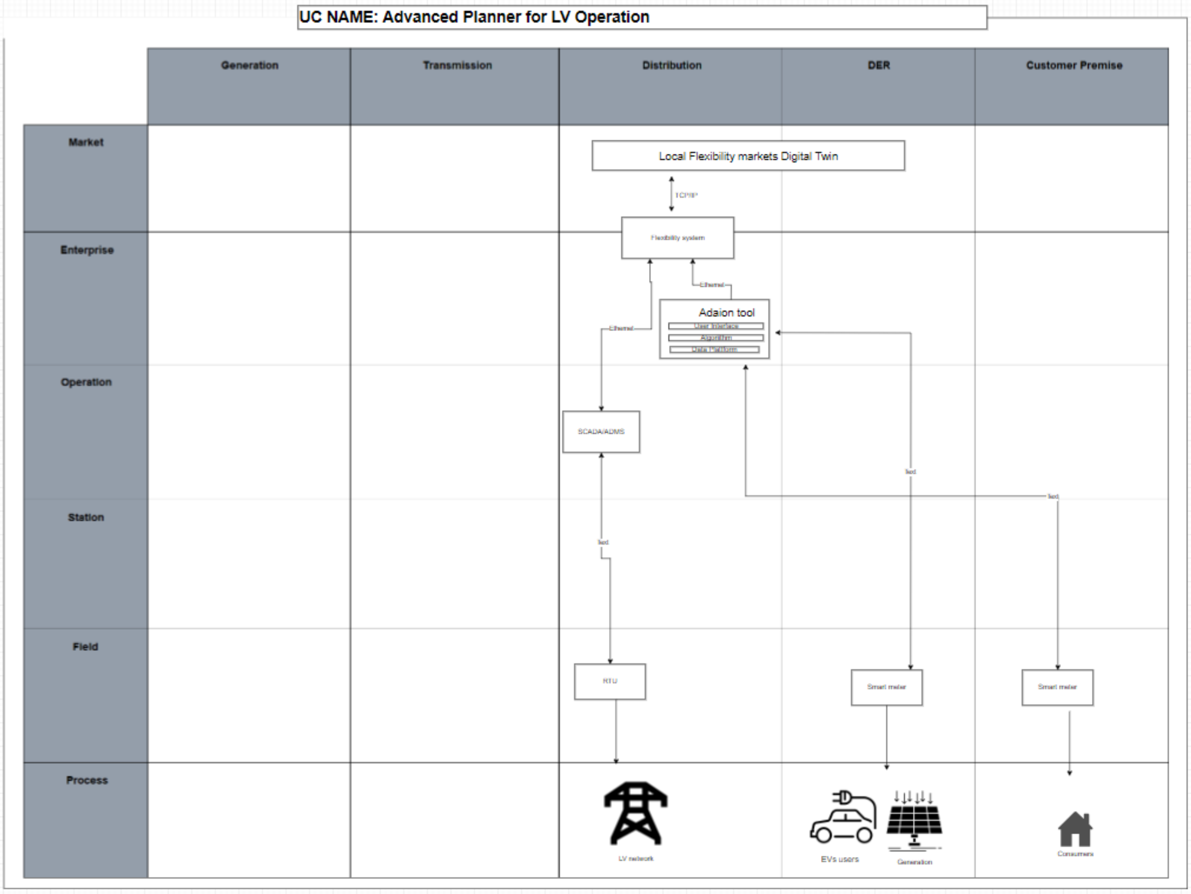


Figure 36 - Ib10 and Ib11 communication layers

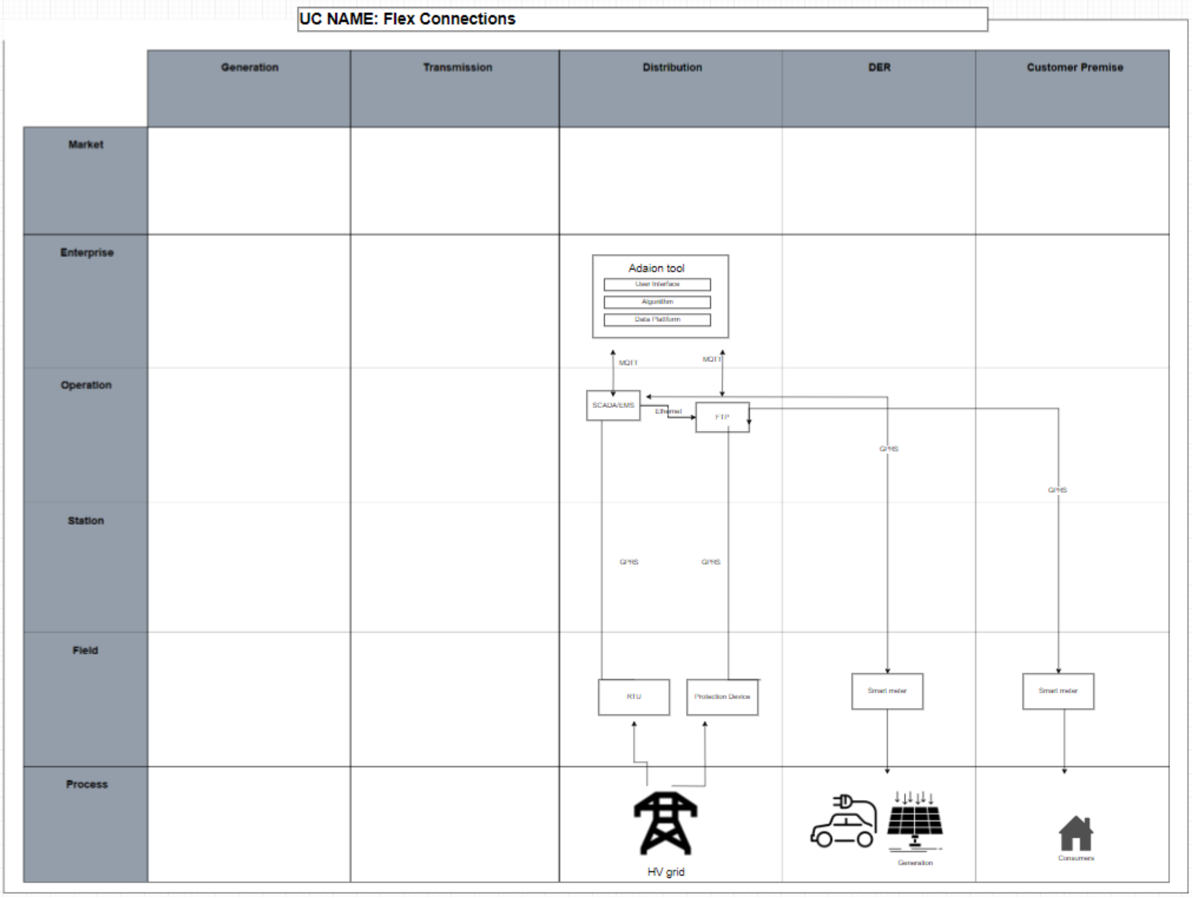


Figure 37 - Ib12 communication layer

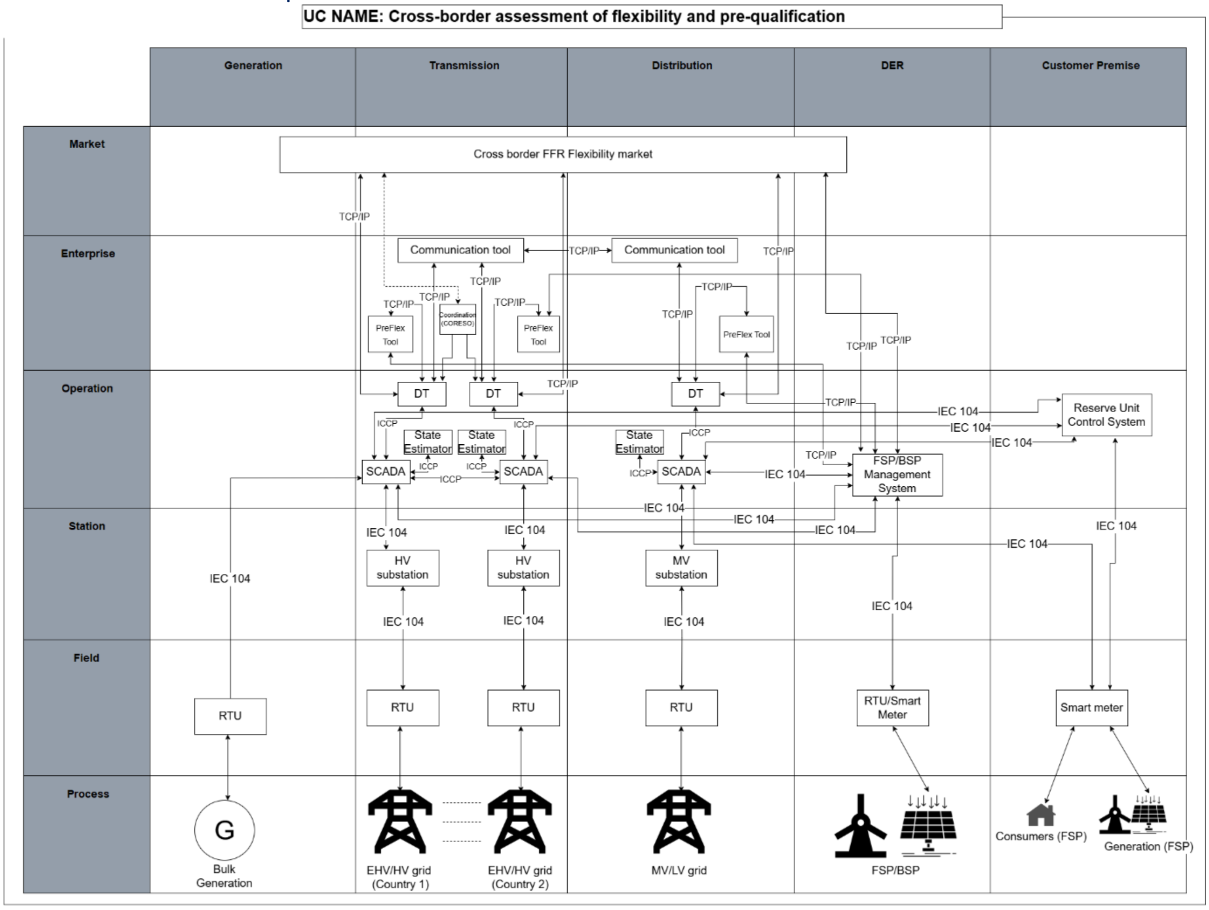


Figure 38 - Ib14 communication layer

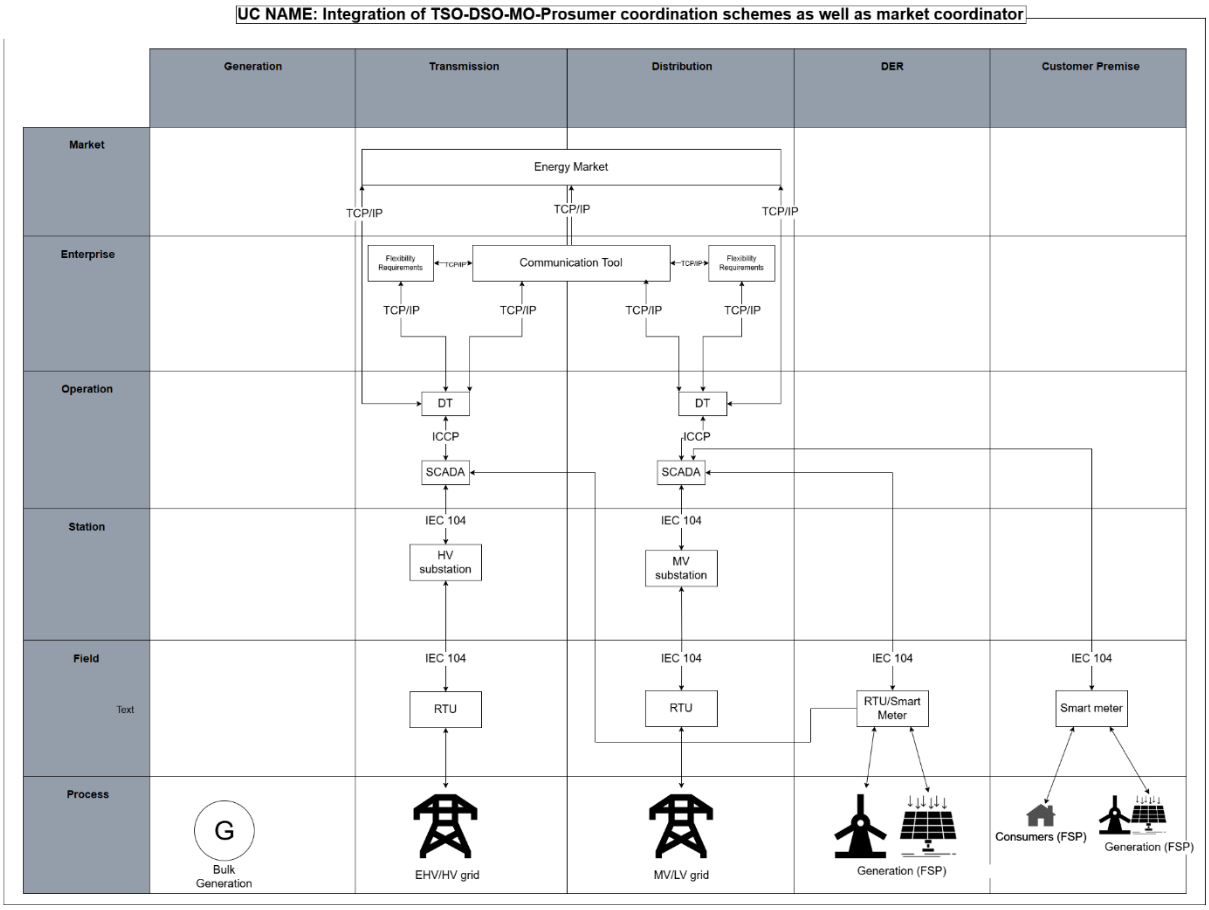


Figure 39 - Ib15 communication layer.

UC NAME: Enhancement of short-circuit models for operational planning

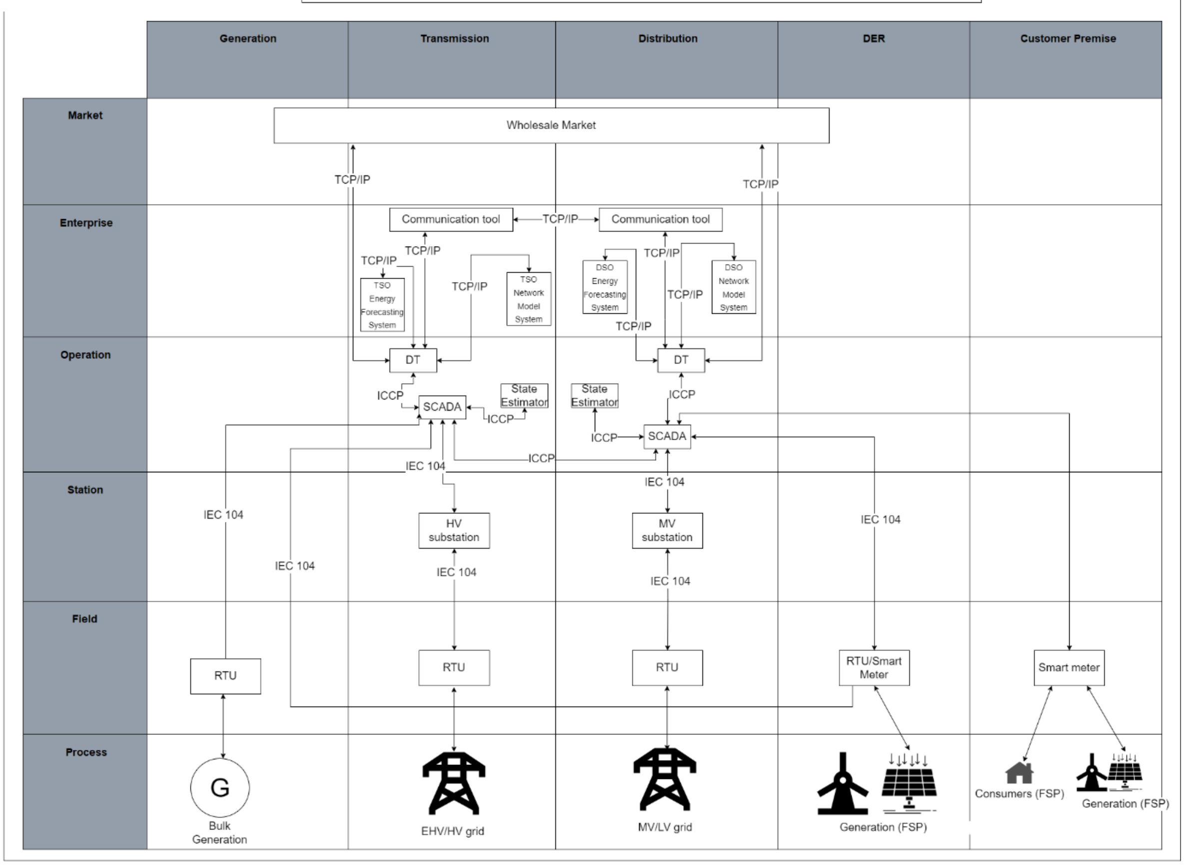


Figure 40 - Ib16 communication layer.

UC NAME: DT-endorsed flexible connection grant through the settlement of a Local Flexibility Market to internally balance the production surplus in congestion-creation hours/scenarios.

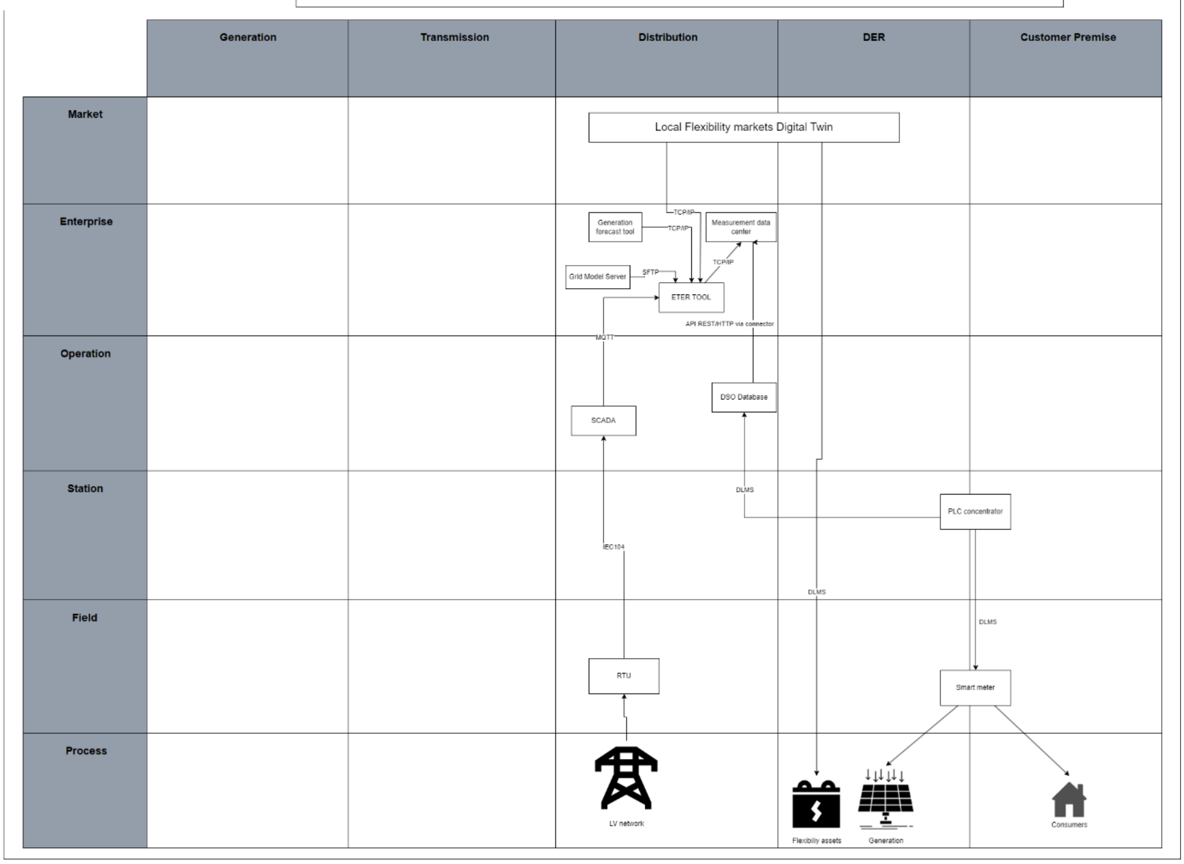


Figure 41 - Ib17 communication layer.

Information layer

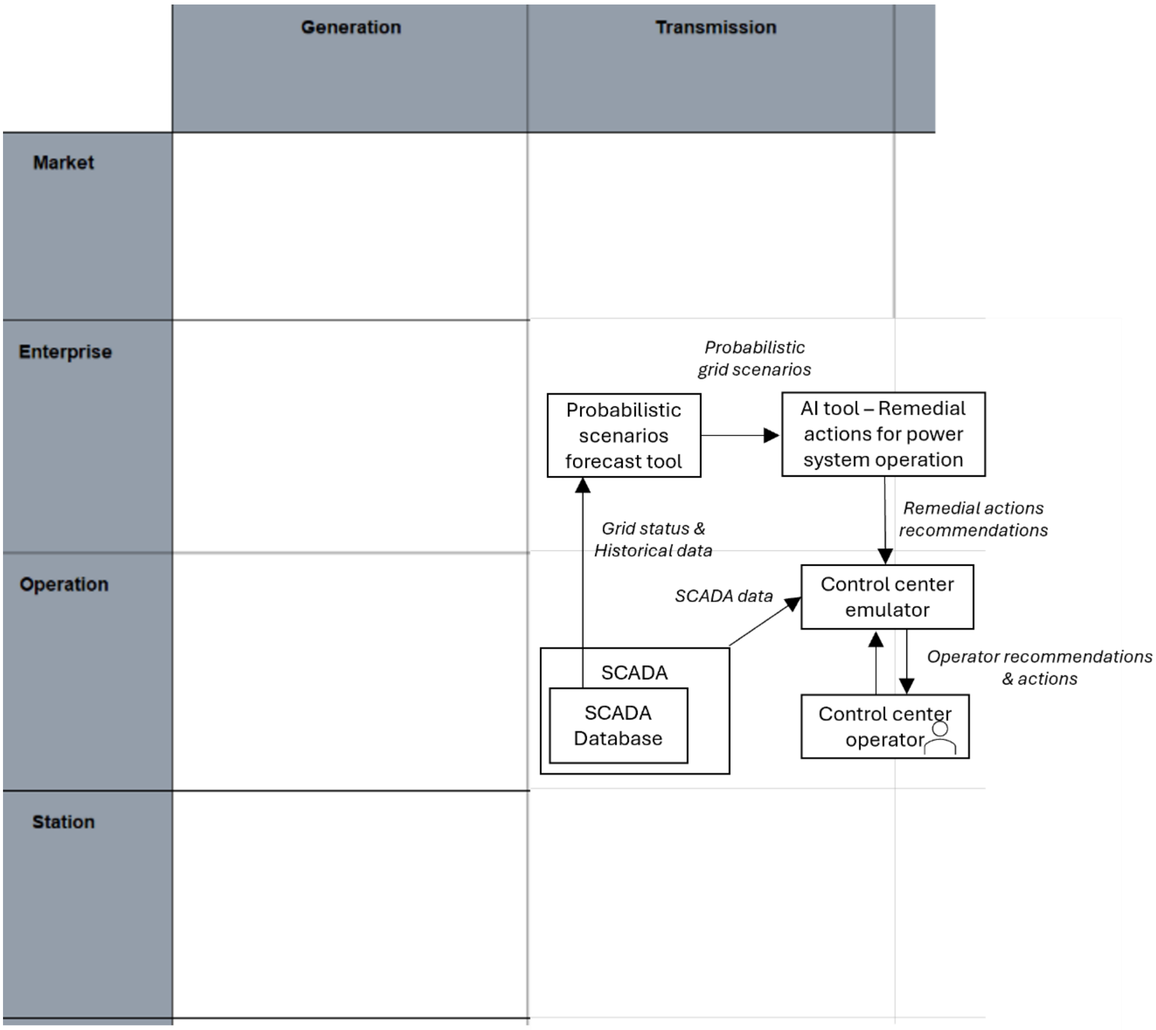


Figure 42 - Ib01 information layer

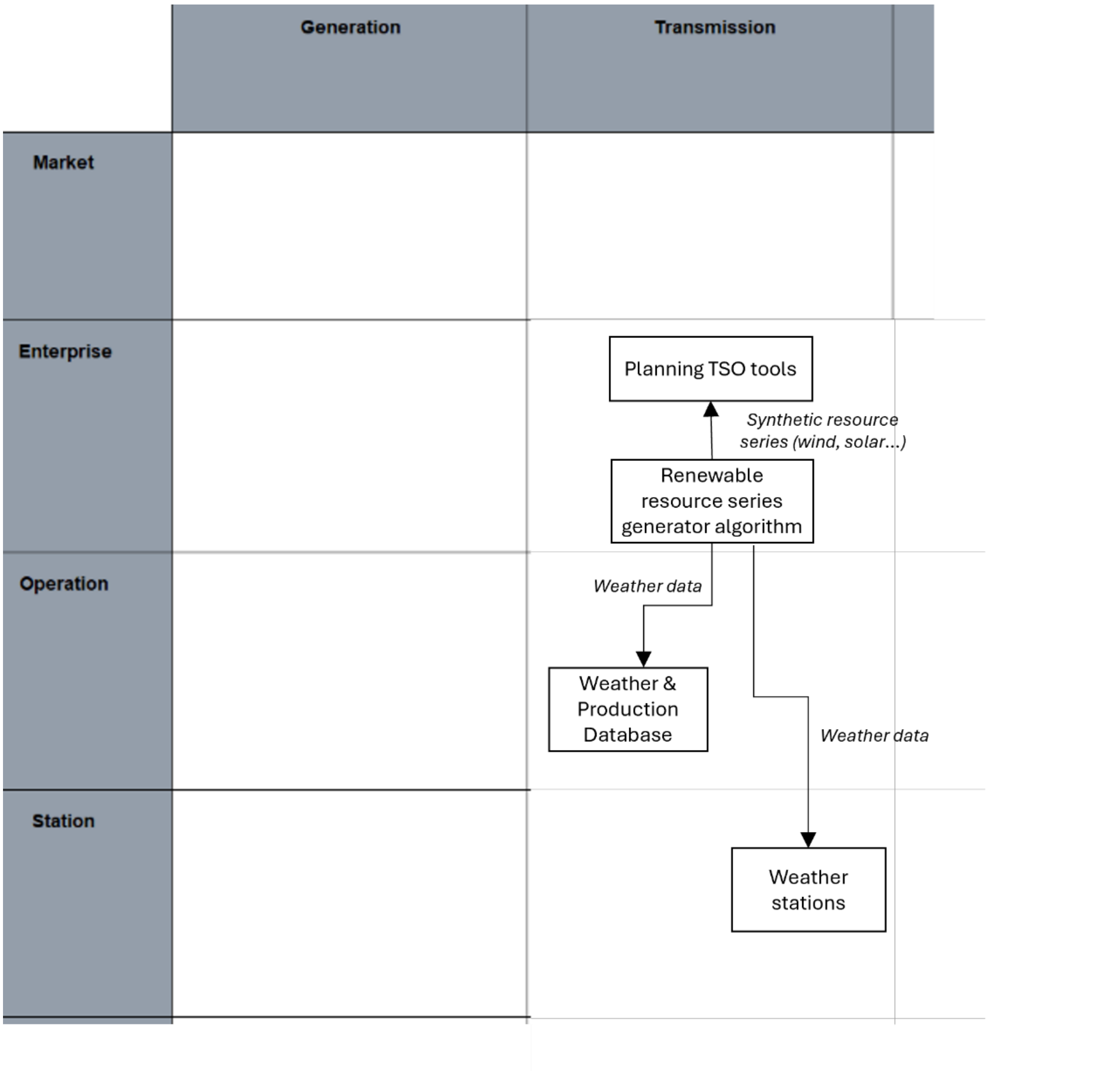


Figure 43 - Ib02 information layer

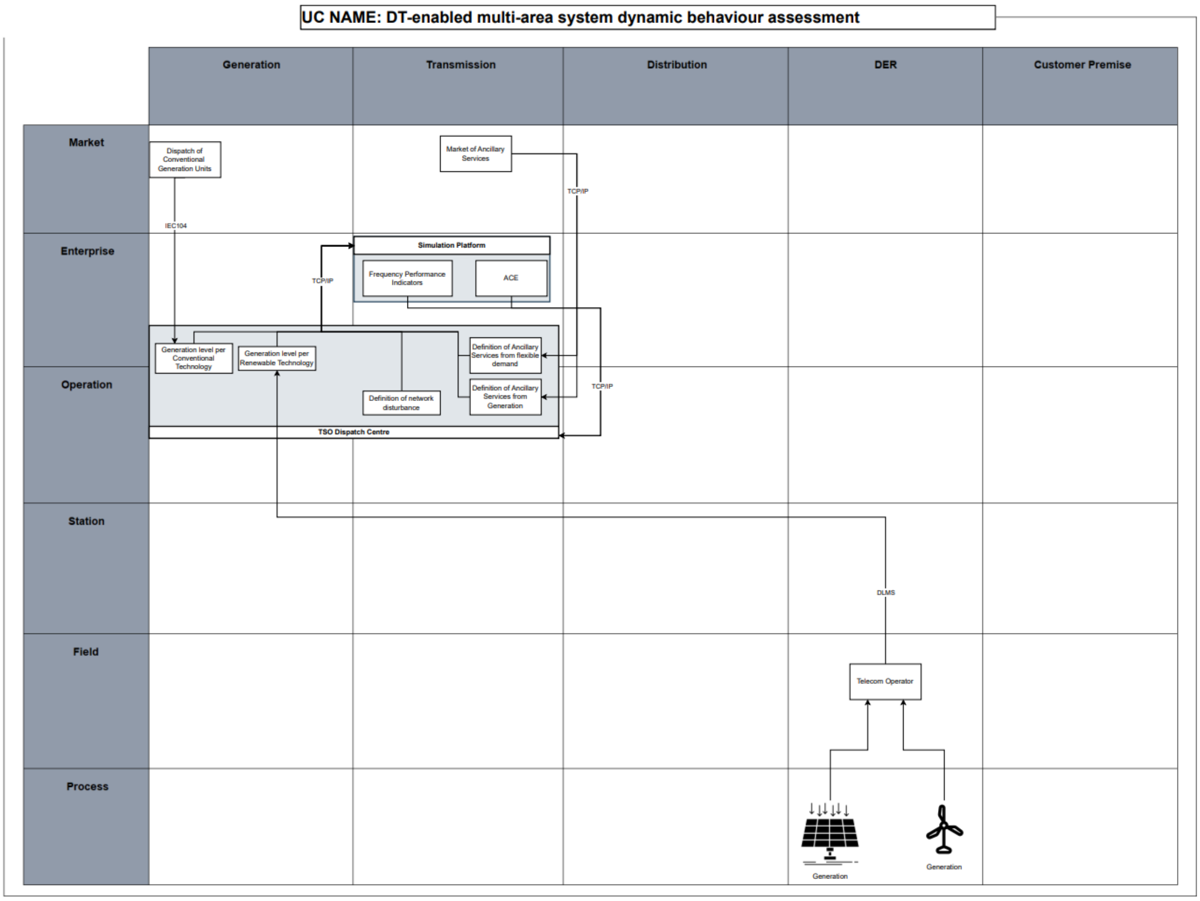


Figure 44 - lb03 information layer

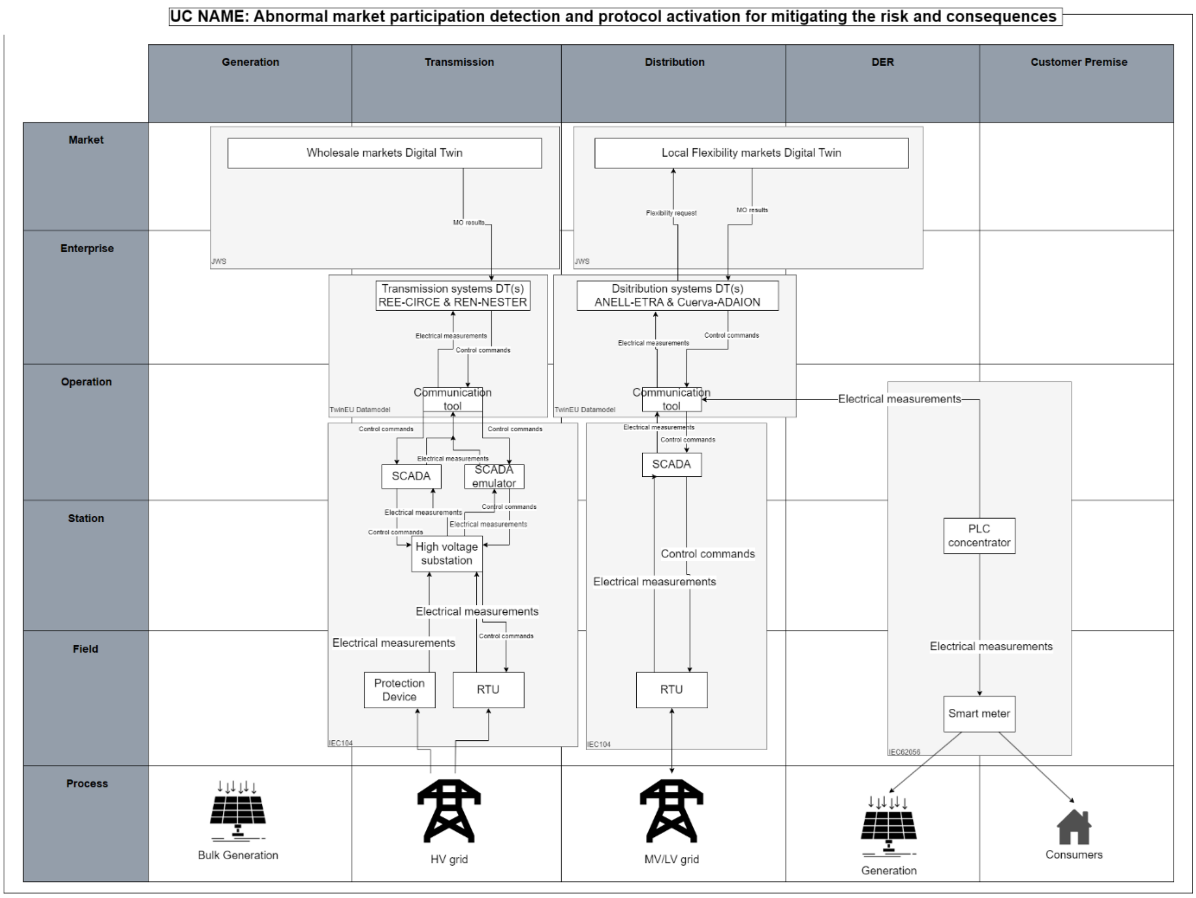


Figure 45 - lb04 information layer

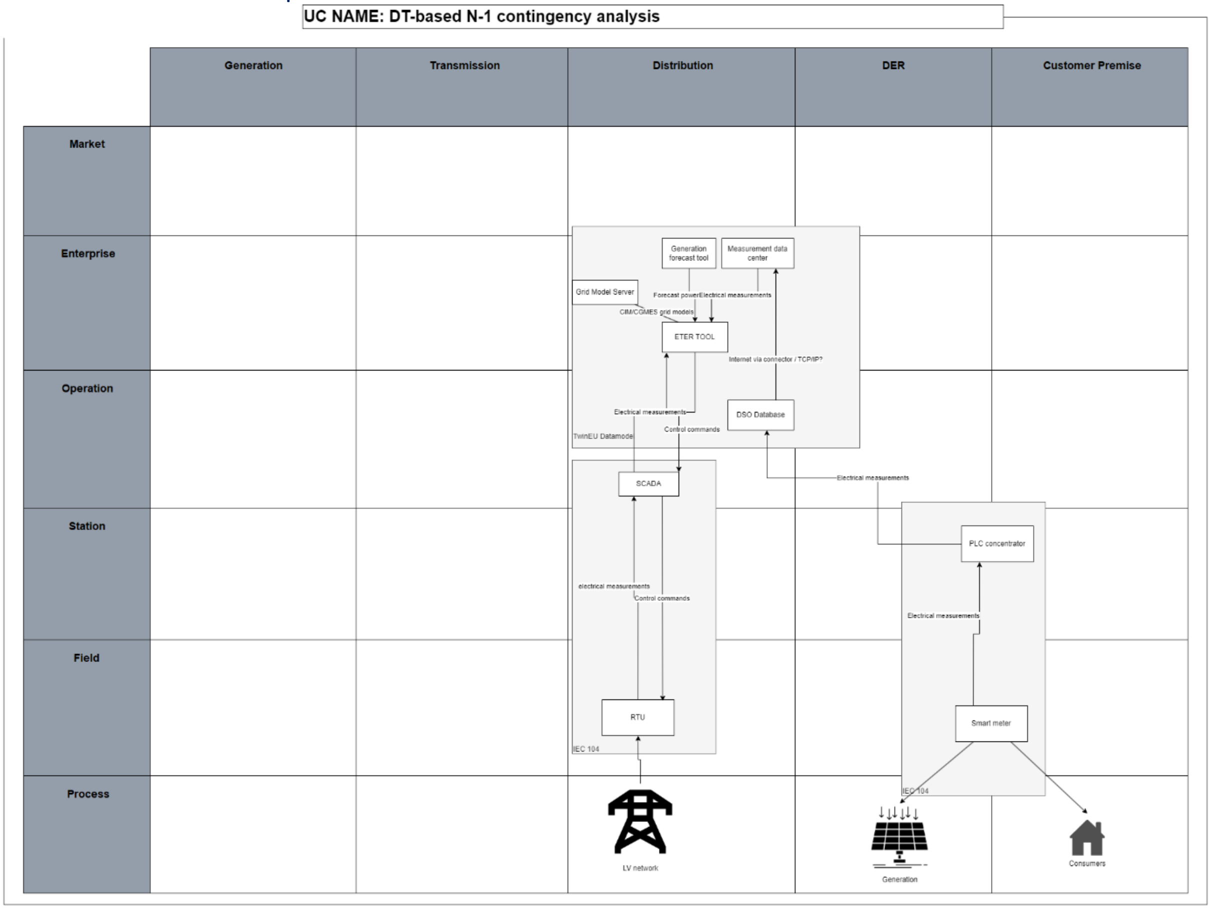


Figure 46 - Ib05, Ib06 and Ib07 information layers

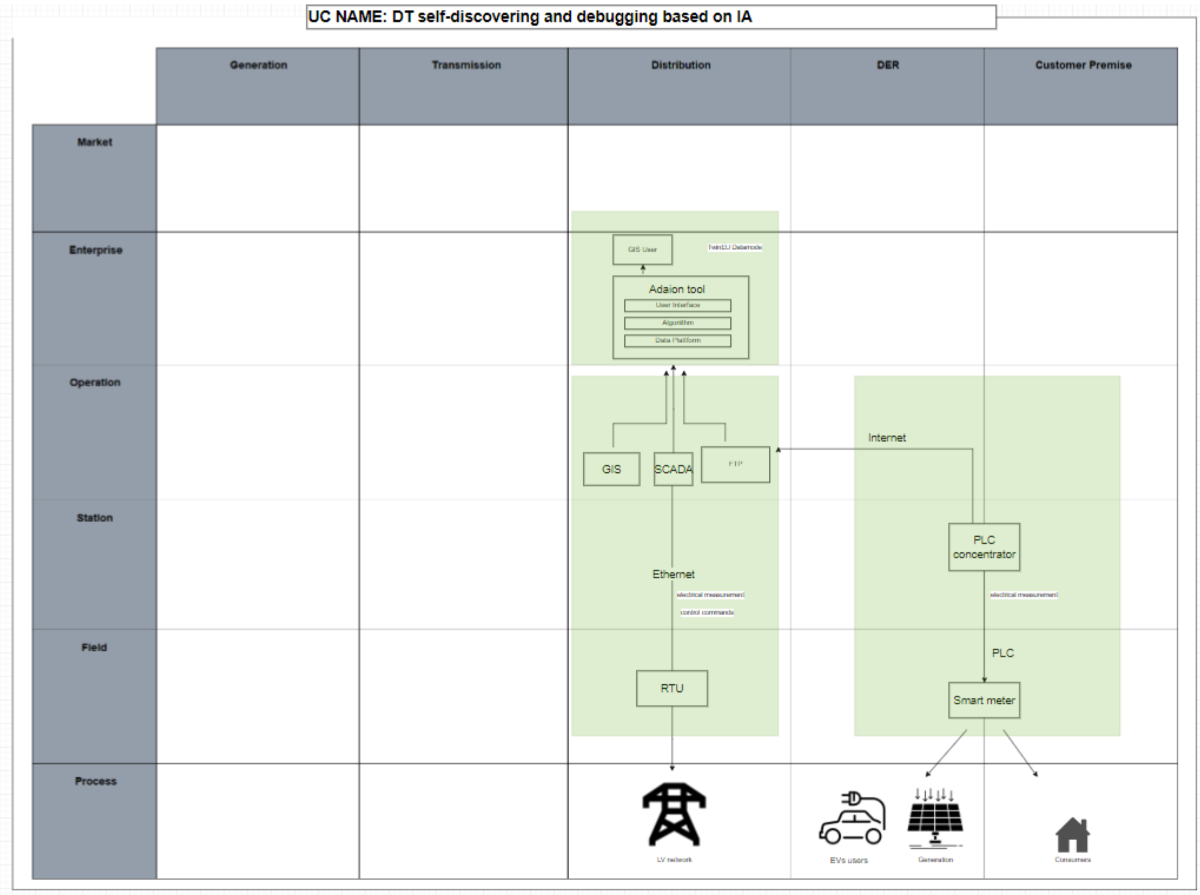


Figure 47 - Ib08 and Ib09 information layer

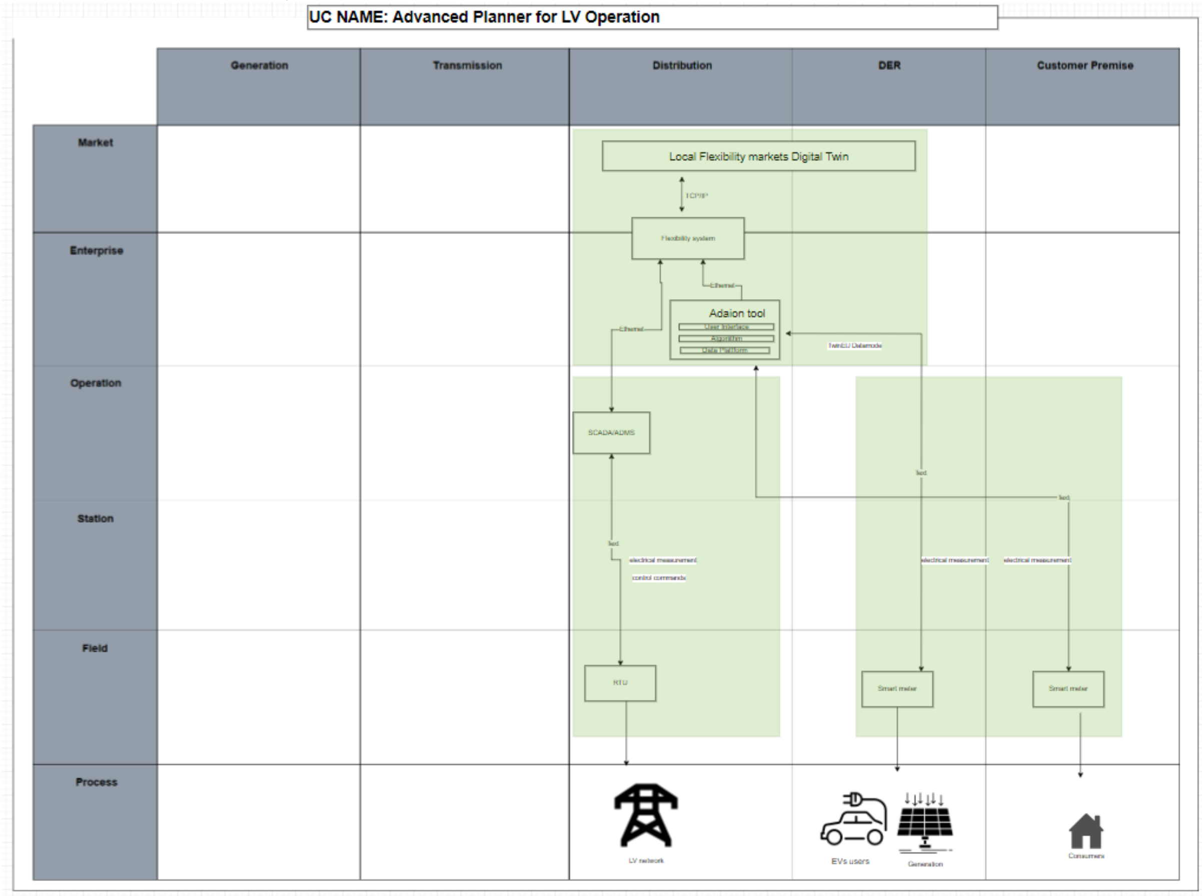


Figure 48 - Ib10 and Ib11 information layers

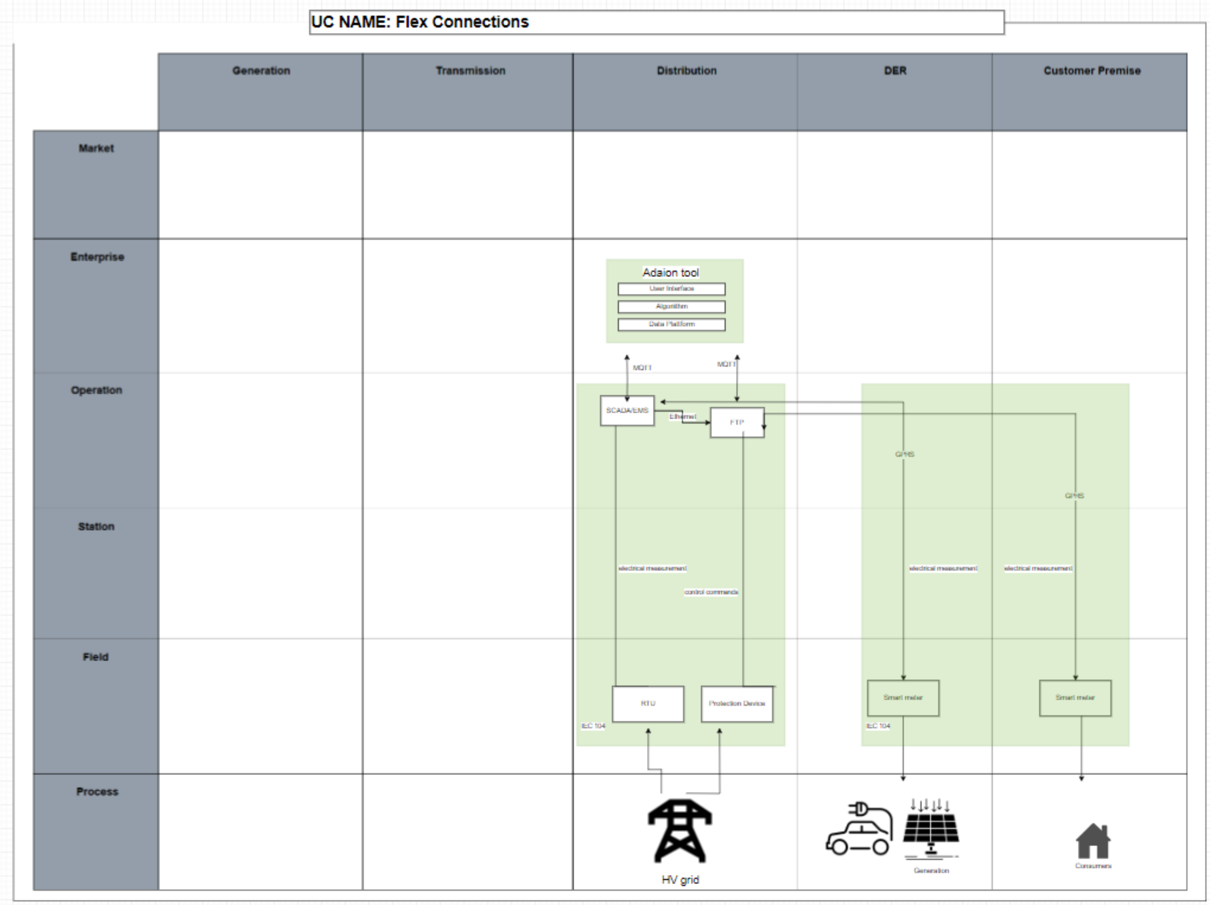


Figure 49 - Ib12 information layer

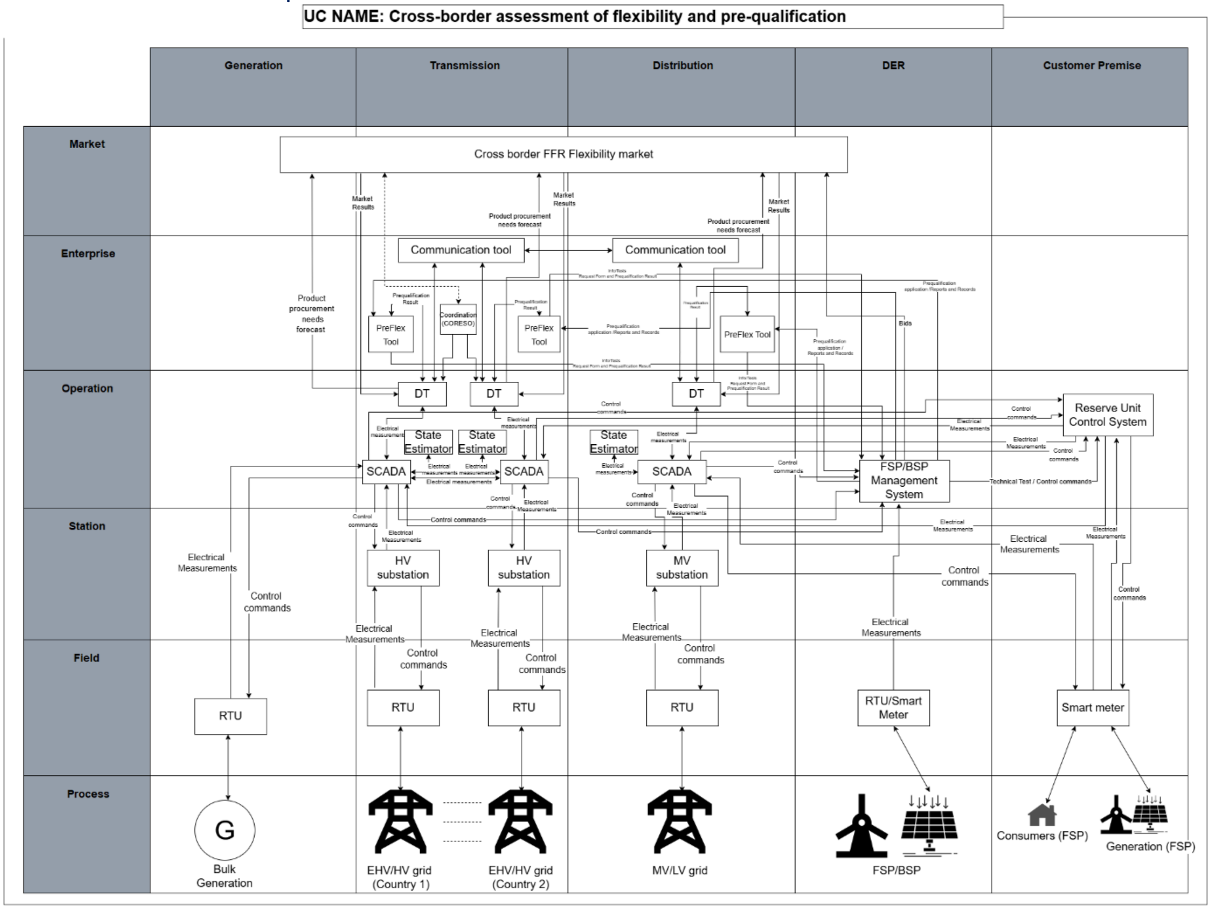


Figure 50 - Ib14 information layer

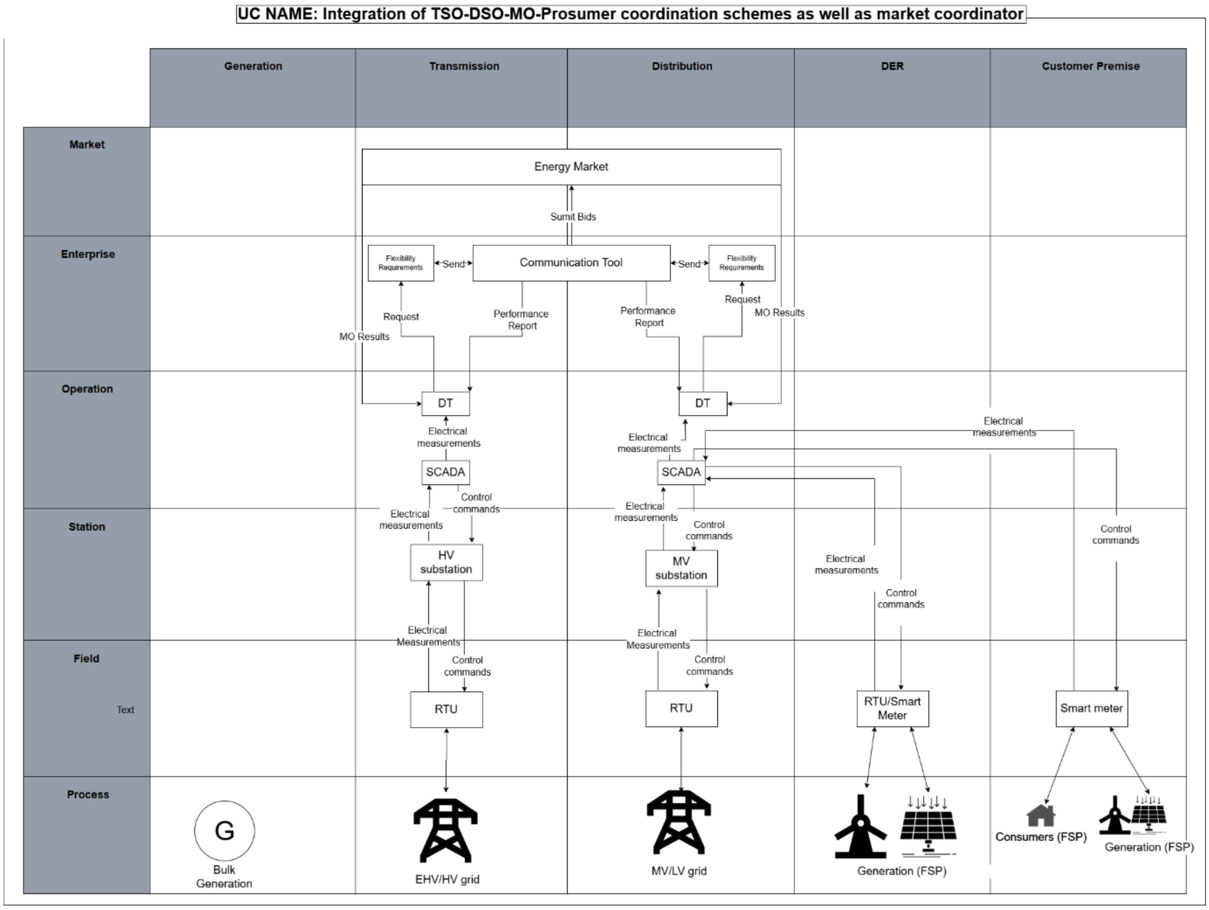


Figure 51 - Ib15 information layer

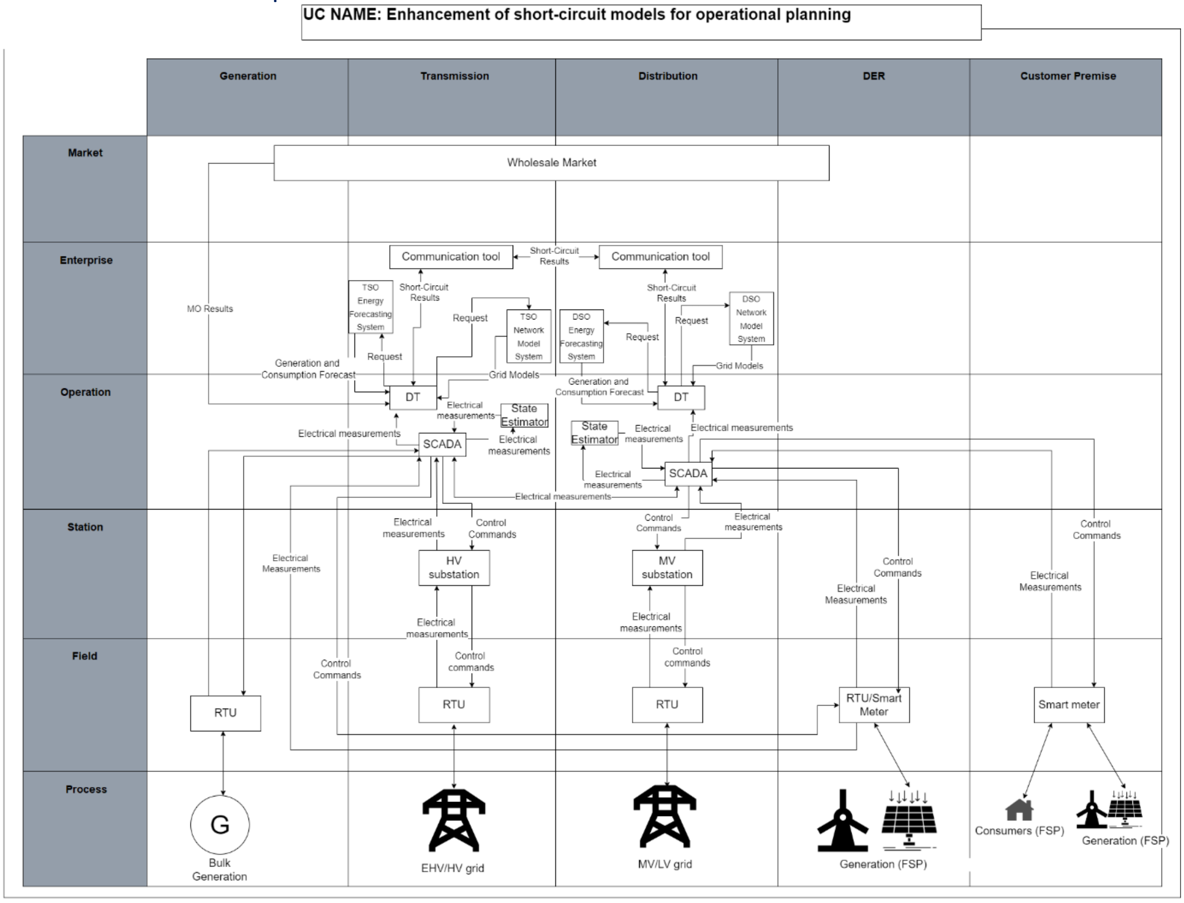


Figure 52 - Ib16 information layer

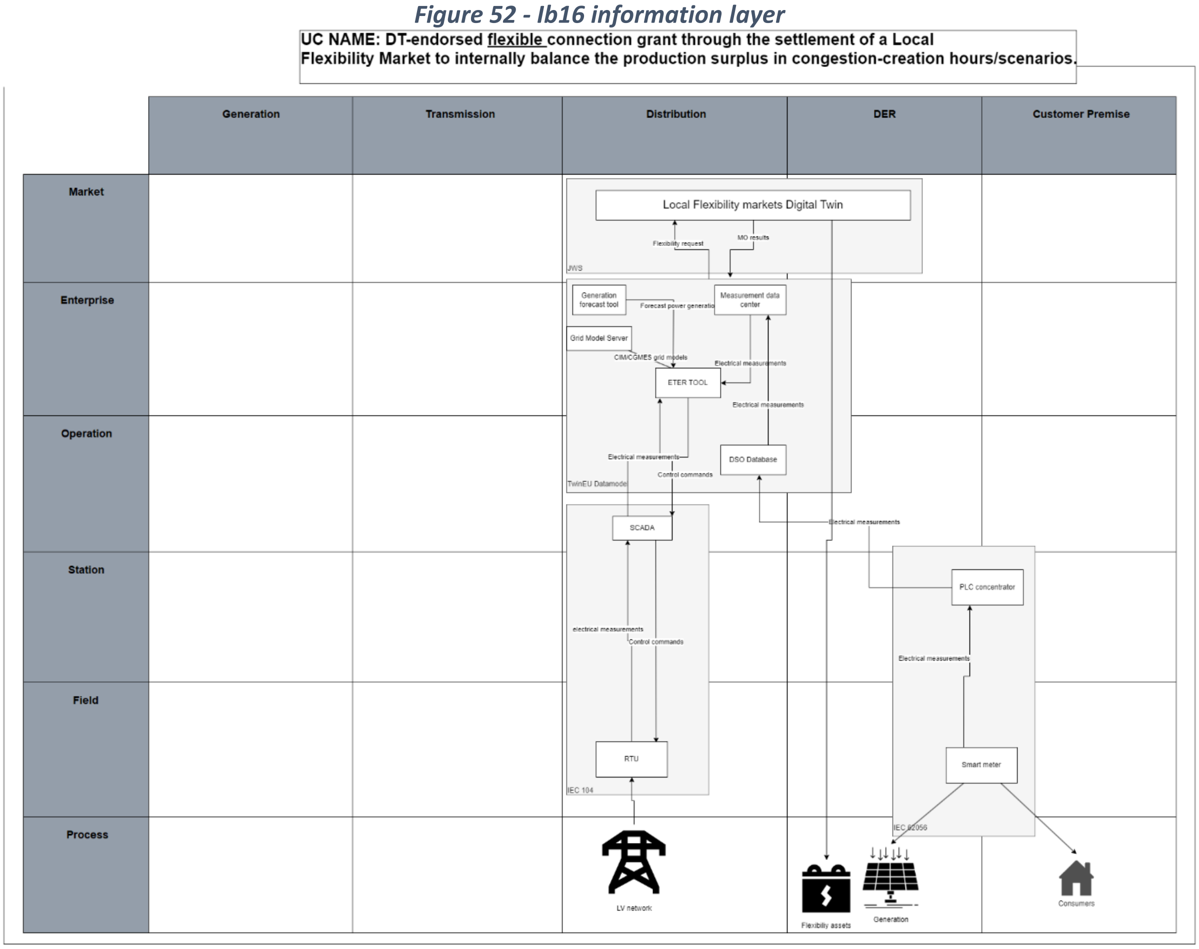


Figure 53 - Ib17 information layer

DT Interaction architectures

Component layer

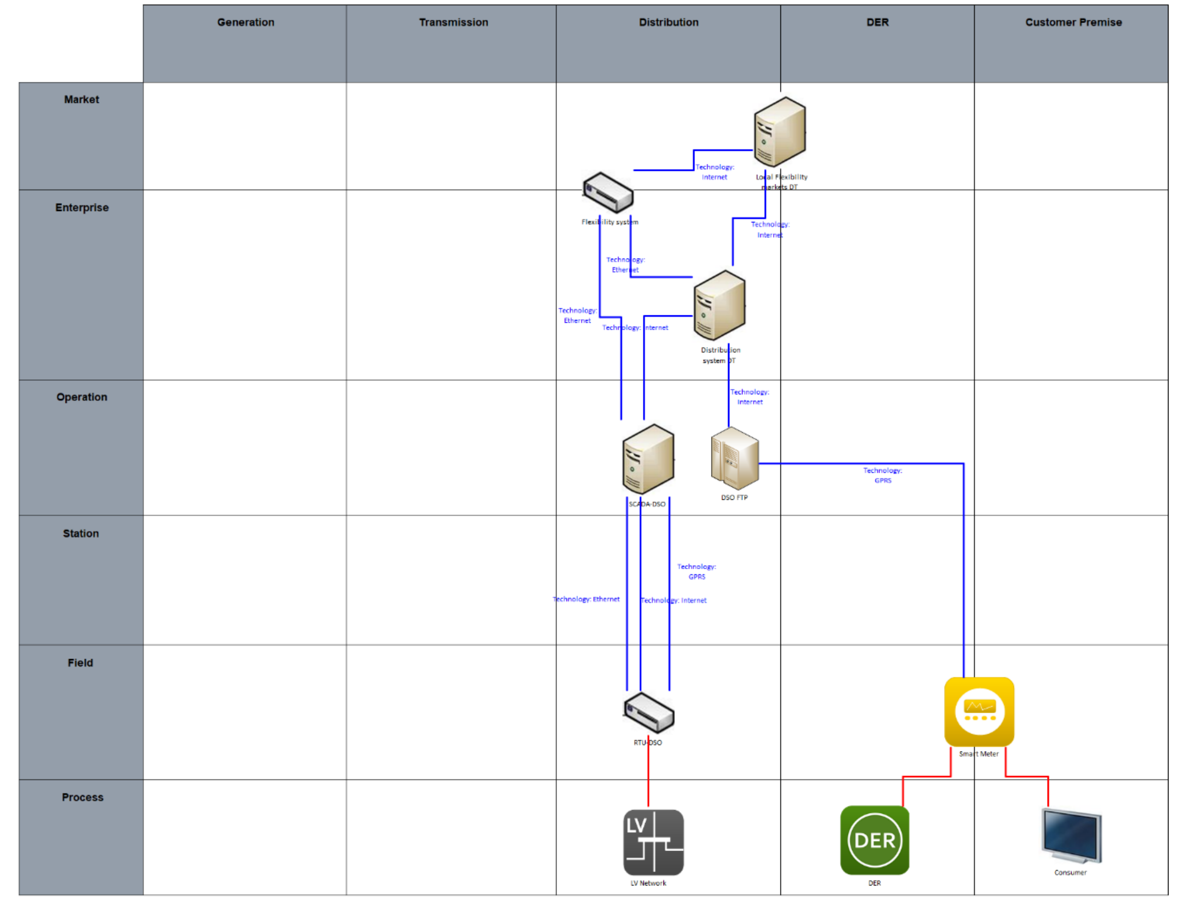


Figure 54 - DSO-MO interaction component layer

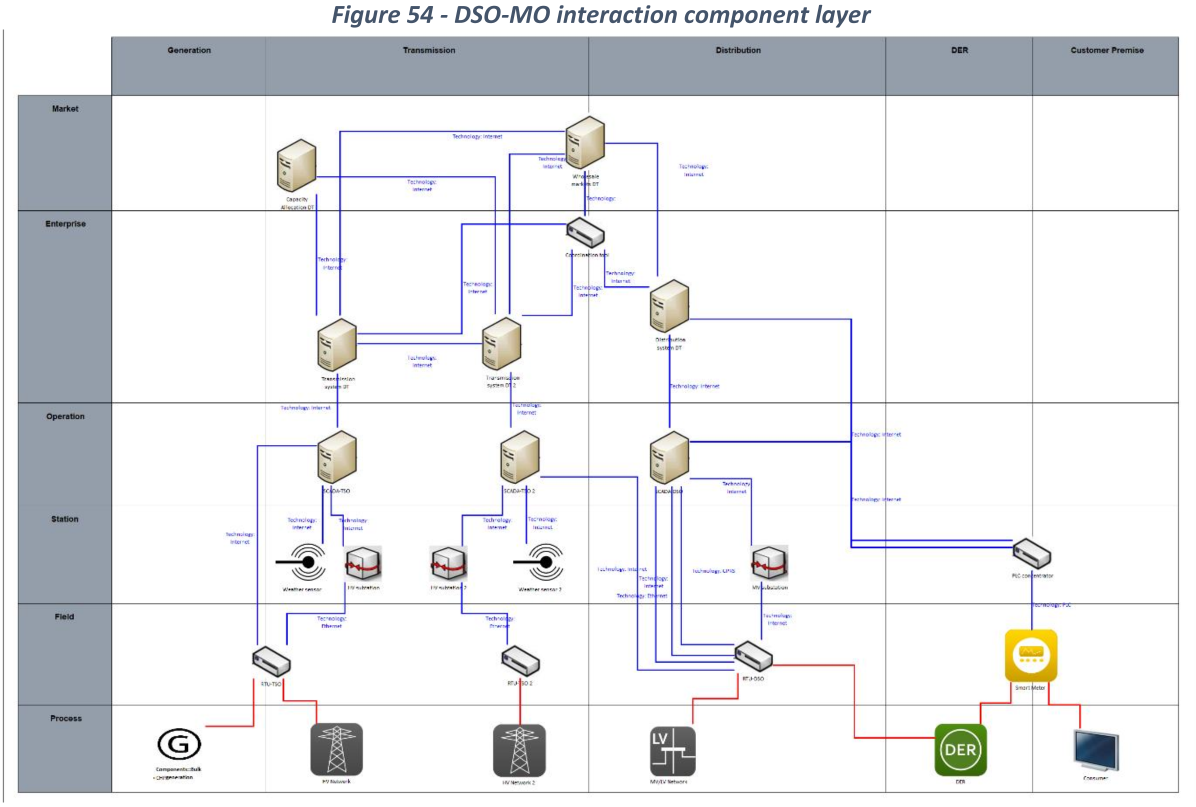


Figure 55 - TSO-DSO interaction component layer

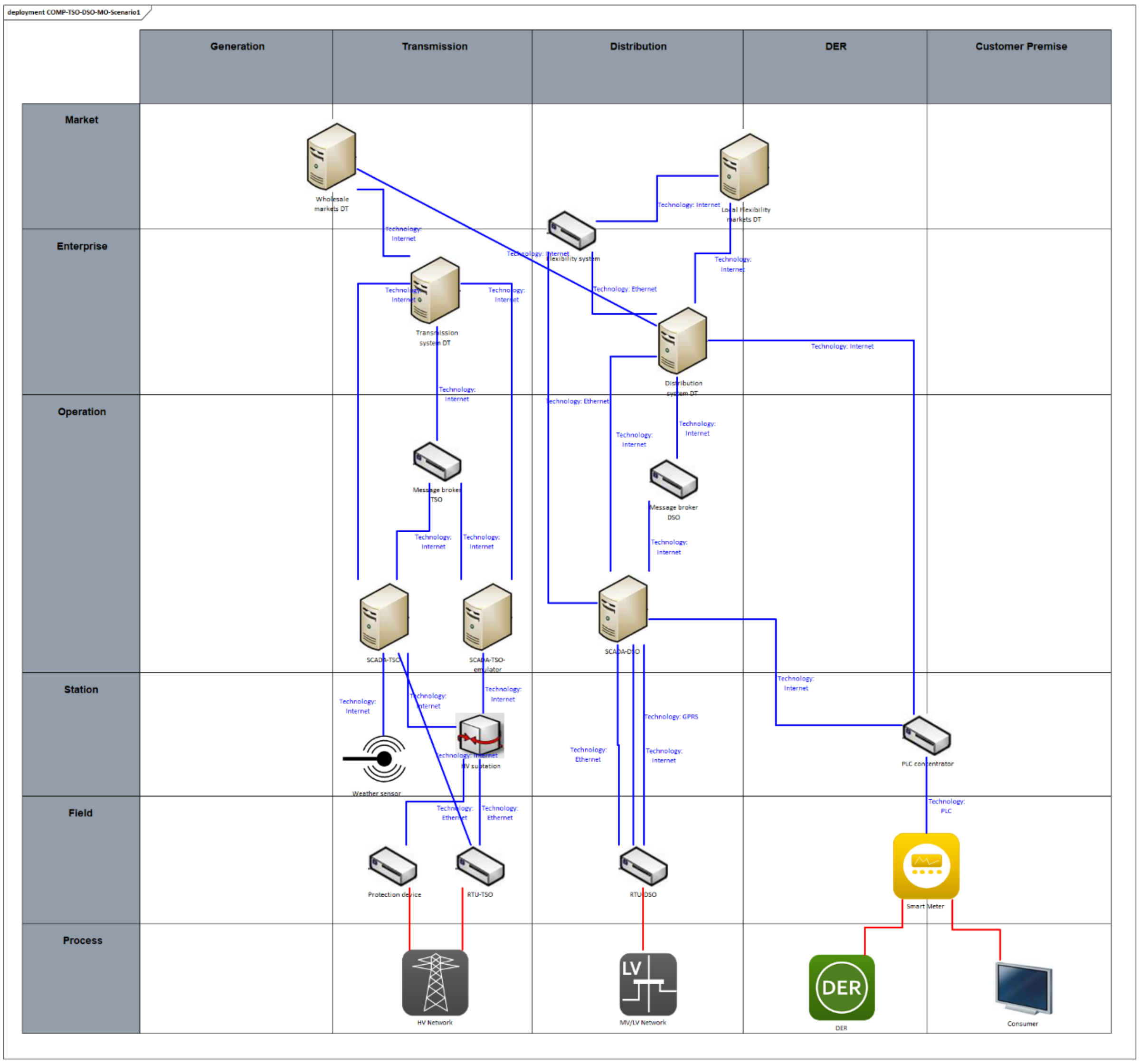


Figure 56 - TSO-DSO-MO interaction component layer

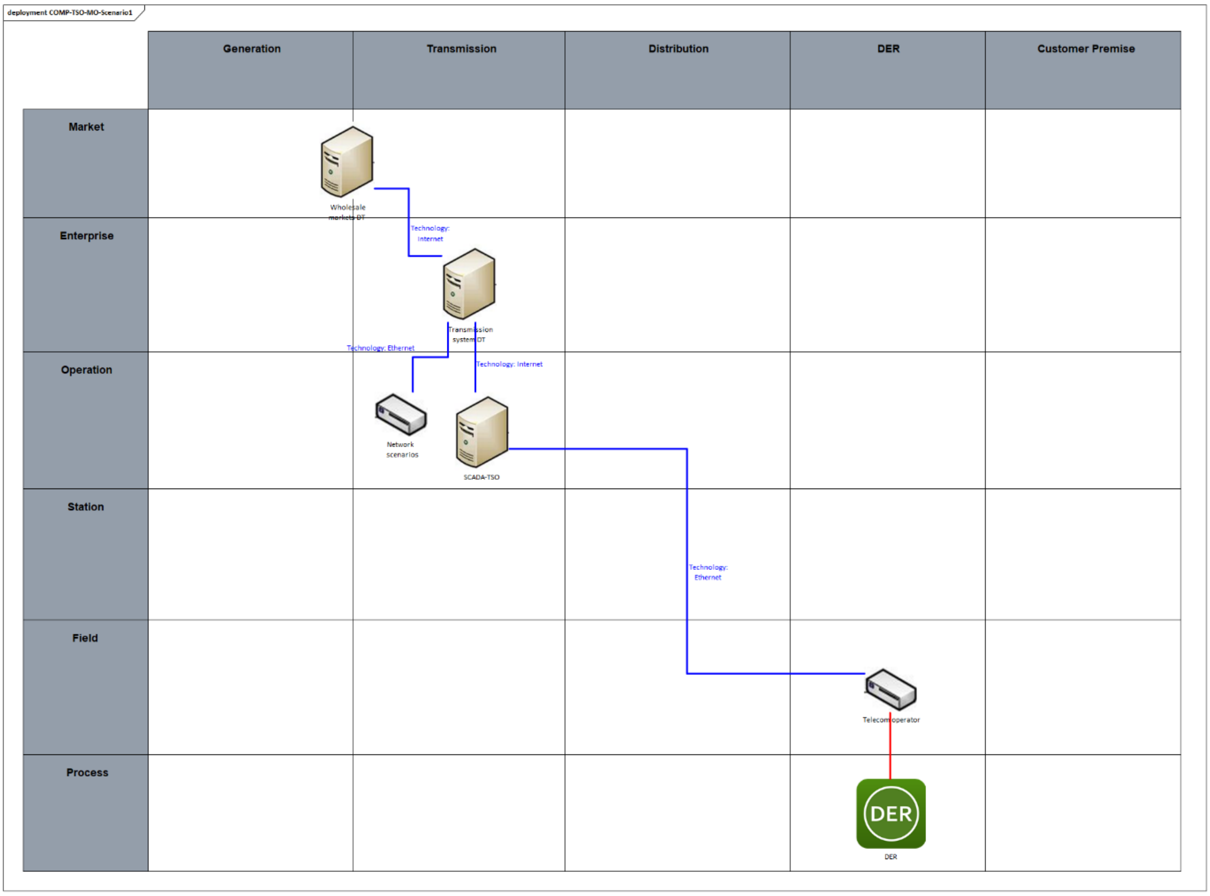


Figure 57 - TSO-MO interaction component layer

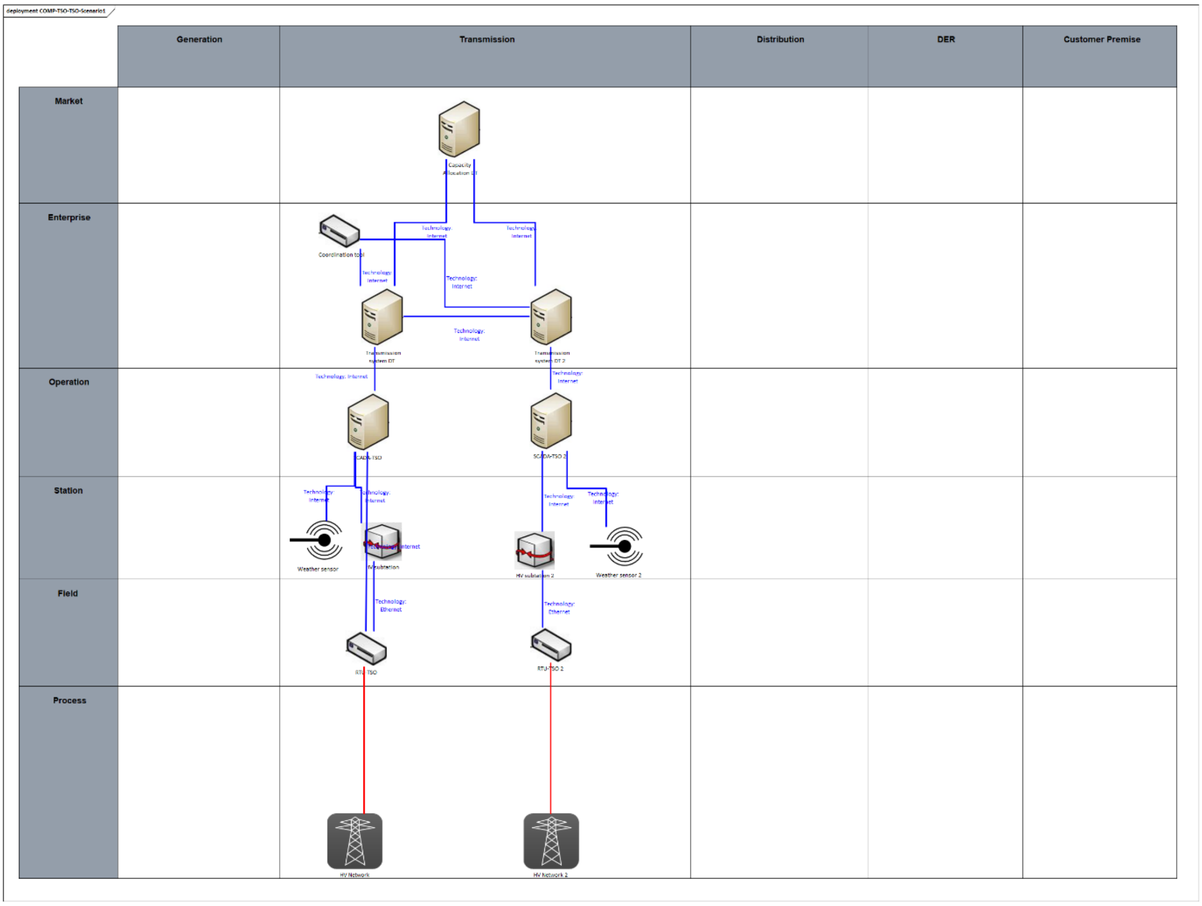


Figure 58 - TSO-TSO interaction component layer

Generalised architecture

Component layer

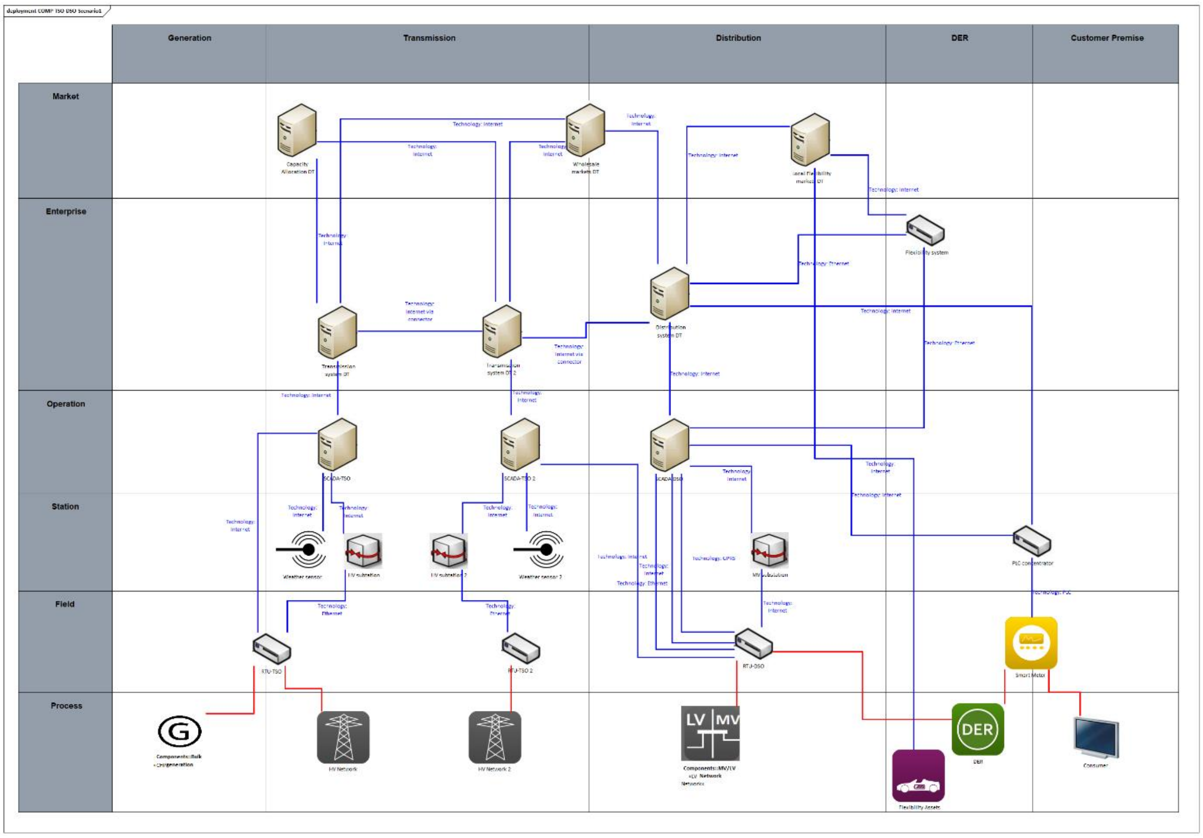


Figure 59 - Iberian Pilot Federated DT component layer

Communication layer

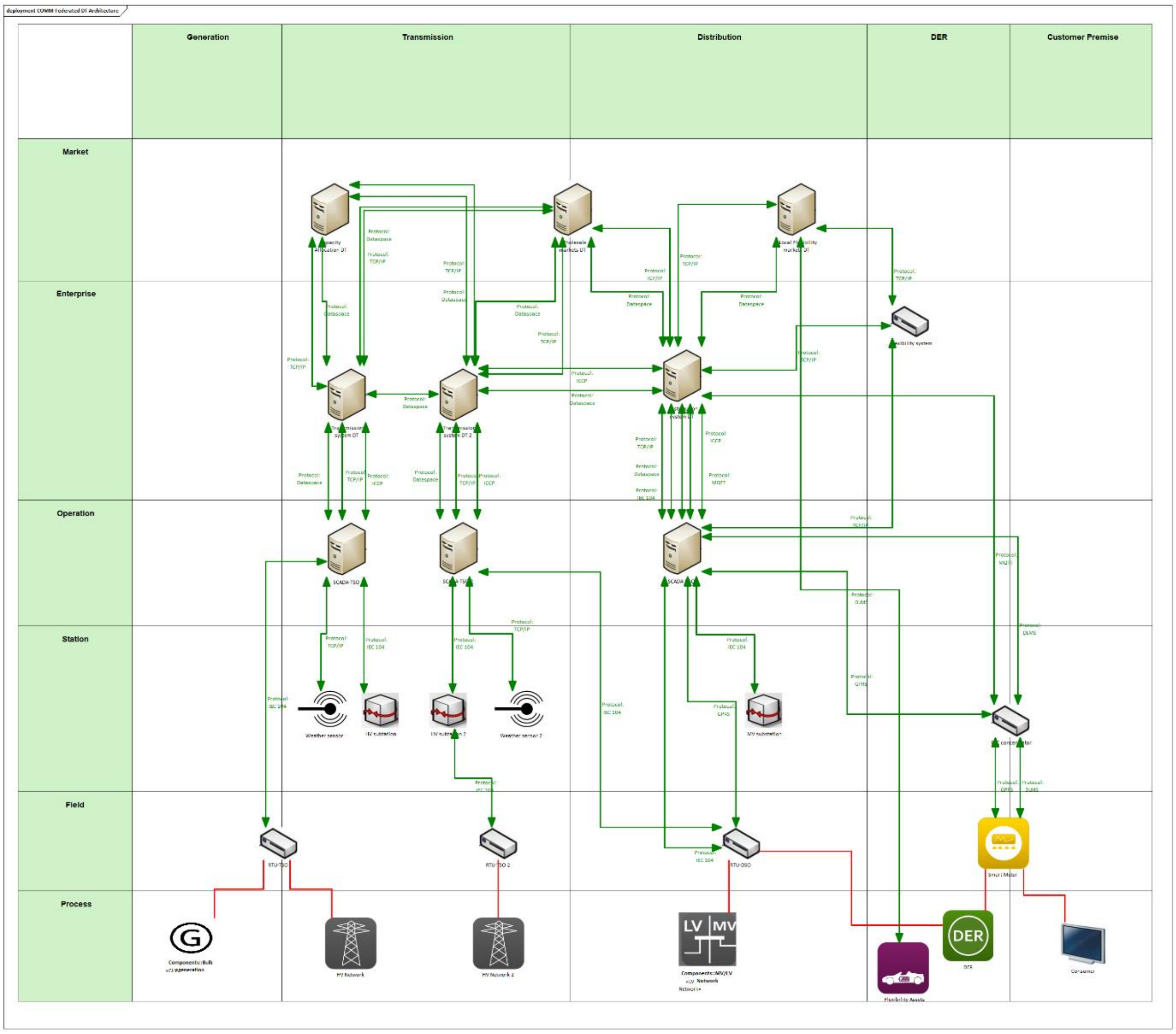


Figure 60 - Iberian Pilot Federated DT communication layer

Information layer

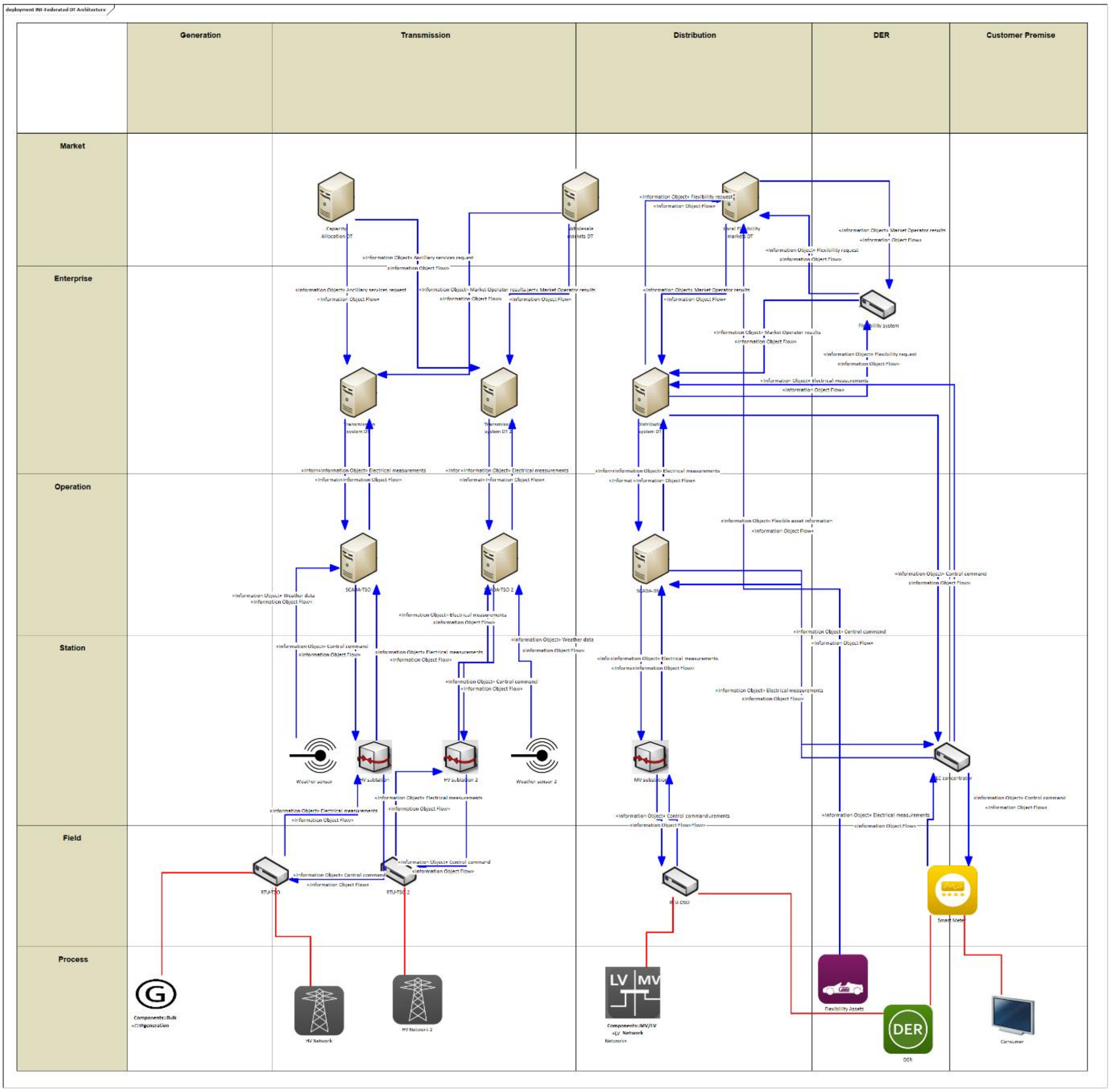


Figure 61 - Iberian Pilot Federated DT information layer

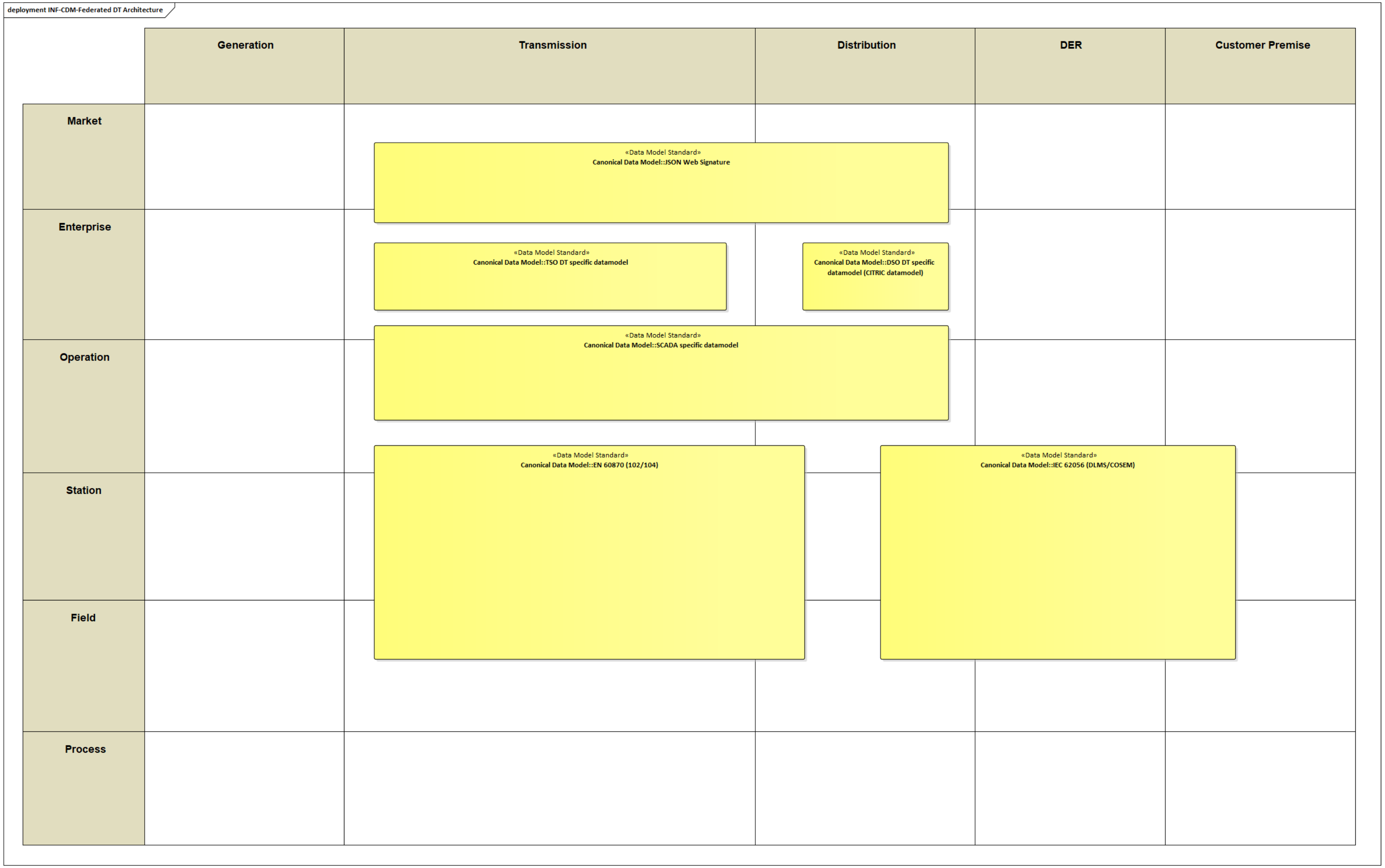


Figure 62 - Iberian Pilot Federated DT information layer - Canonical Data Model.

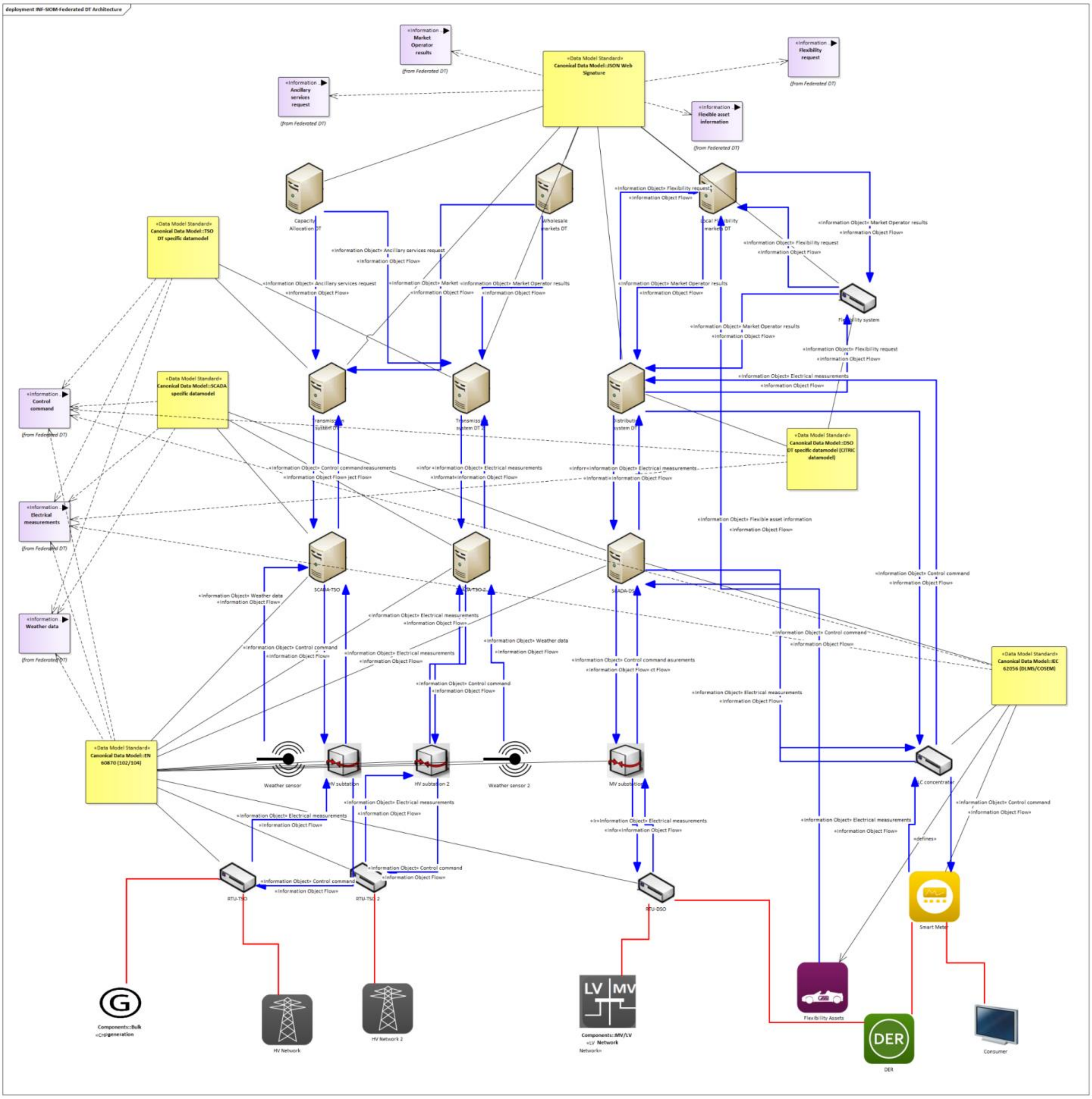


Figure 63 - Iberian Pilot Federated DT information layer - Standard and Information Object Mapping

D.2 Second generalised architecture using TwinEU pilots' contributions

Eastern Mediterranean region pilot

Component layer

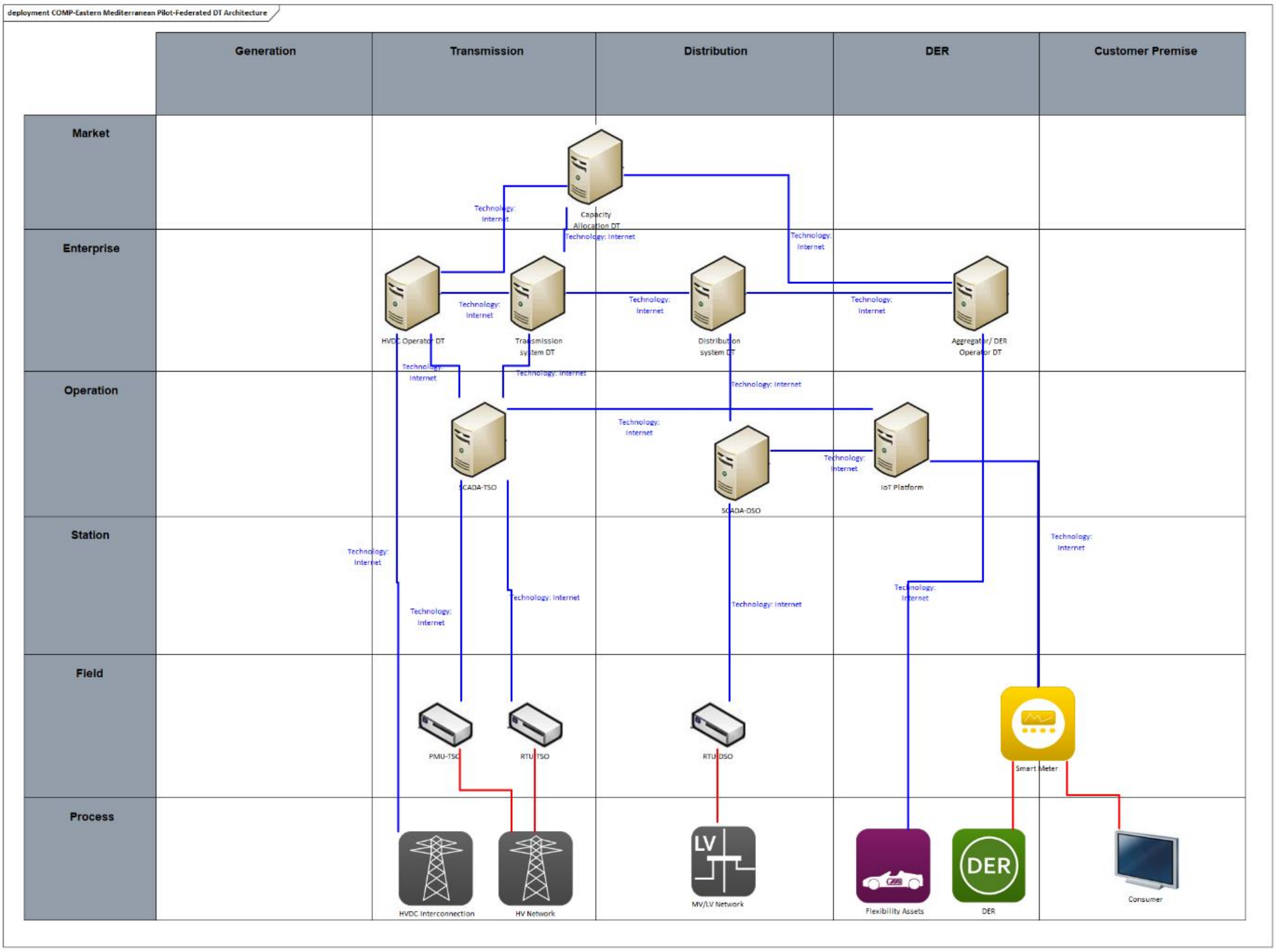


Figure 64 - Eastern Mediterranean region pilot component layer

Communication layer

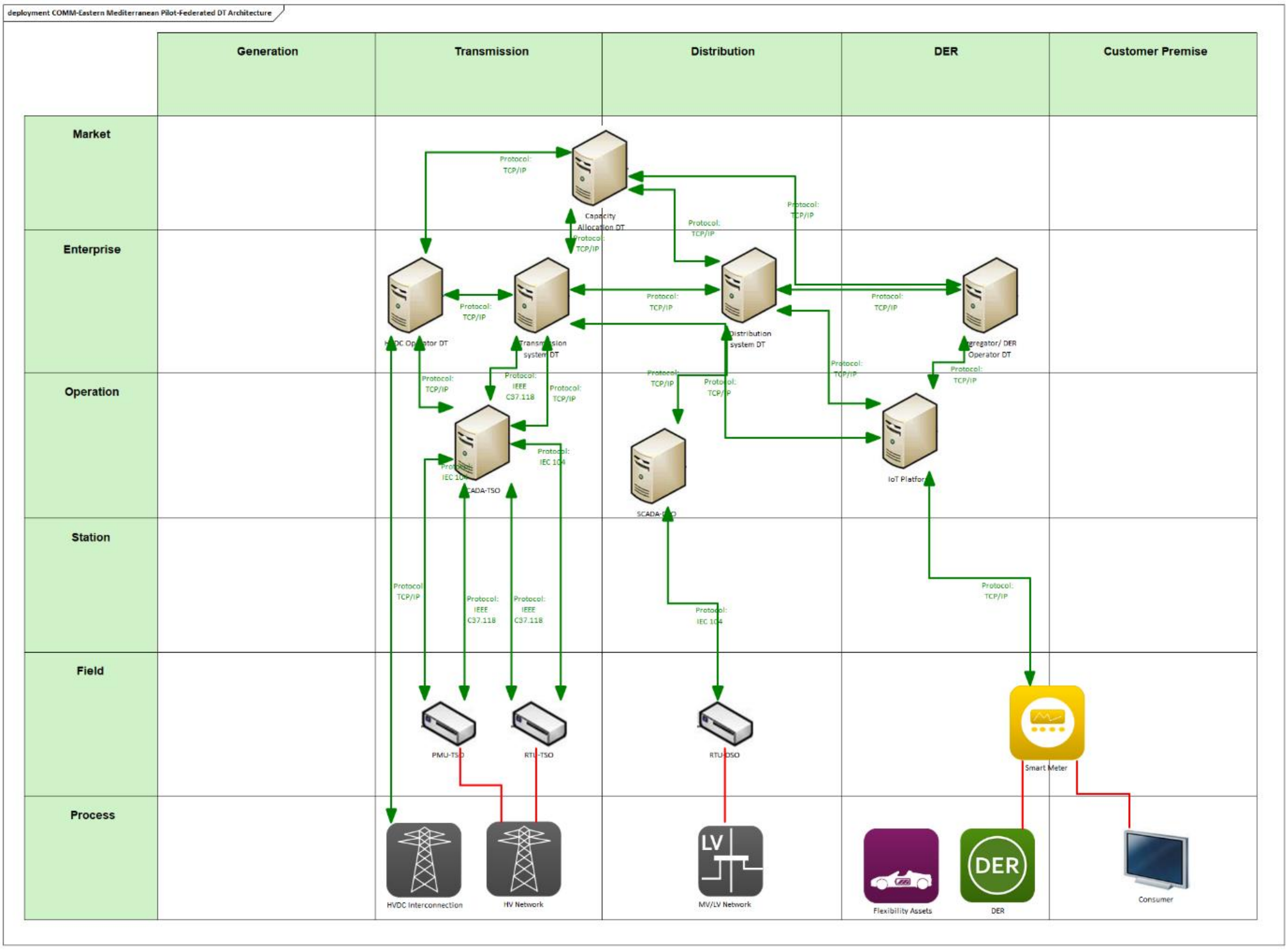


Figure 65 - Eastern Mediterranean region pilot communication layer

Information layer

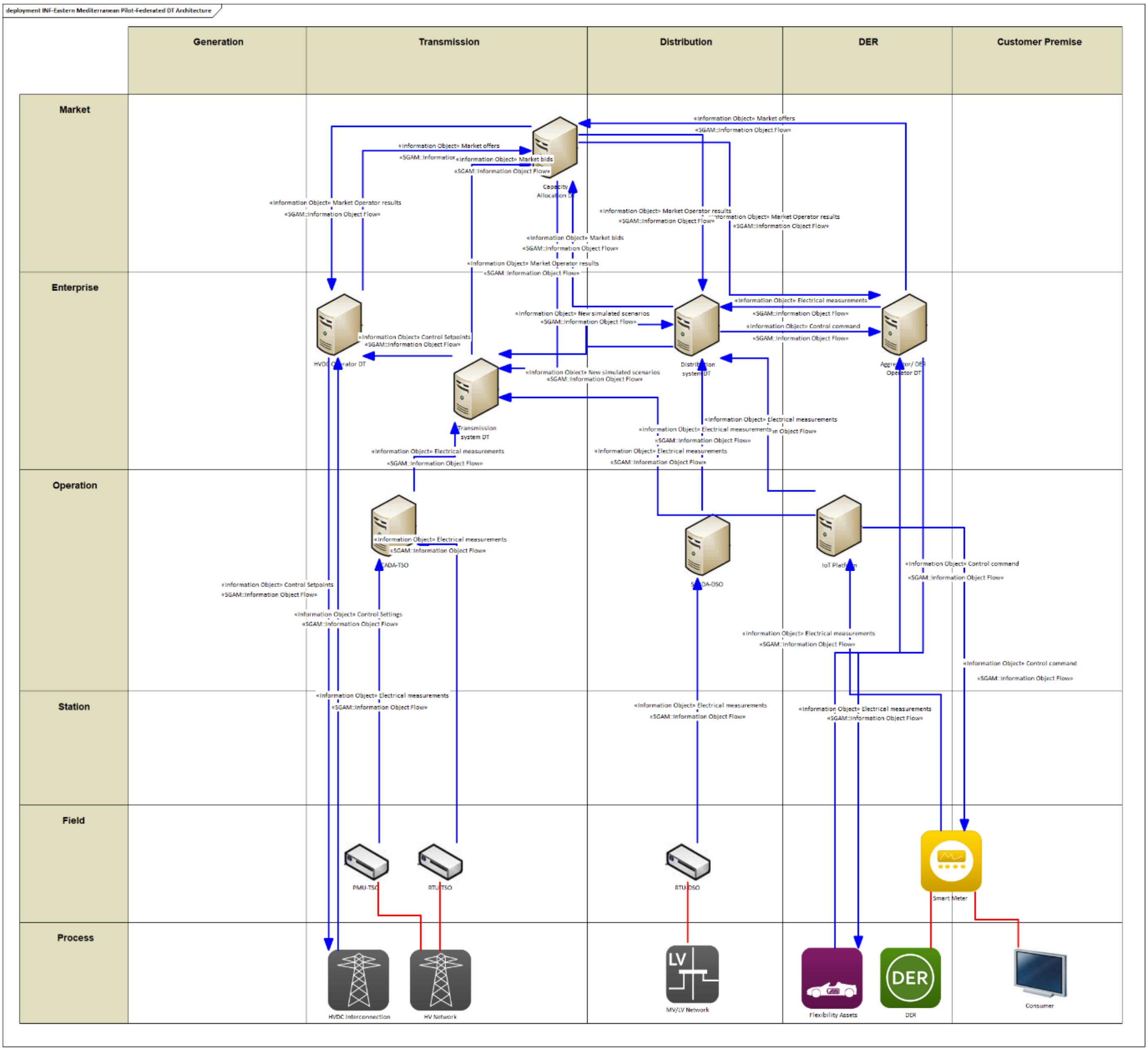


Figure 66 - Eastern Mediterranean region pilot information layer

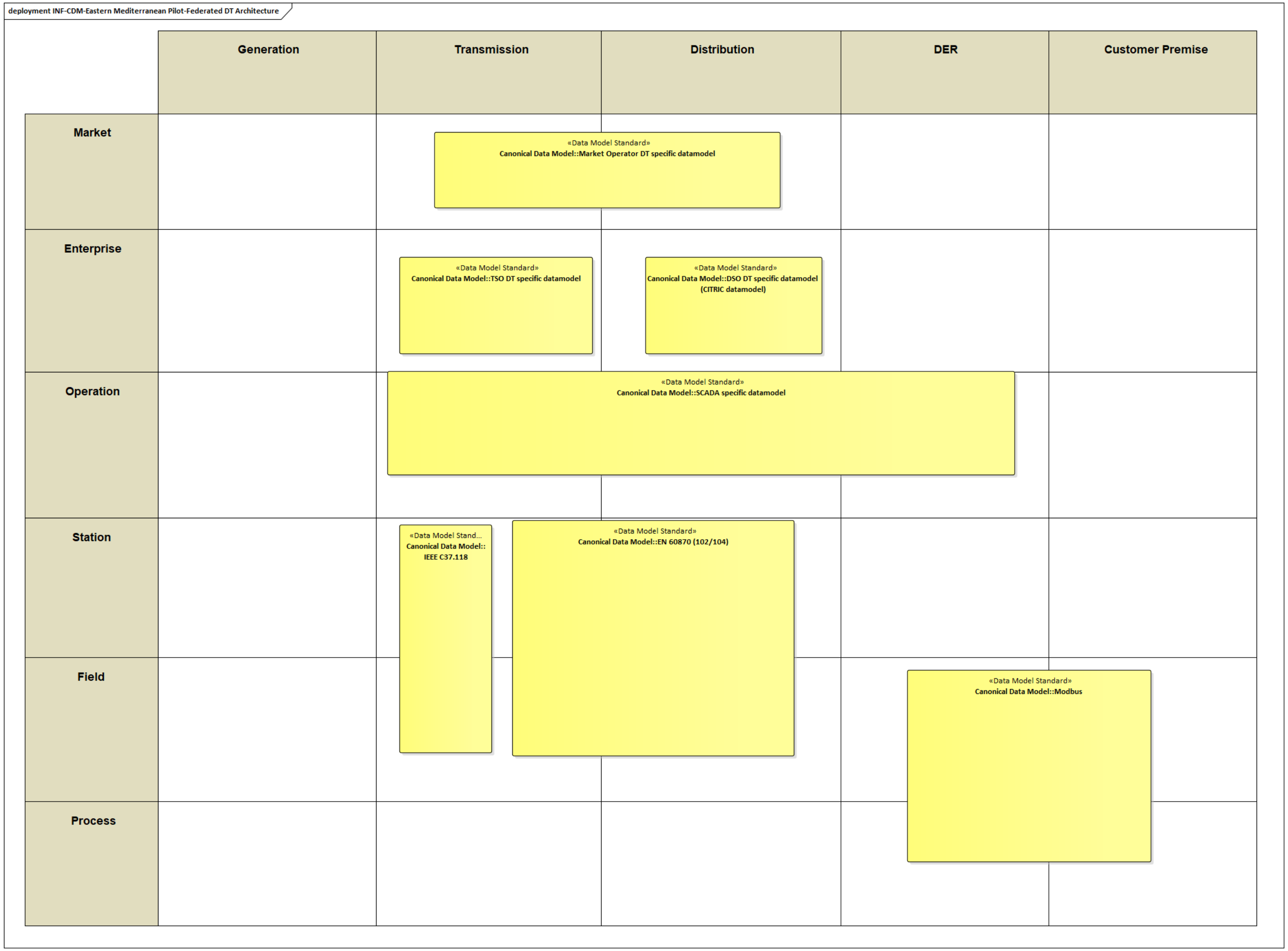


Figure 67 - Eastern Mediterranean region pilot information layer - Canonical Data Model.

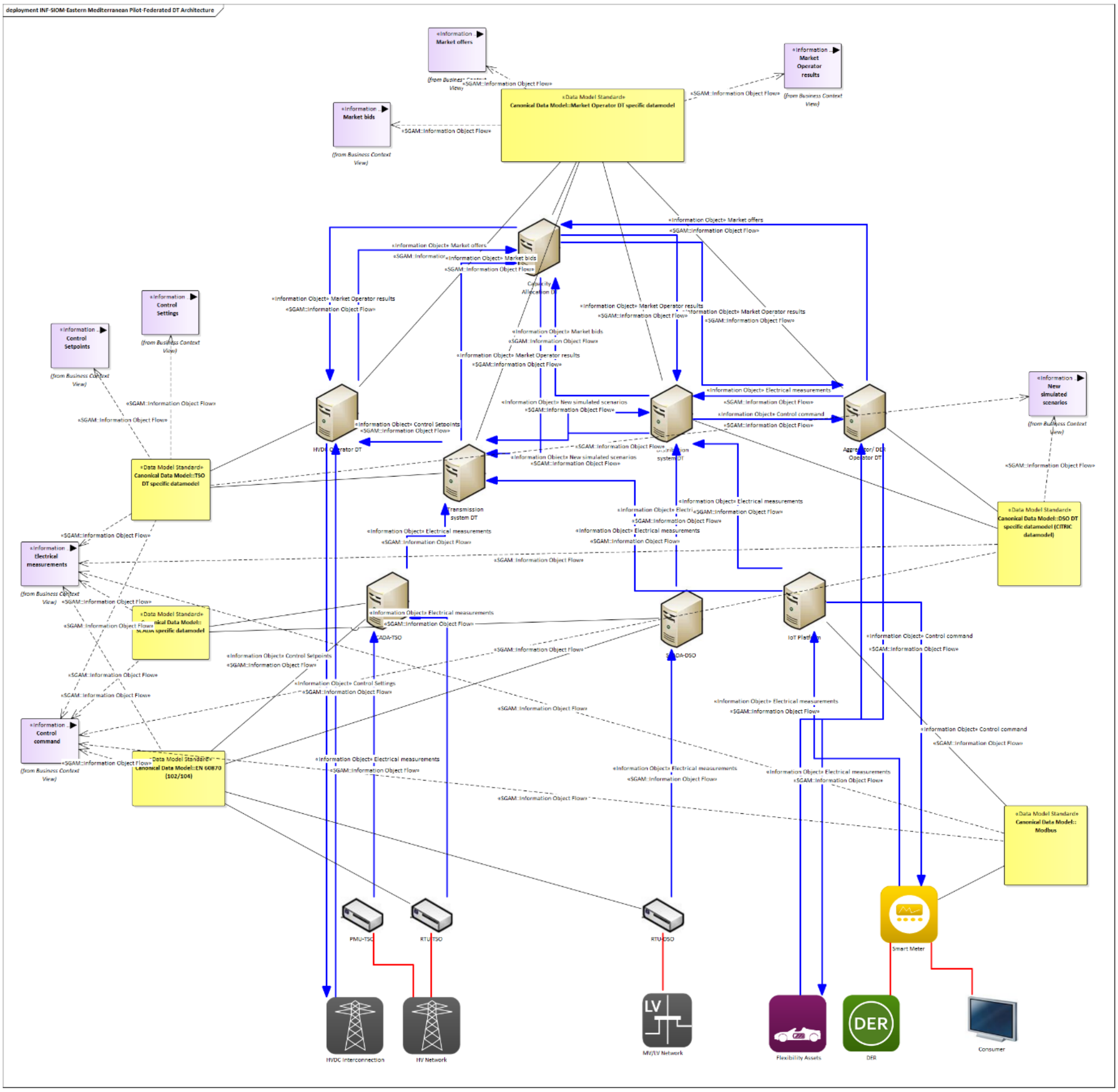


Figure 68 - Eastern Mediterranean region pilot information layer - Standard and Information Object Mapping.

Bulgarian pilot

Component layer

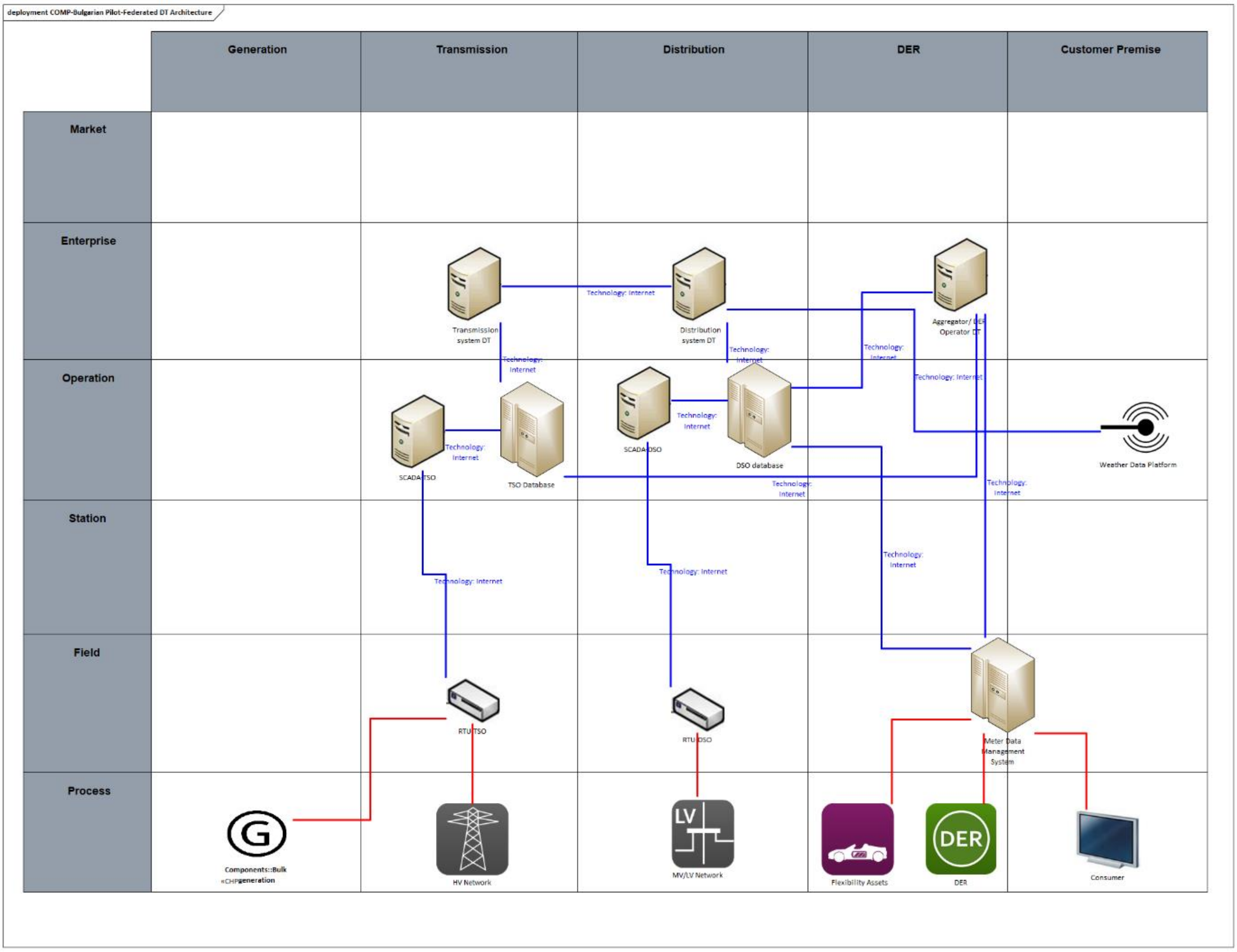


Figure 69 - Bulgarian pilot component layer

Communication layer

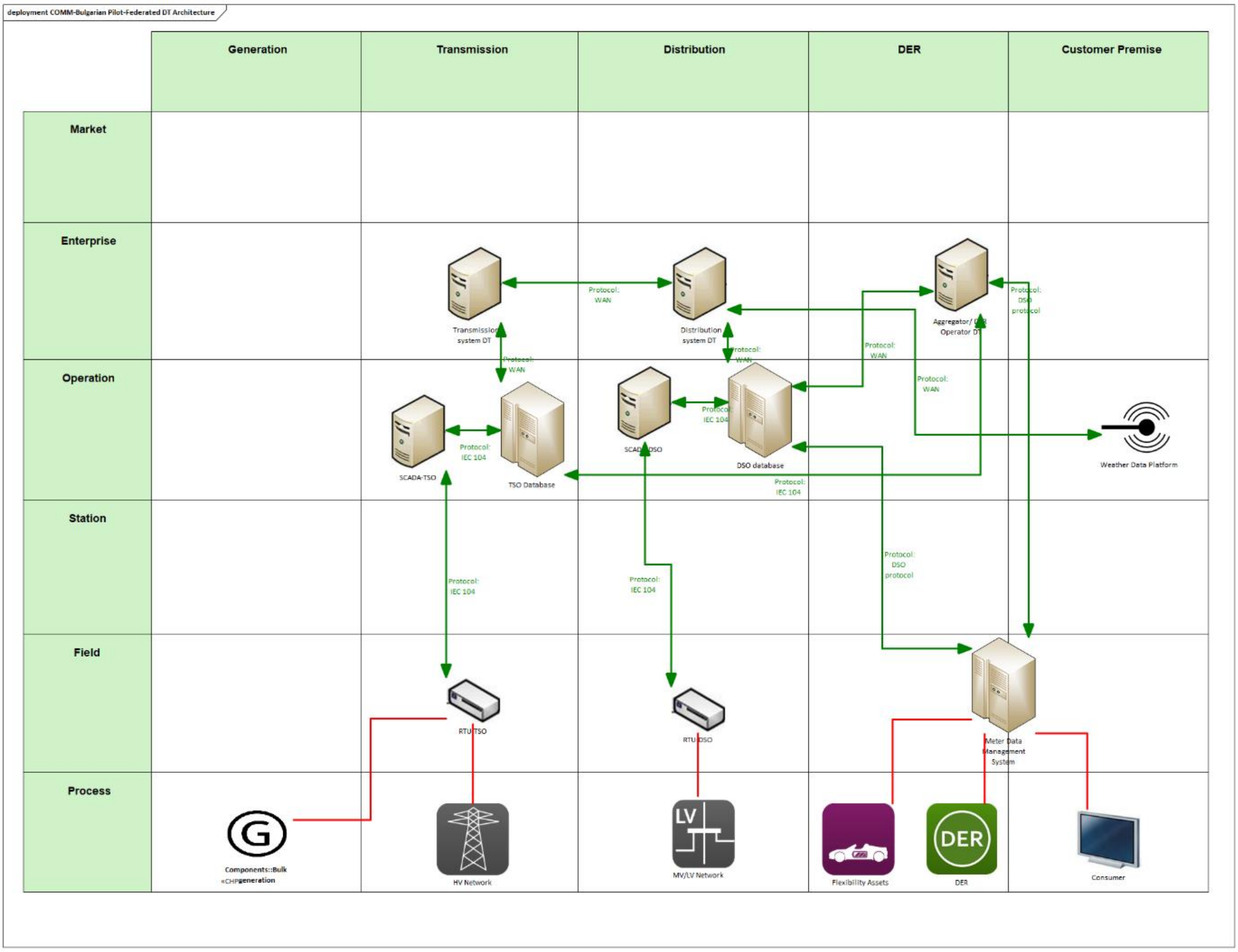


Figure 70 - Bulgarian pilot communication layer

Information layer

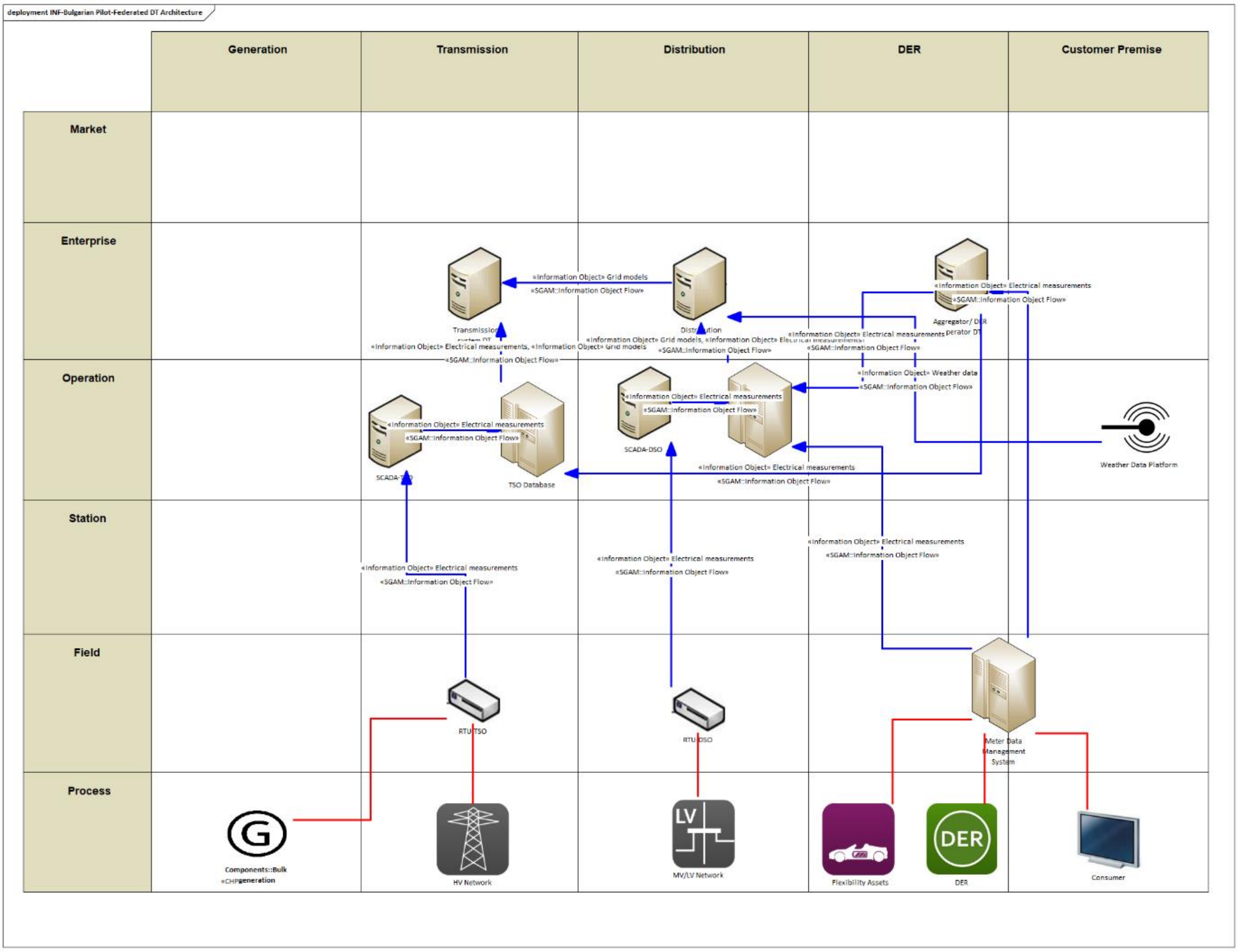


Figure 71 - Bulgarian pilot information layer

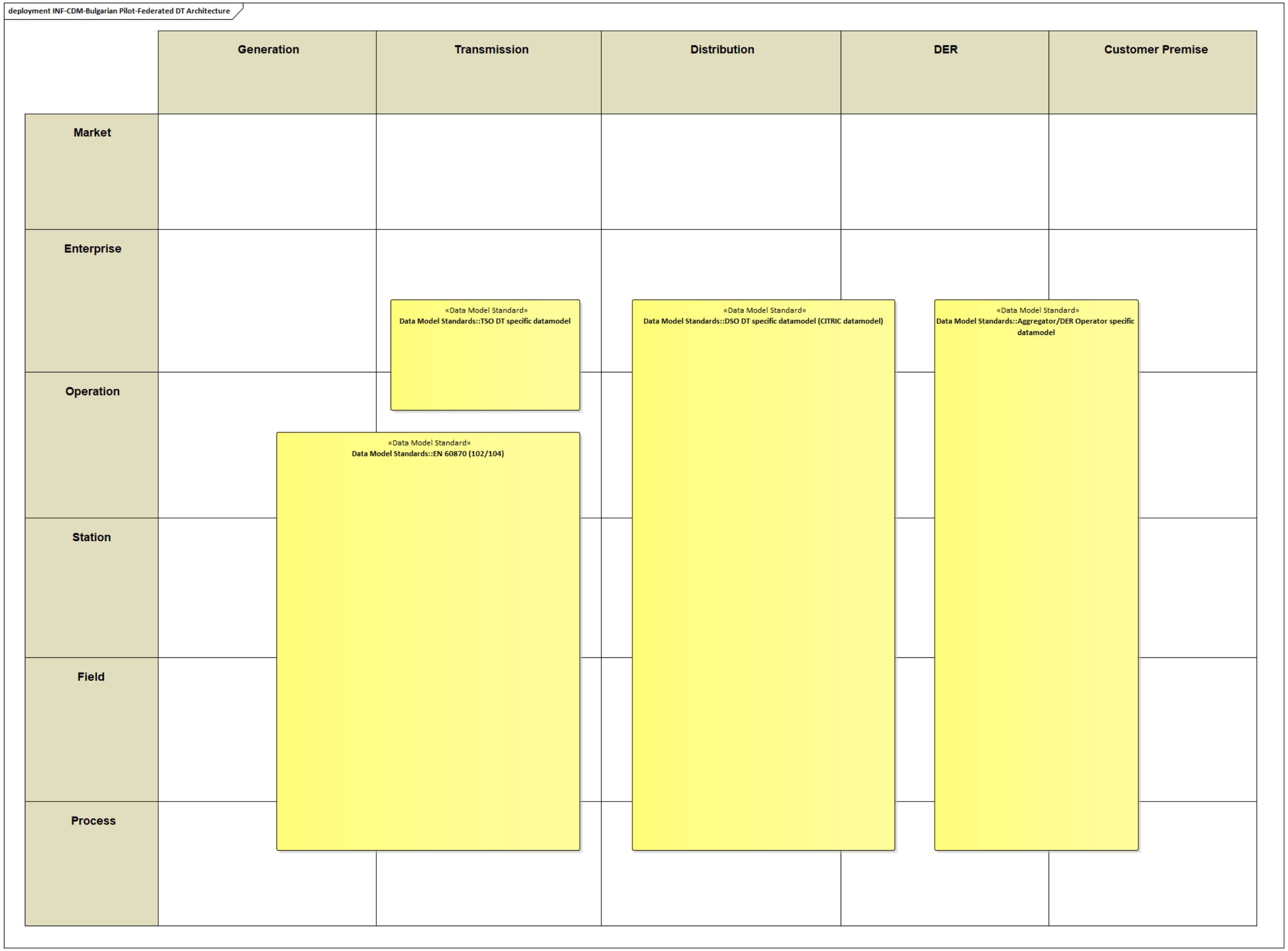


Figure 72 - Bulgarian pilot information layer - Canonical Data Model.

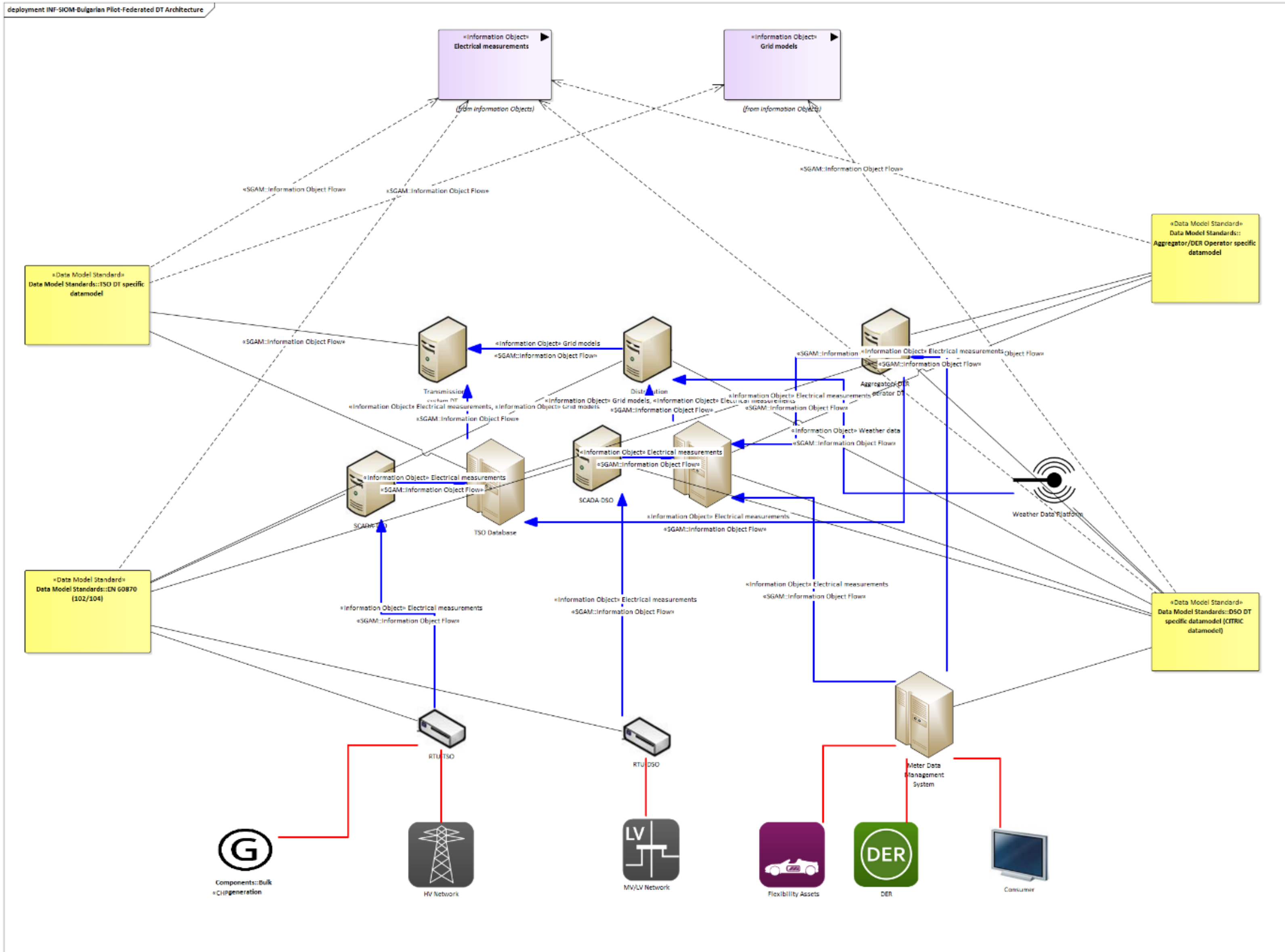


Figure 73 - Bulgarian pilot information layer - Standard and Information Object Mapping.

German pilot

Component layer

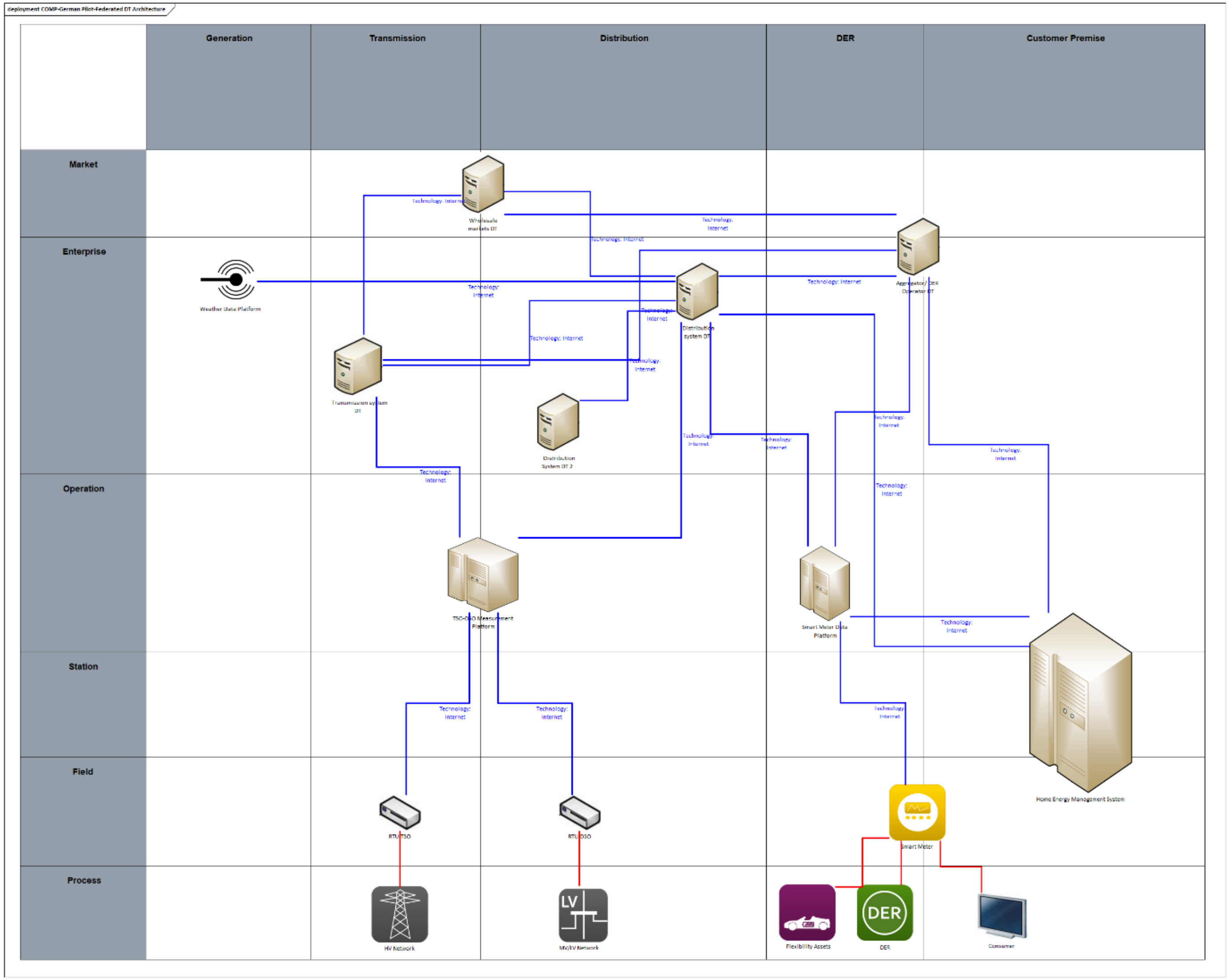


Figure 74 - German pilot component layer.

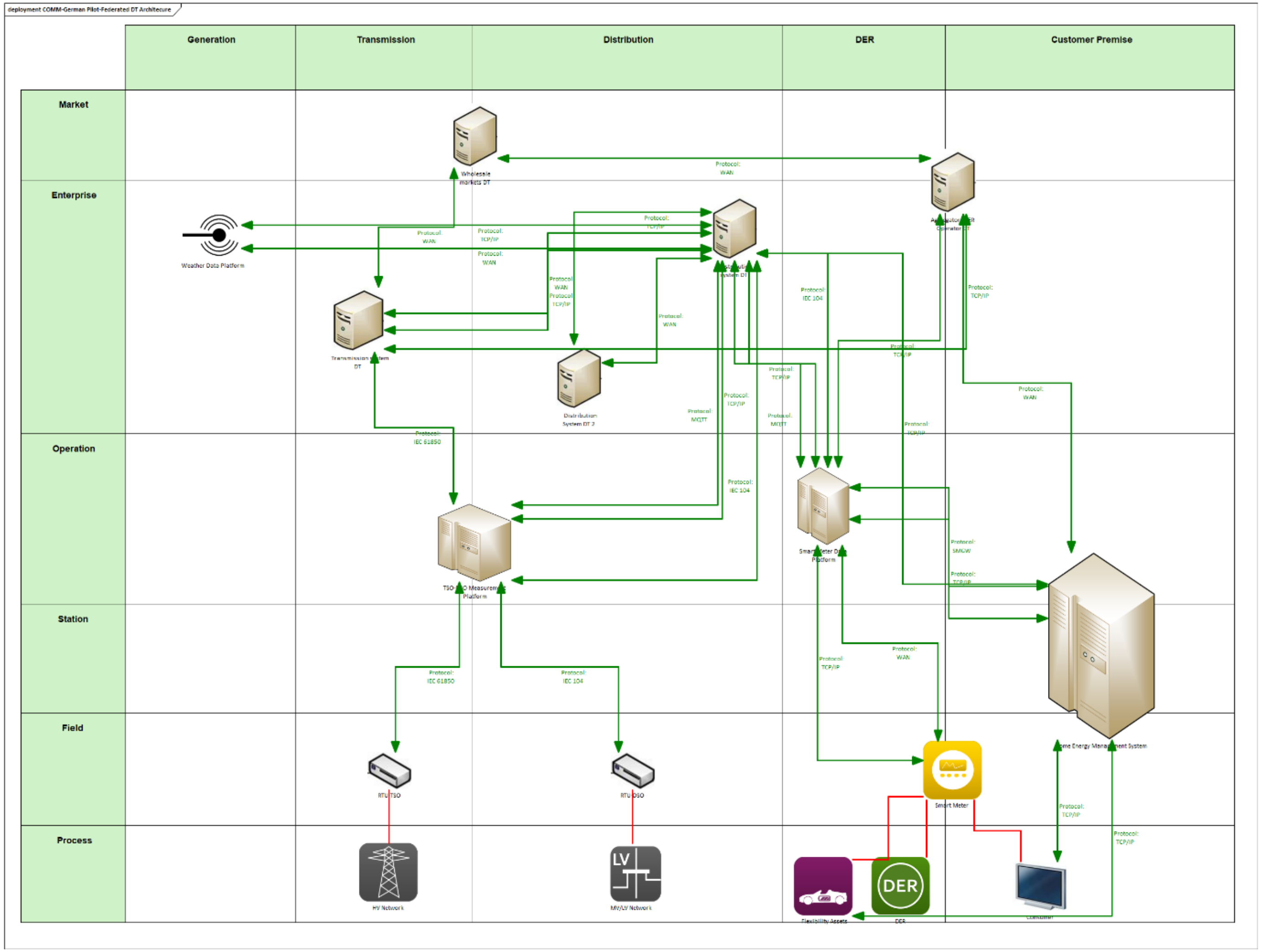


Figure 75 - German pilot communication layer

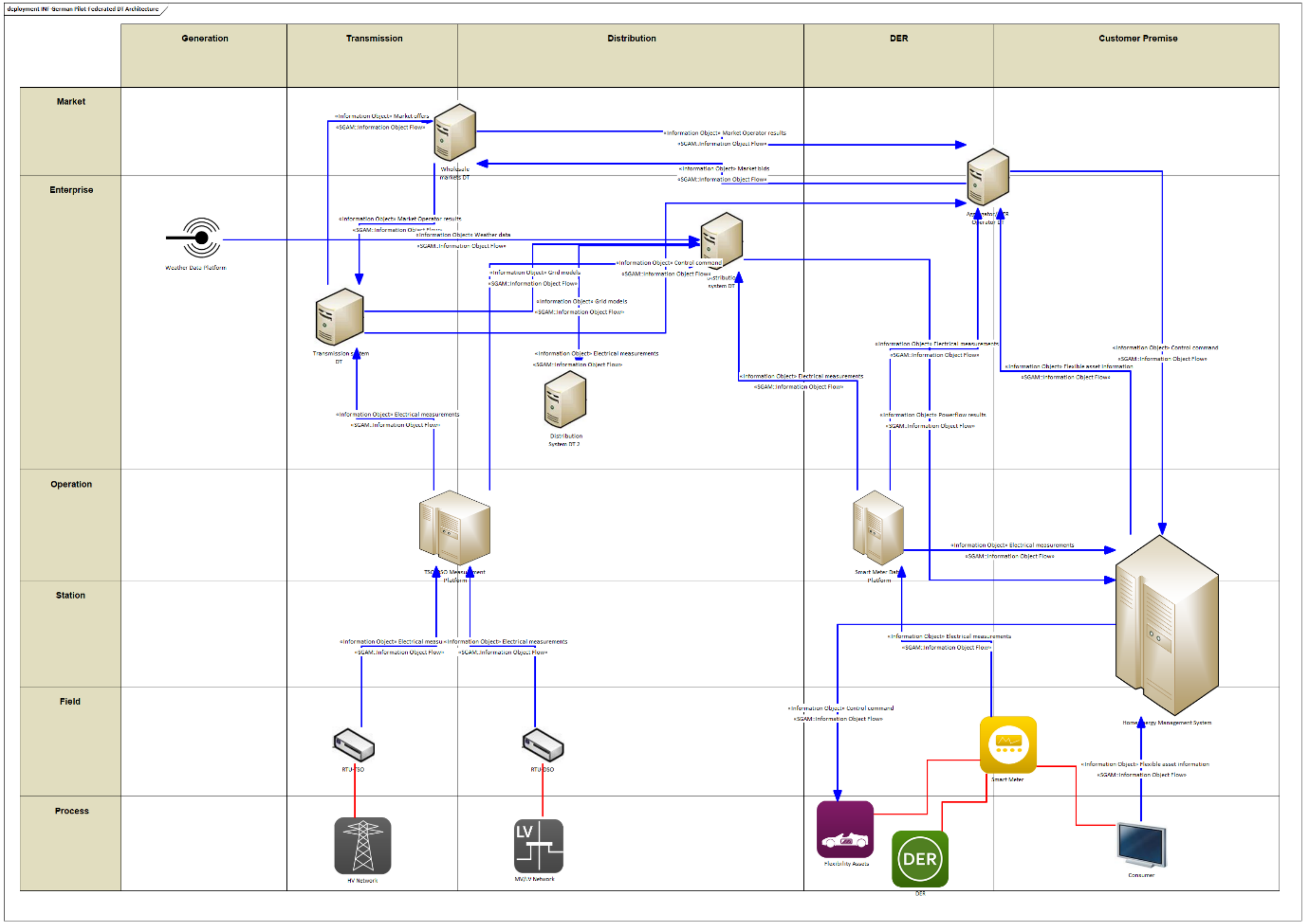


Figure 76 - German pilot information layer.

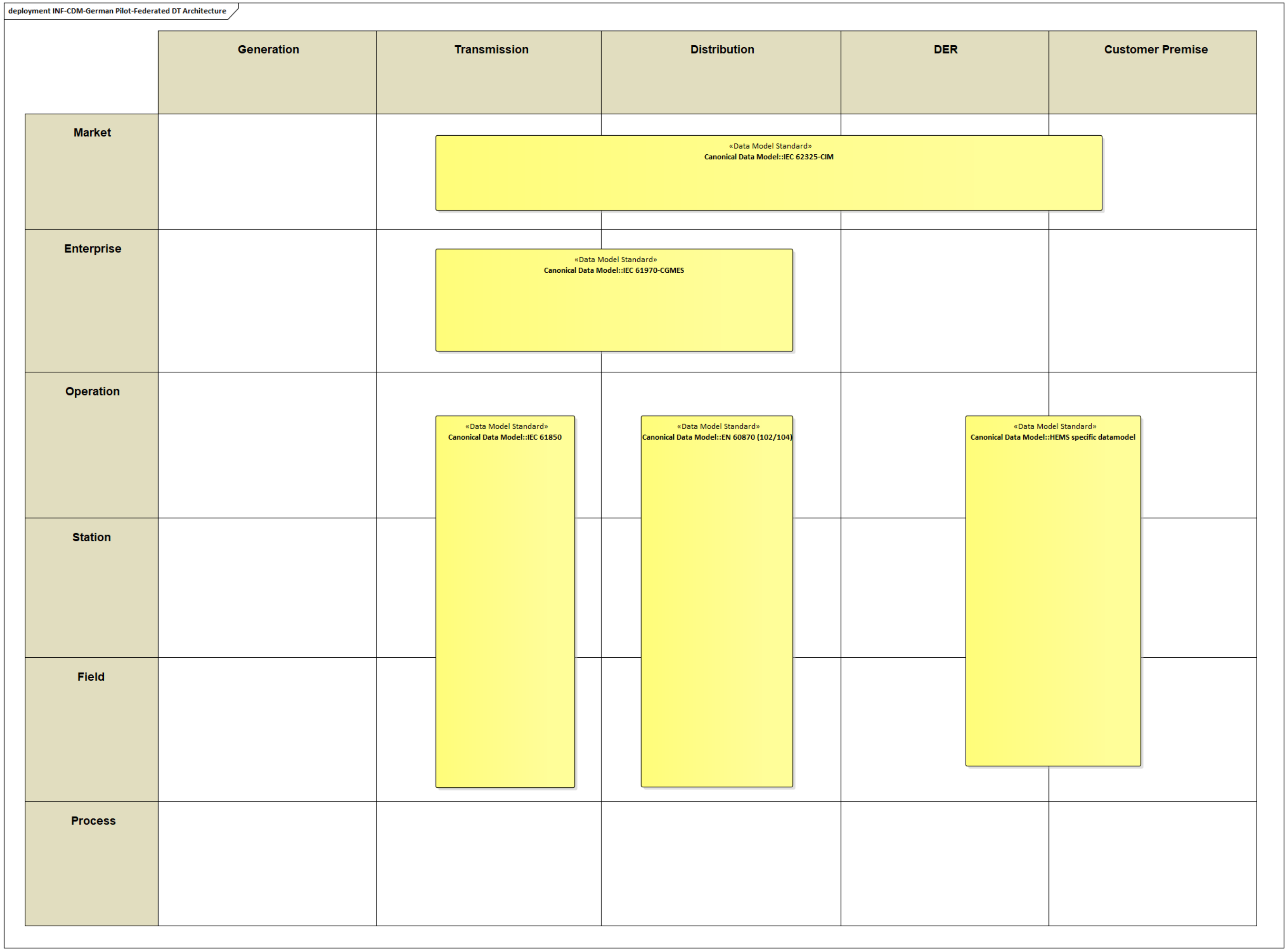


Figure 77 - German pilot information layer - Canonical Data Model

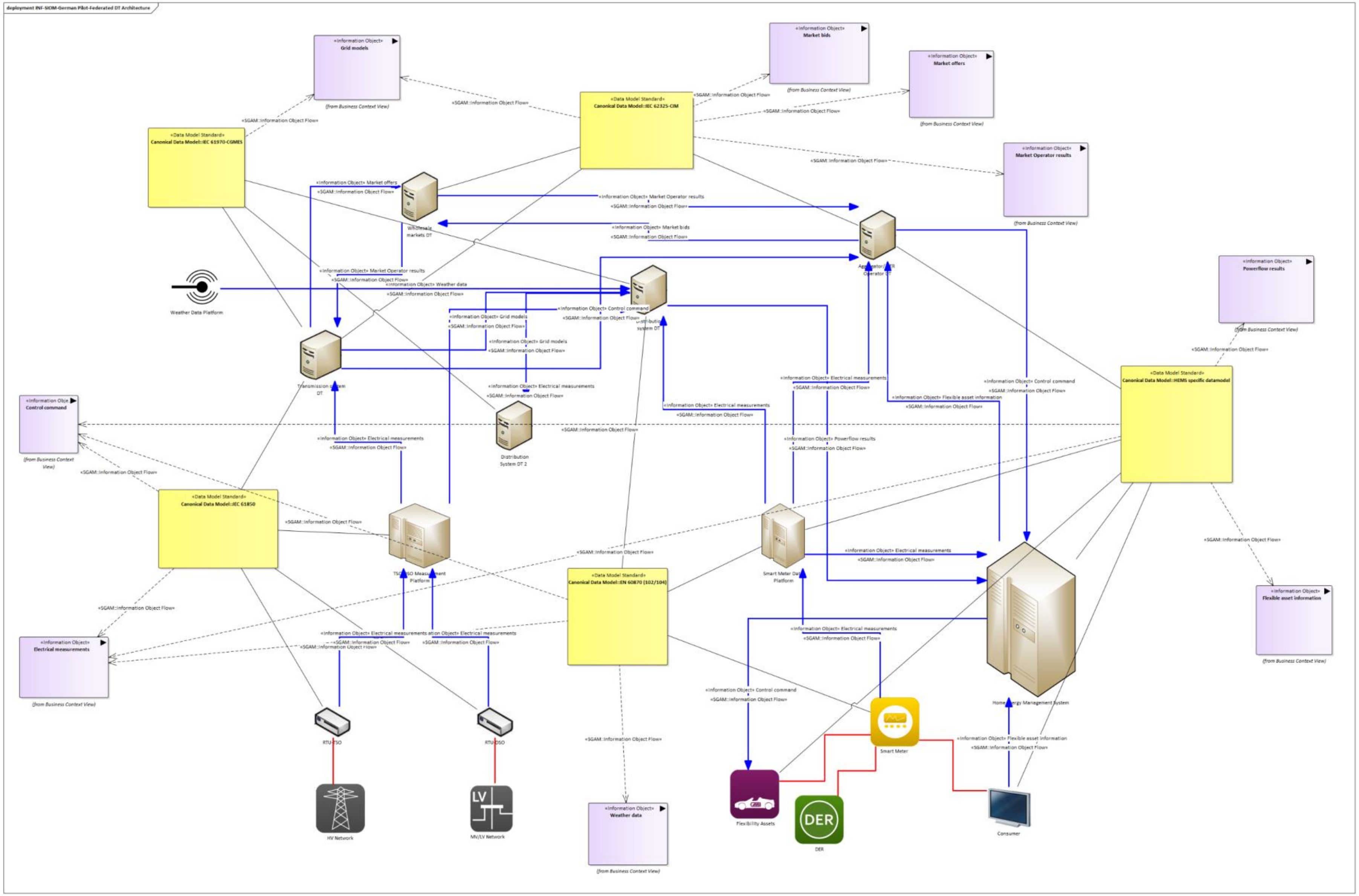


Figure 78 - German pilot information layer - Standard and Information Object Mapping

Italian pilot

Component layer

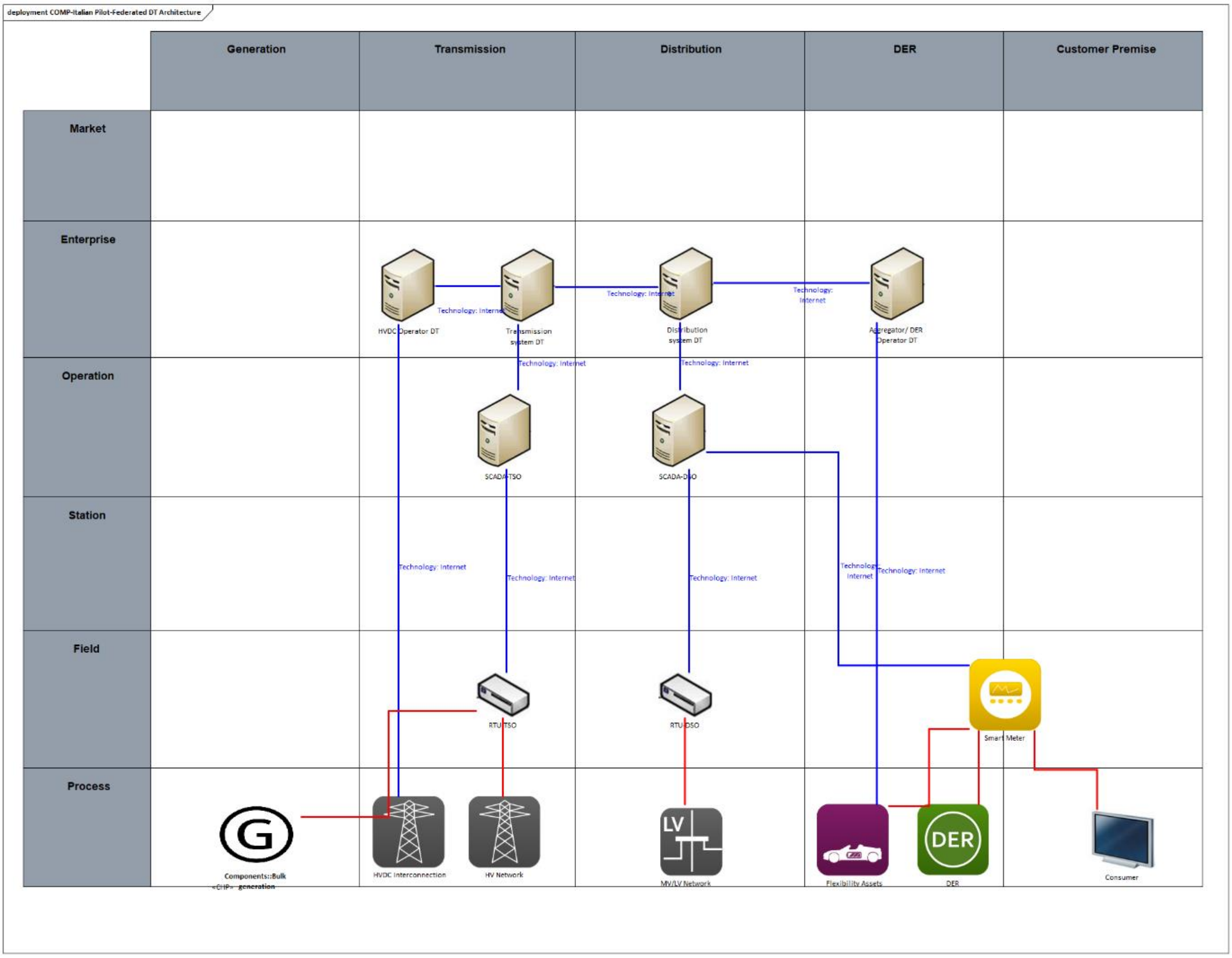


Figure 79 - Italian pilot component layer

Slovenian pilot

Component layer

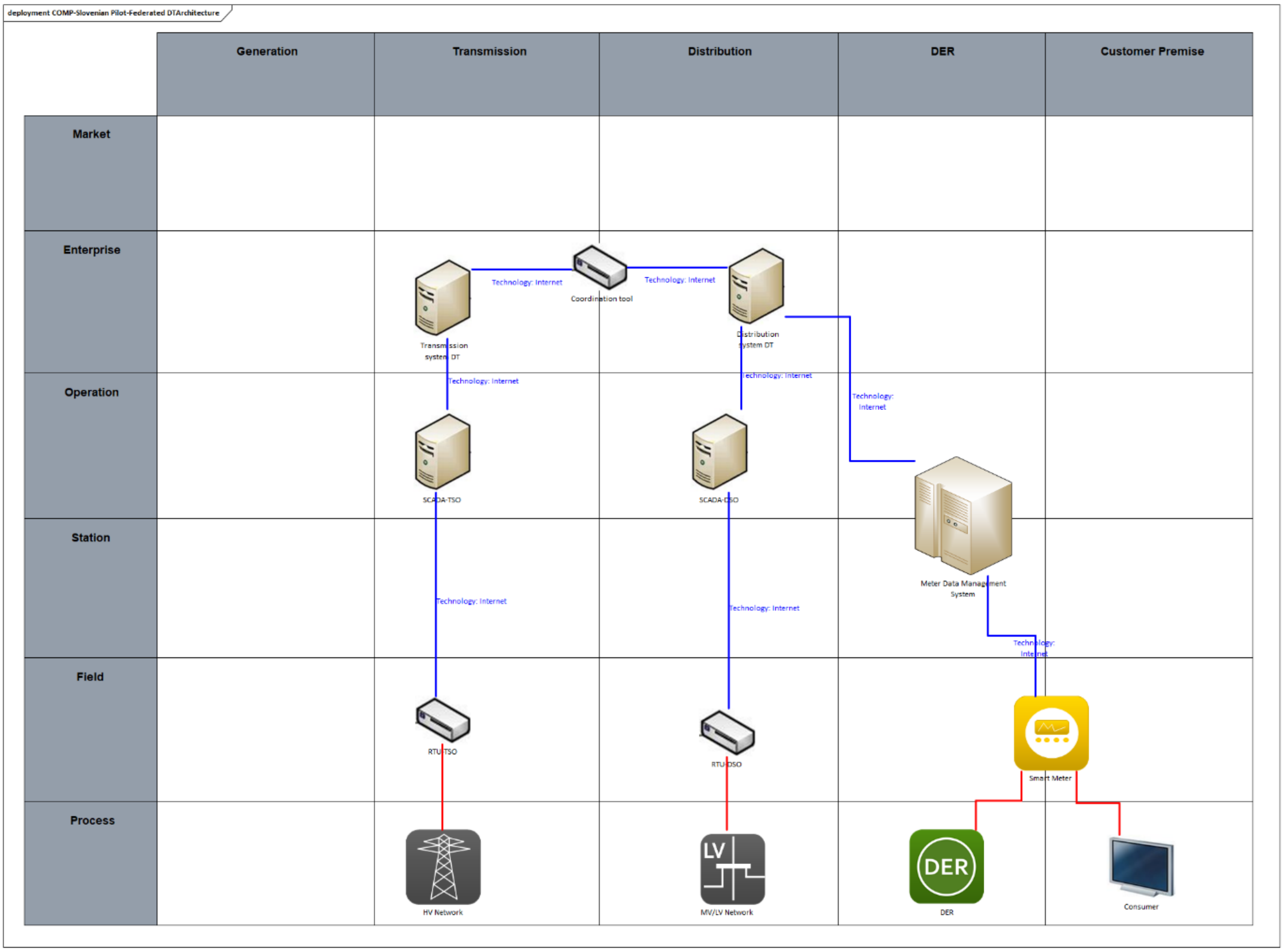


Figure 80 - Slovenian pilot component layer

Communication layer

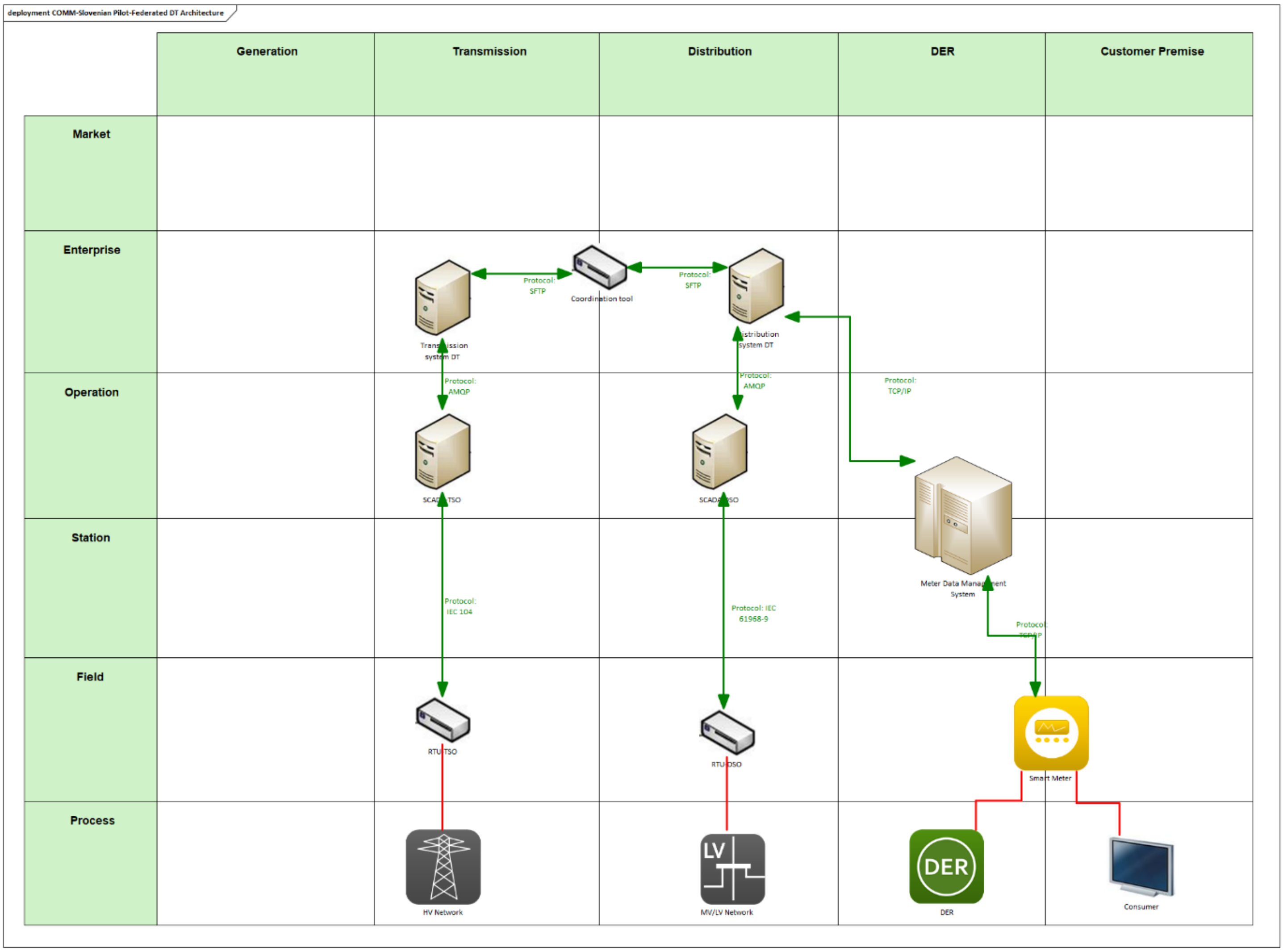


Figure 81 - Slovenian pilot communication layer

Information layer

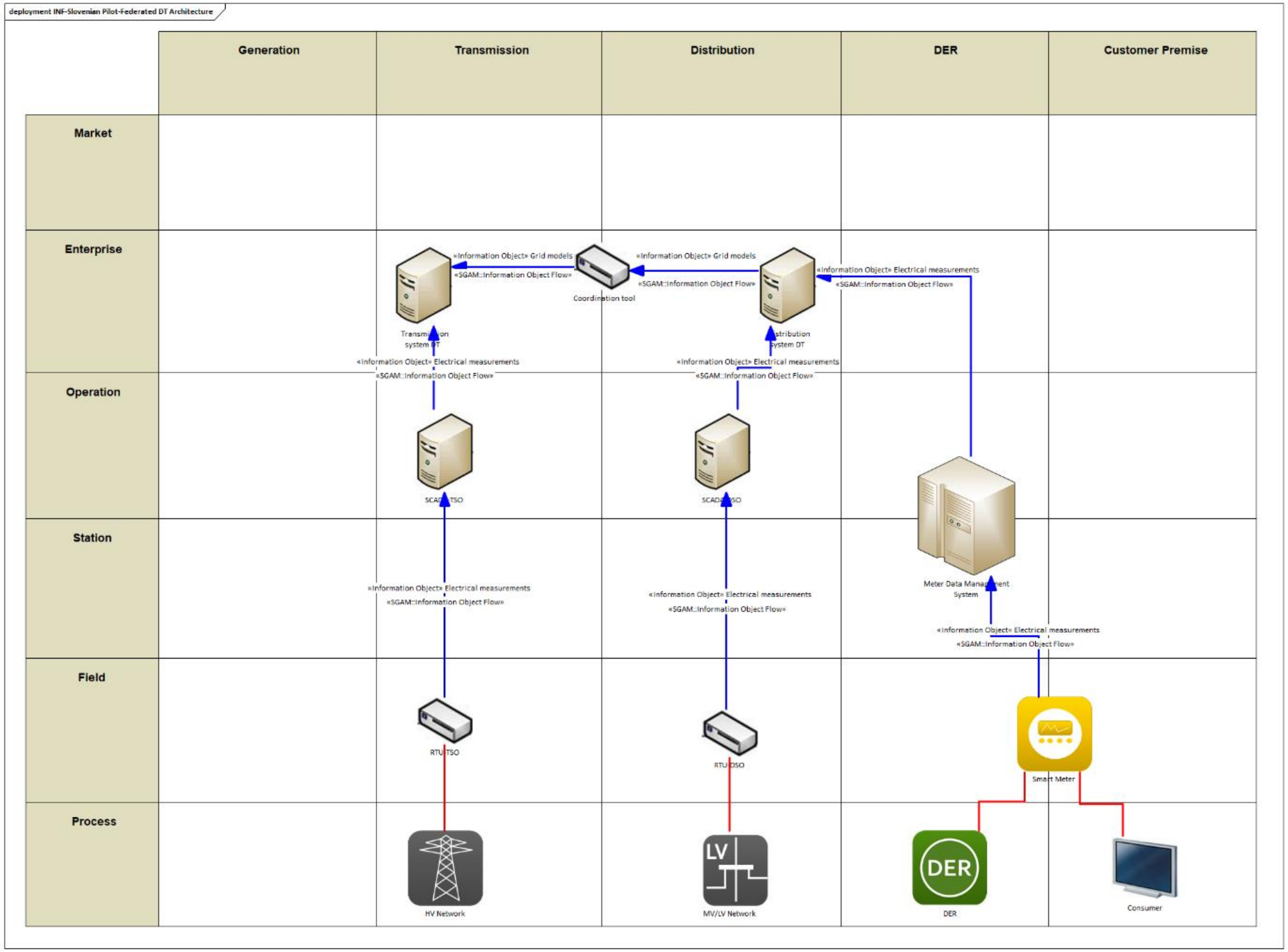


Figure 82 - Slovenian pilot information layer

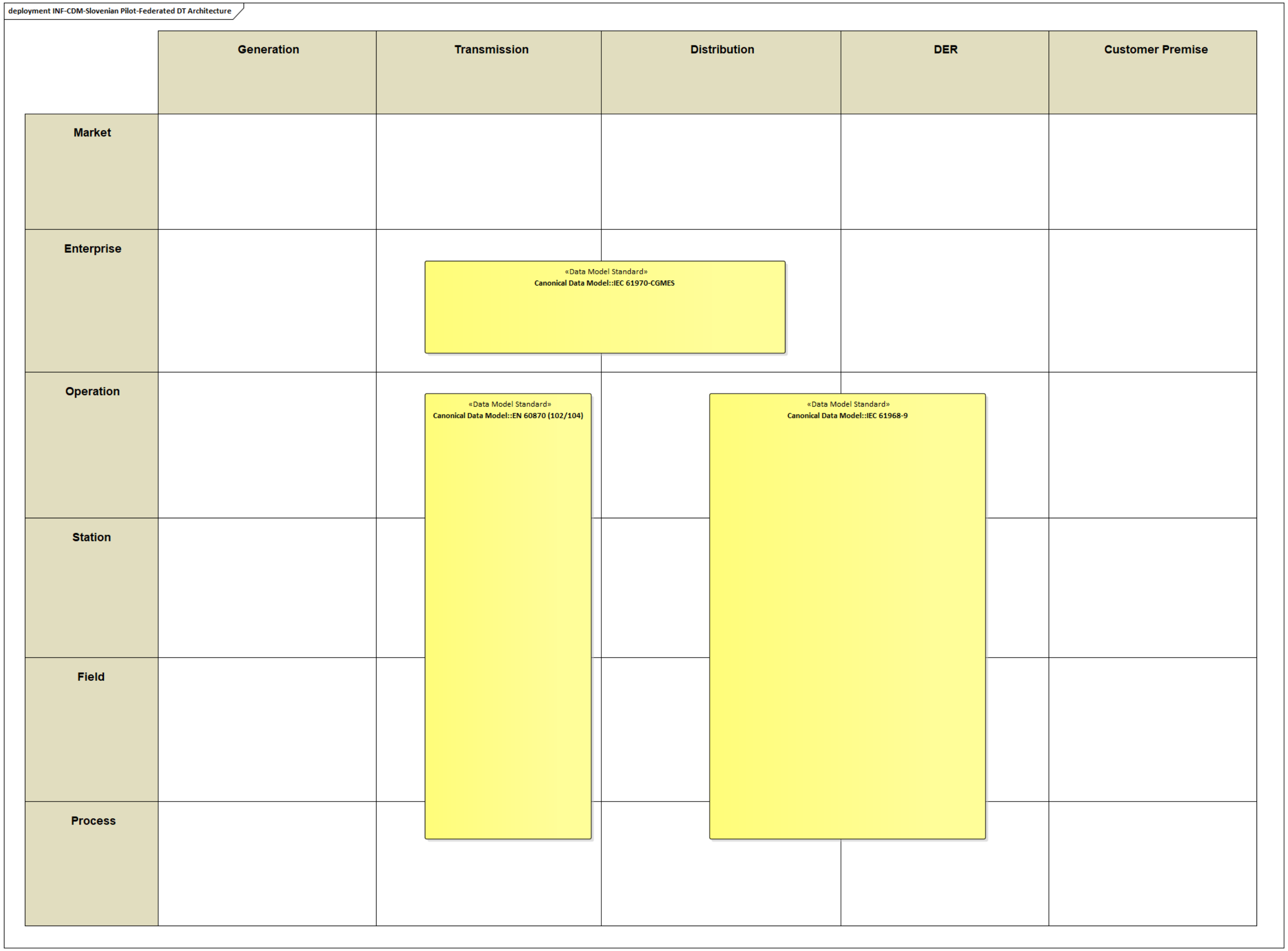


Figure 83 - Slovenian pilot information layer - Canonical Data Model

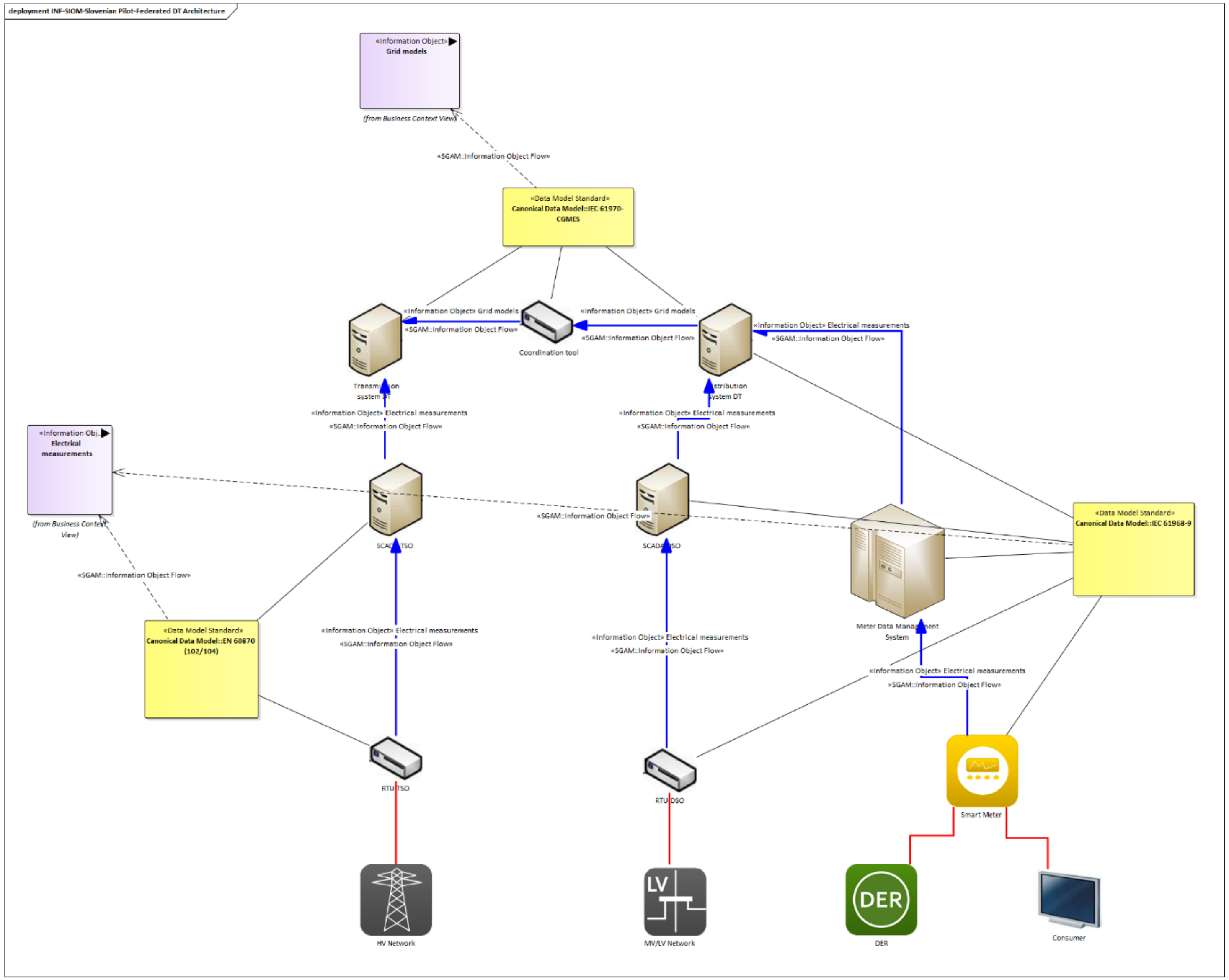


Figure 84 - Slovenian pilot information layer - Standard and Information Object Mapping.

French Dutch pilot

Component layer

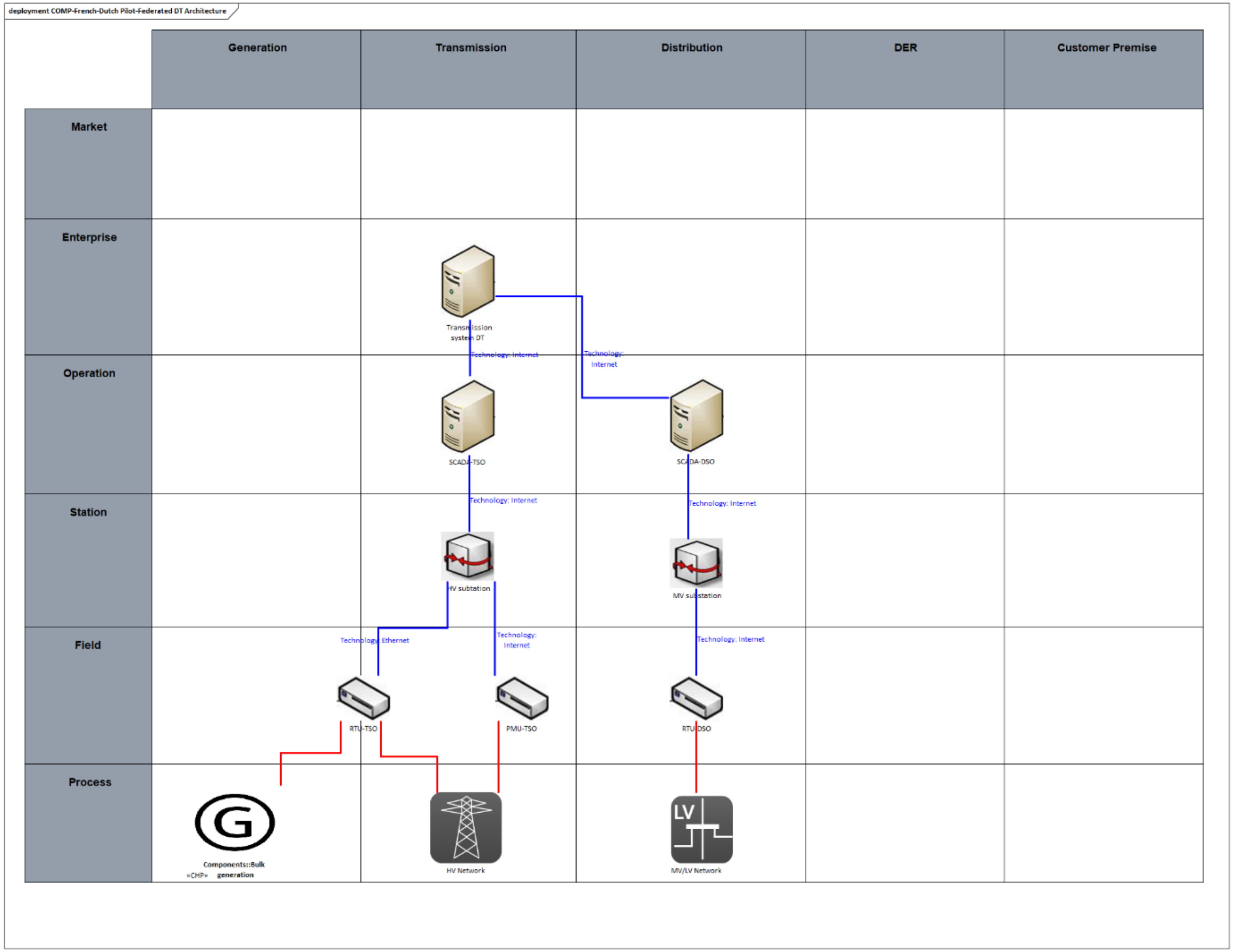


Figure 85 - French Dutch pilot component layer.

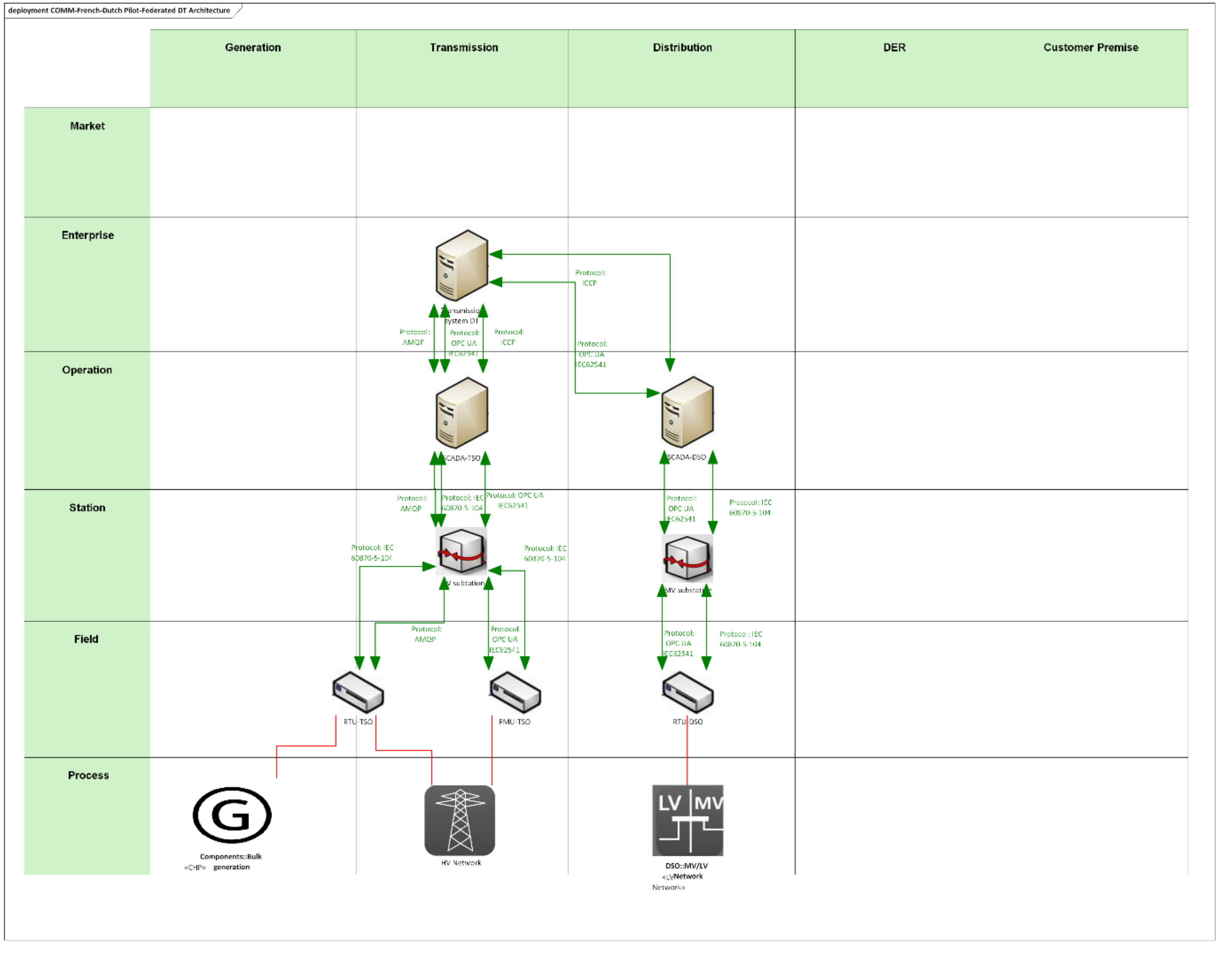


Figure 86 - French Dutch pilot communication layer

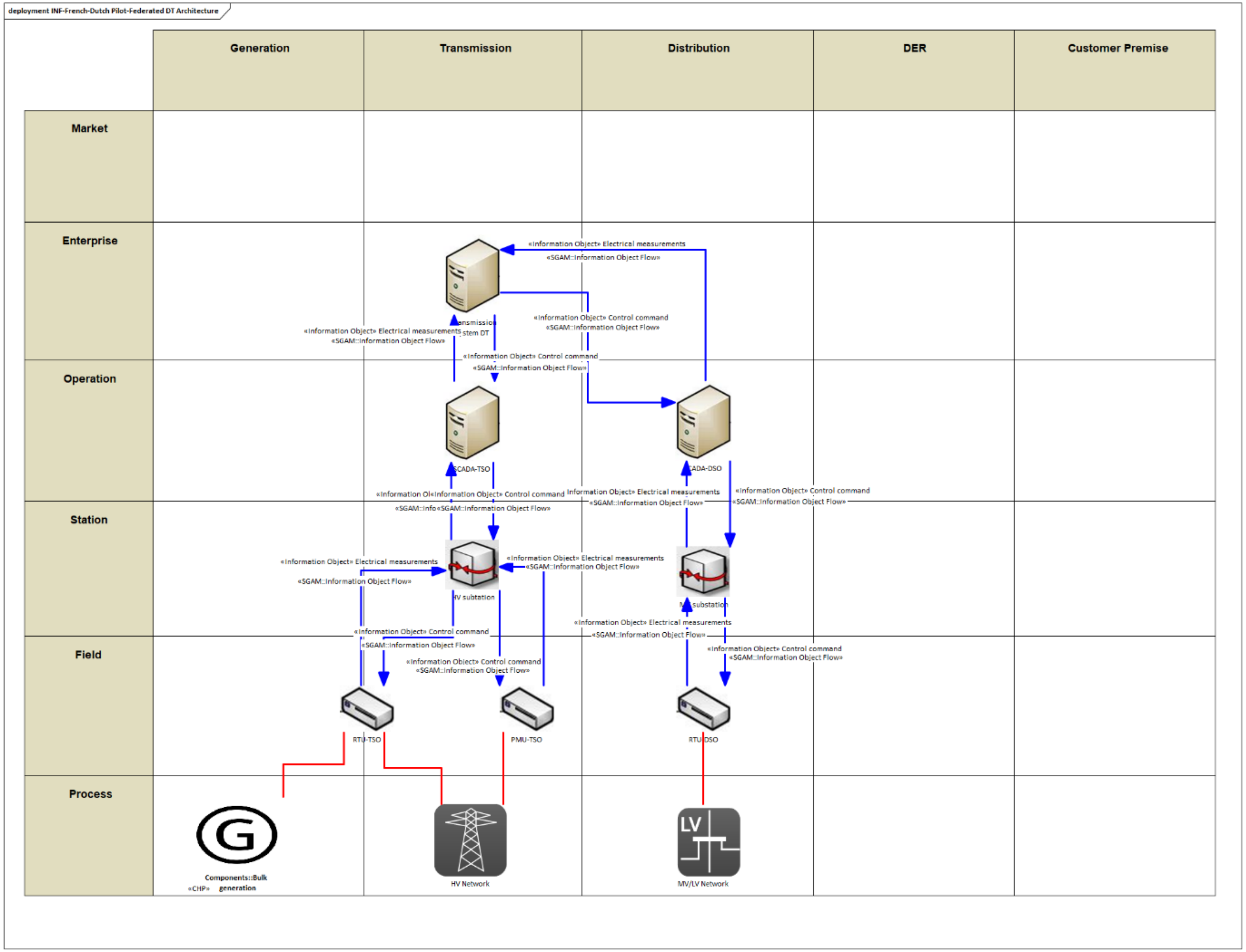


Figure 87 - French Dutch pilot information layer

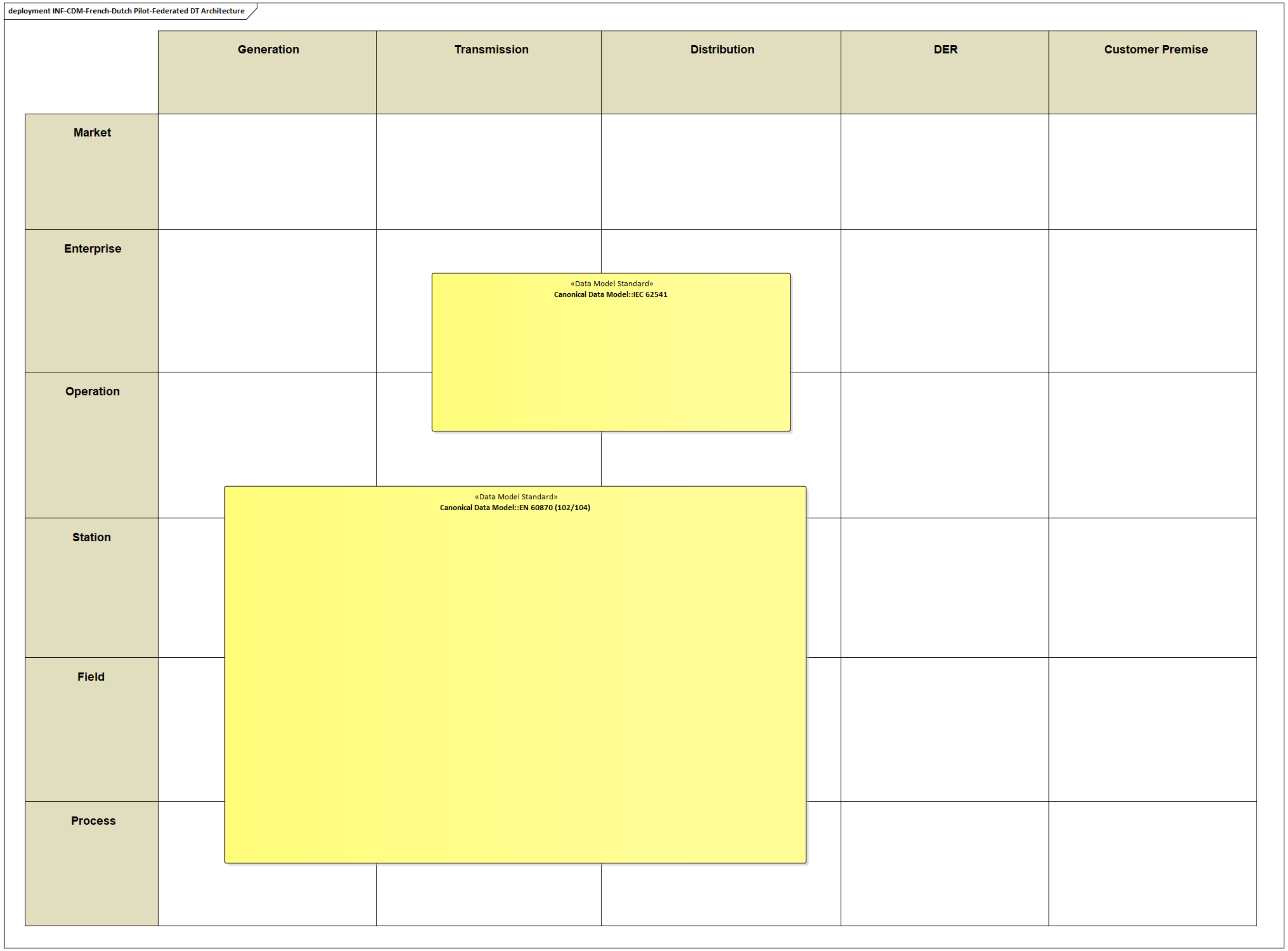


Figure 88 - French Dutch pilot information layer - Canonical Data Model

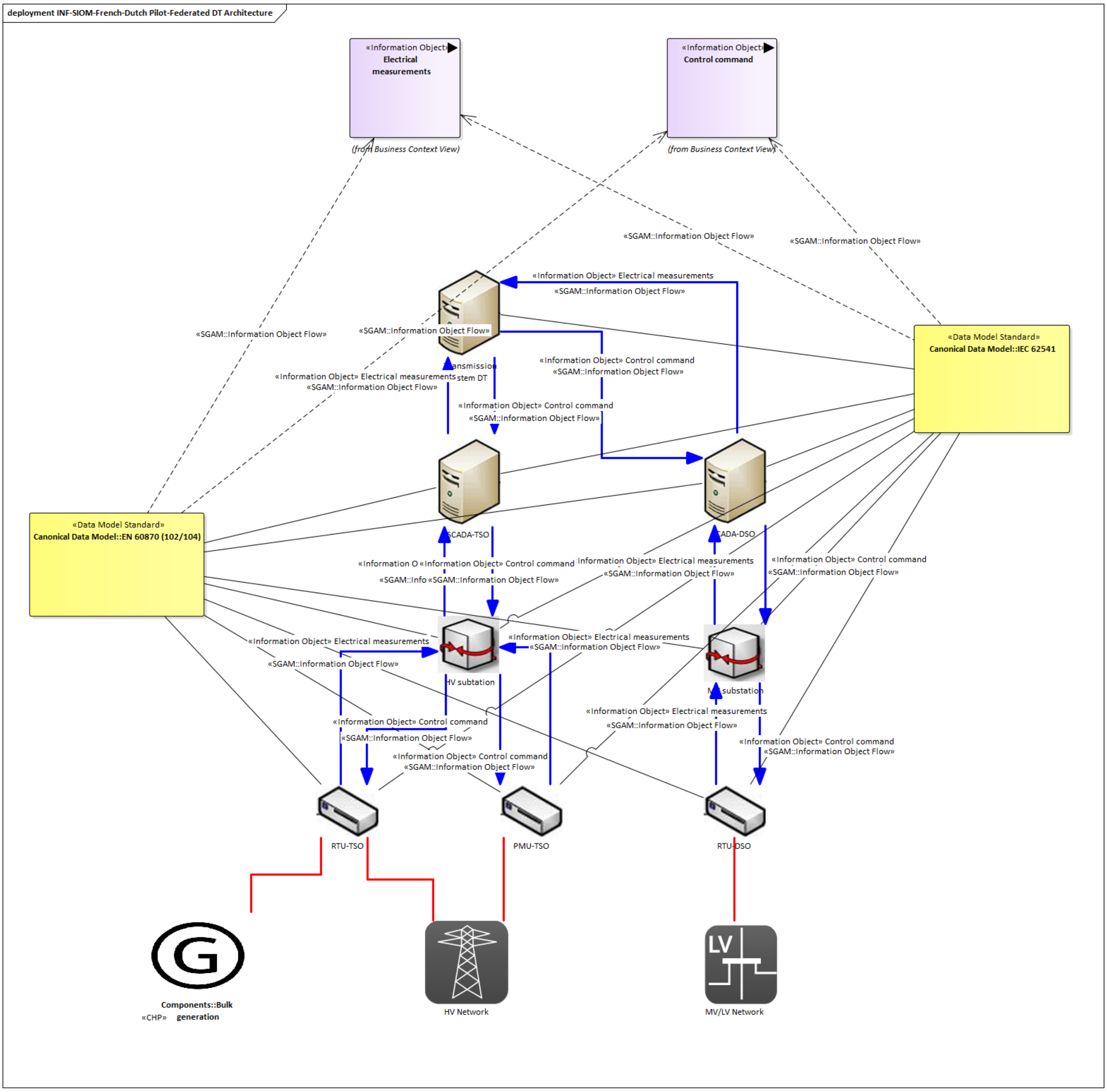


Figure 89 - French Dutch pilot information layer - Standard and Information Object Mapping

Generalised architecture

Component layer

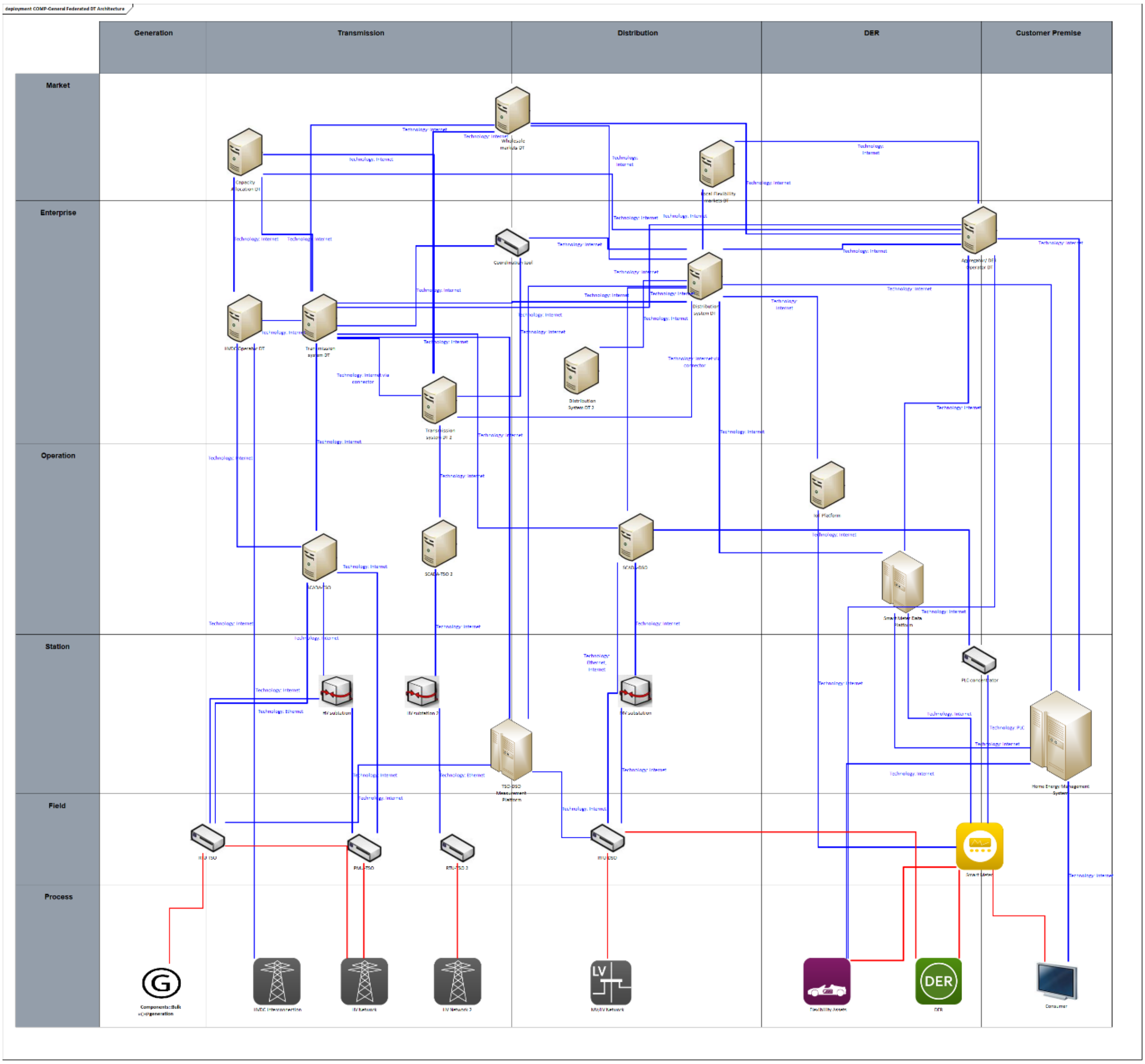


Figure 90 - General federated DTs architecture second version. Component layer

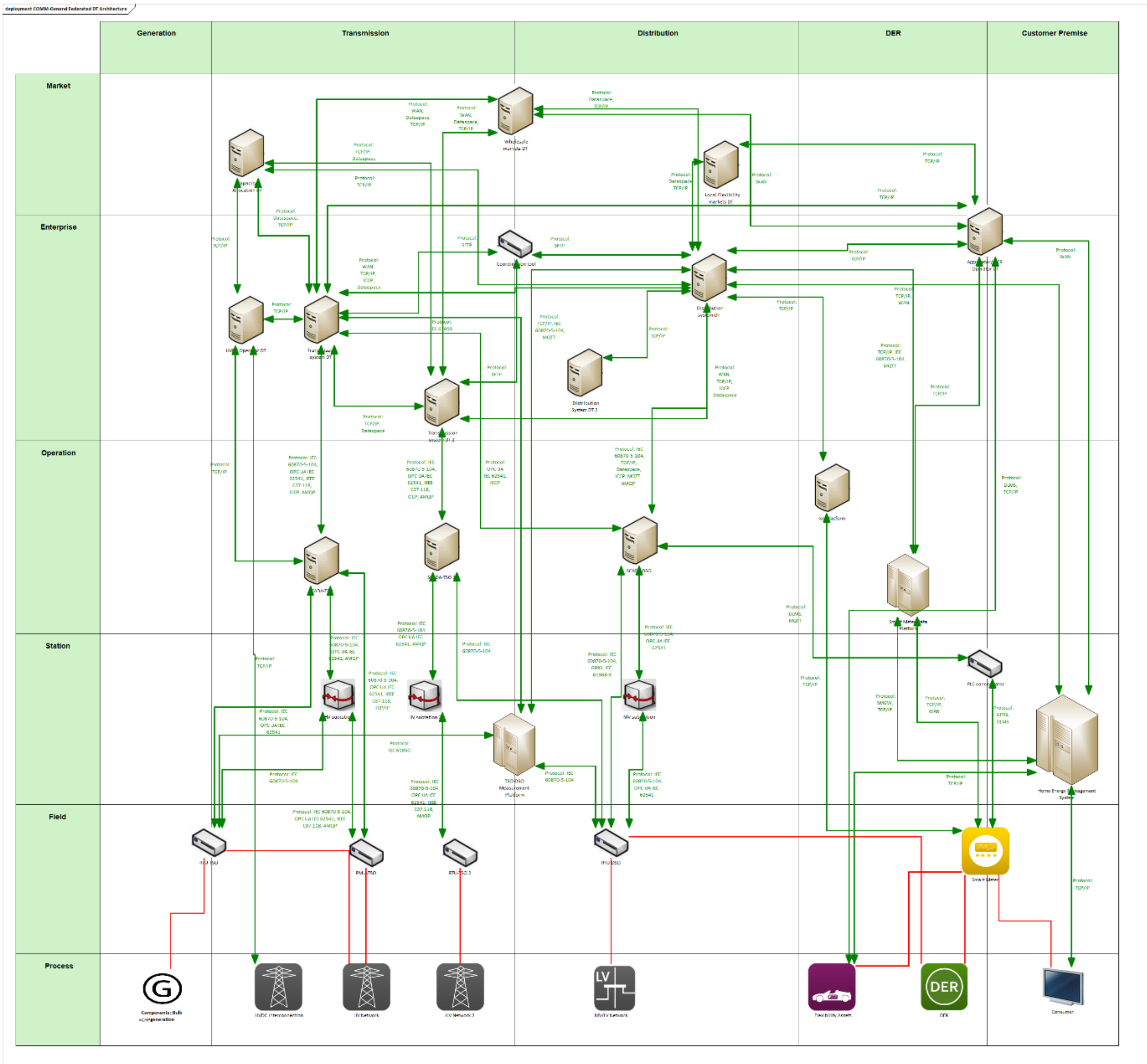


Figure 91 - General federated DTs architecture second version. Communication layer

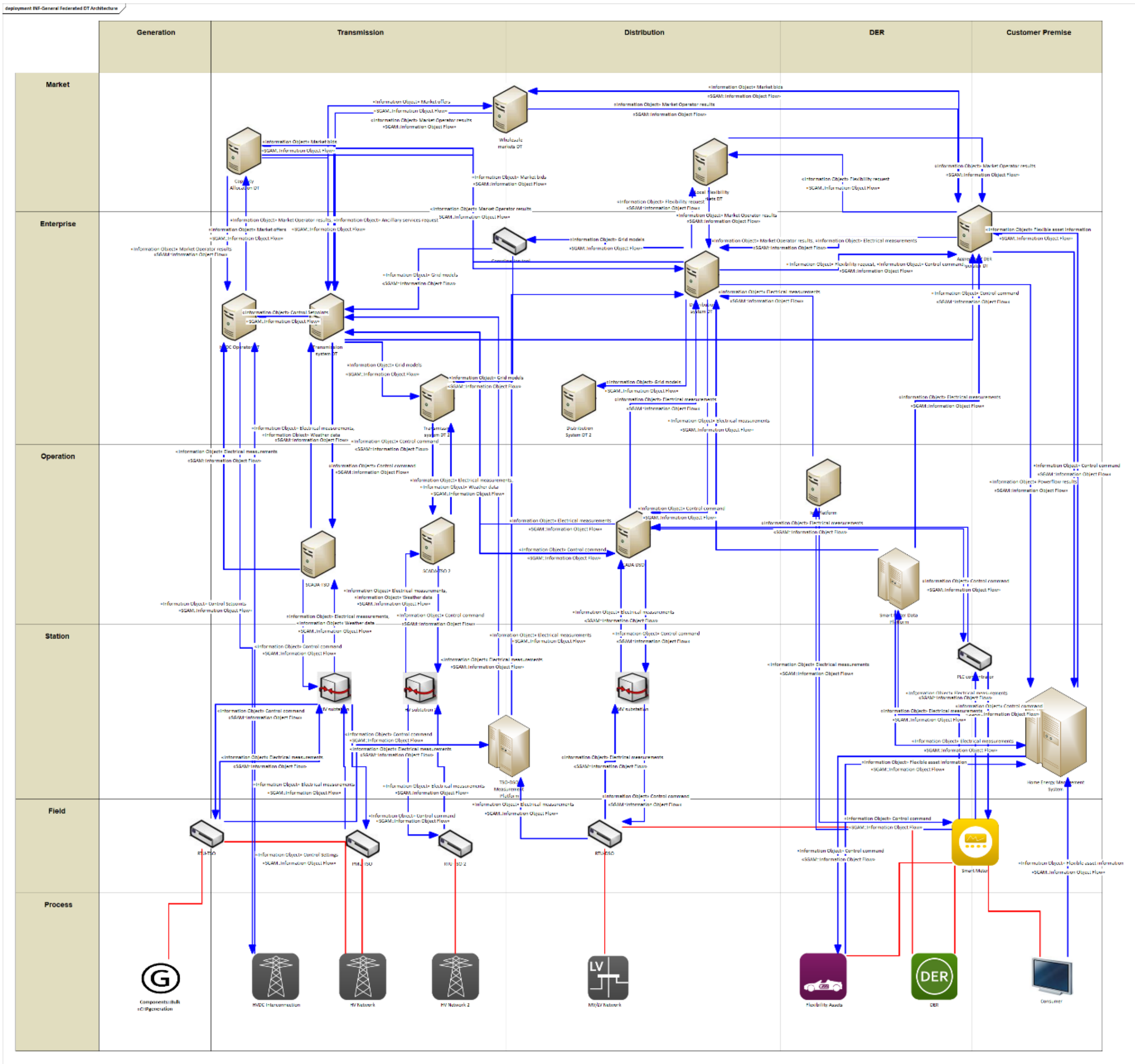


Figure 92 - General federated DTs architecture second version. Information layer

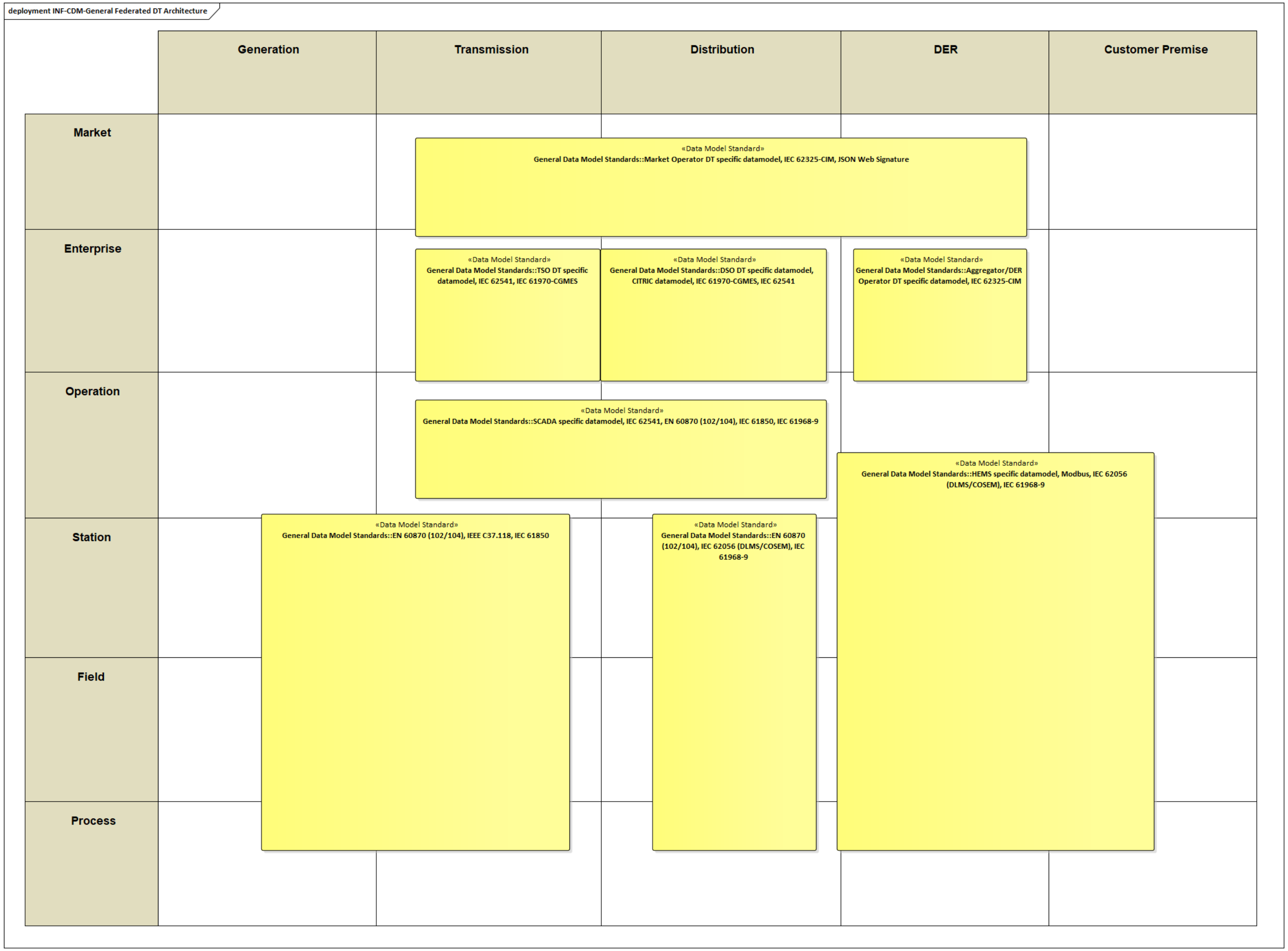


Figure 93 - General federated DTs architecture second version. Information layer - Canonical Data Model

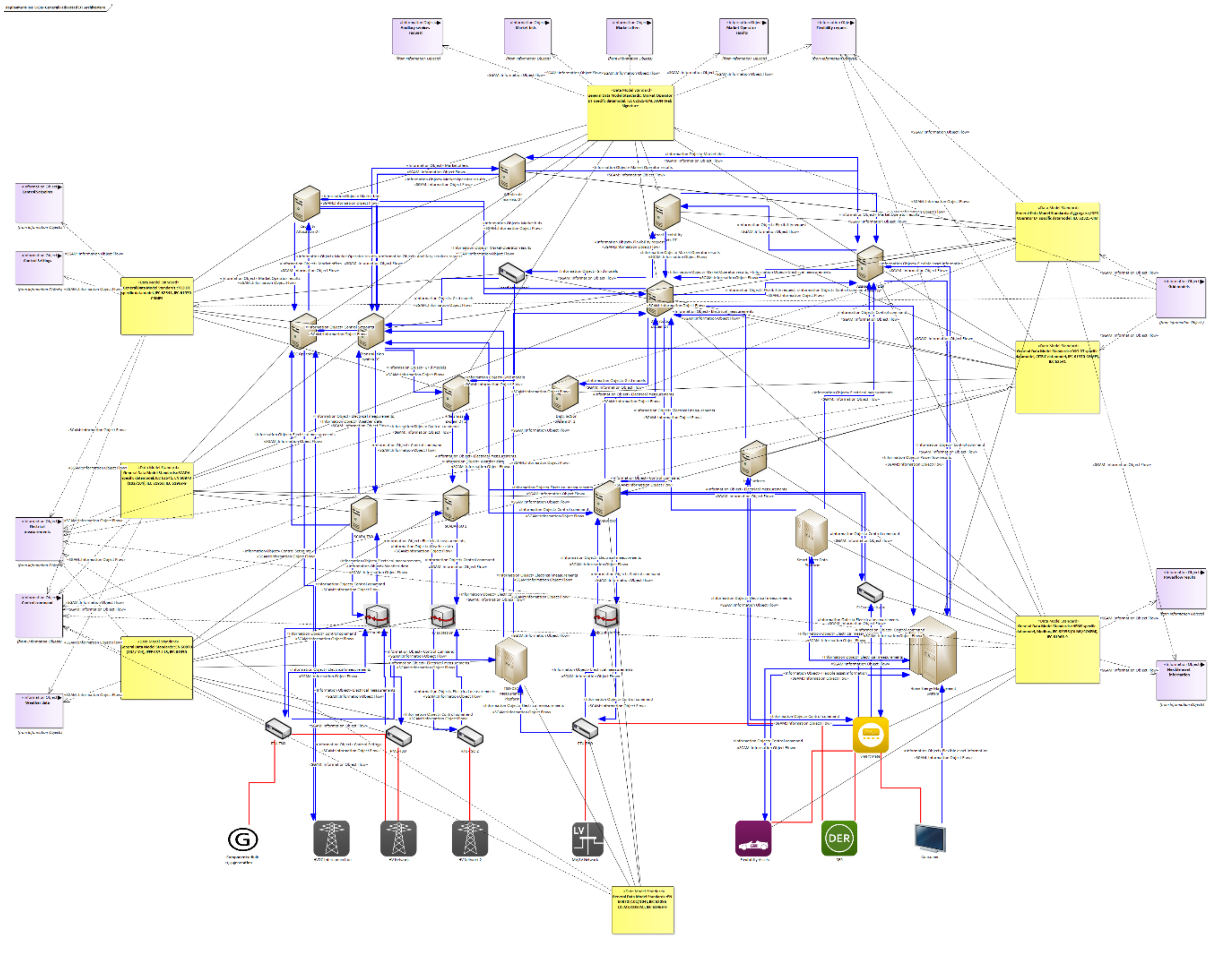


Figure 94 - General federated DTs architecture second version. Information layer - Standard and Information Object Mapping