



From conceptual use cases to real demonstration - DT for grid management, operation and monitoring

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List of Abbreviations and Acronyms

Acronym	Meaning
ADMS	Advanced Distribution Management System
AI	Artificial Intelligence
AN	Artificial Neural Network
BIM	Building Information Model
CDE	Common Data Environment
CGMES	Common Grid Model Exchange Standard
CIM	Common Information Model
DER	Distributed Energy Resource
DNP	Distributed Network Protocol
DSA	Dynamic Security Assessment
DSO	Distribution System Operator
DSP	Data Space Protocol
DT	Digital Twin
EMS	Energy Management System
ENTSO-E	European Network of Transmission System Operators for Electricity
EV	Electric Vehicle
FSP	Flexibility Service Provider
GOOSE	Generic Object-Oriented Substation Event
HEMSSP	House Energy Management System Service Provider
HIL	Hardware In the Loop
HV	High Voltage
ICCP	Intercontrol Center Communications Protocol
IDS	Information Delivery Specification
IEC	International Electrotechnical Commission
IFC	Industry Foundation Classes
IGM	Individual Grid Model
IGP	Intelligent Grid Platform
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
LOIN	Level of Information Need
LV	Low Voltage

MMS	Manufacturing Message Specification
MPO	Metering Point Operator
MV	Medium Voltage
NAS	Network-Attached Storage
RD 3.0	Redispatch 3.0
SCADA	Supervisory Control And Data Acquisition
SDSA	Static and Dynamic Security Assessment
SFTP	Secured File Transfer Protocol
SO	System Operator
TSO	Transmission System Operator
UCTE	Union for the Coordination of Transmission of Electricity
UCTE-DEF	UCTE-Data Exchange Format
WDS	Weather Data Supplier
WP	Work Package

Executive Summary

The TwinEU project aims to establish a pan-European Digital Twin ecosystem by federating local Digital Twins. Within this initiative, Work Package 6 (WP6) explores the potential of Digital Twin technologies for **grid management, operation, and monitoring**. Four demonstration areas - **Italy, Germany, Slovenia, and Hungary** - are involved in this Work Package. This deliverable D6.1 analyses the similarities and differences among WP6 pilots, fostering knowledge exchange to maximize synergies and mutual benefits.

WP6 pilots address different applications: **grid management applications** optimize infrastructure planning and resource allocation, **grid monitoring applications** enhance real-time visibility into network conditions, enabling proactive maintenance and operational decision-making, **grid operation applications** focus on real-time control, congestion management, and system stability.

The development of WP6 Digital Twins is driven by diverse **strategic and business objectives**, ranging from cost optimization to enhancing grid security and observability.

A key finding from the homogenization analysis is that **TSO-DSO interactions** are a central focus across all pilots. However, challenges persist, including limited real-time data sharing, interoperability issues, regulatory constraints, and reliance on manual updates. These challenges can be addressed through shared data models and standards, automation of real-time exchanges, policy alignments, and a transition toward automated grid adjustments.

Real-time data exchange is essential for Digital Twin platforms, as they provide dynamic digital representations of physical systems. However, successful implementation requires overcoming challenges related to scalability, data access, security, and interoperability. Moreover, the adoption of **standardized data models** is crucial to ensuring integration and interoperability across different systems.

WP6 Digital Twins incorporate key capabilities that contribute to the development of the **TwinEU Digital Twin** framework. These include real-time data monitoring and visualization, the use of advanced predictive algorithms and simulation tools, the support for asset planning and design before deployment and the use of innovative ways of connection with other systems.

WP6 **Key Performance Indicators** (KPIs) include both common cross-pilot validation metrics and pilot-specific indicators linked to its own objectives. Common KPIs assess aspects such as model accuracy, computational performance, interoperability, transferability, and stakeholder acceptance.

Finally, all pilots have tested the possibility of integration into the **TwinEU federated architecture** based on the TwinEU **DT Federator** and data space principles for data and model exchange, mostly by participating in pan-European scenarios. The results confirm the potential of the federated approach, while also highlighting open issues related to cybersecurity, operational constraints, and real-environment deployment.

1 Introduction

The electricity sector is undergoing a profound transformation driven by digitalization, the integration of high-share renewables, advancements in storage technologies, and the deployment of smart metering systems. In this context, operators must revolutionize how they interact with their systems, leveraging innovative digital technologies to meet emerging challenges. One such technology is **Digital Twin** (DT) platforms, which provide a digital replica of electro-energy systems. These platforms can significantly enhance the capabilities of grid operators, aiding them in daily operations and strategic planning. Further information on the state of the art of DT technologies is provided in chapter 3 of deliverable 2.2 of this project (D2.2 – TwinEU use cases, pan-European scenarios and KPIs).

The **TwinEU** project is dedicated to designing a pan-European Digital Twin ecosystem by federating local Digital Twins. This initiative aims to ensure reliable, resilient, and safe infrastructure operations while enabling new business models to accelerate the adoption of renewable energy sources across Europe. Within this project, Work Package 6 (WP6) focuses on exploring the potential of Digital Twin technologies for **grid management, operation, and monitoring** tasks. To achieve this, four demonstration areas - Italy, Germany, Slovenia and Hungary – have been involved, each addressing key aspects of grid management, operation and monitoring:

- Validating asset design and planning phases;
- Using simulations to evaluate specific defence system strategies, and to test and validate scenarios in a controlled and digital environment;
- Developing end-to-end flexibility solutions to enhance grid planning and dynamic monitoring;
- Demonstrating advanced static and dynamic security assessment tools for assessing network operating conditions;
- Utilizing Artificial Neural Network (ANN)-based models to improve line monitoring and support better power line utilization.

This deliverable, D6.1, details the activities of Task 6.1, which focuses on the **homogenization of WP6 pilots** through the identification and application of common Digital Twin features, as outlined in Work Package 2 (WP2) “Digital Twins EU-level cross-stakeholder use-case capitalization and preparation”.

The primary features under consideration include:

- Testbeds, requirements and methodologies
- Communication flows, data models and architectures
- Digital Twin validation.

Task 6.1 highlights the similarities and differences across WP6 pilots, fostering knowledge sharing to maximize mutual benefits. This comprehensive analysis will ultimately contribute to the project's validation and operational success.

1.1 Task 6.1

The aim of this task is to transfer and adapt the TwinEU concept to pilots developed within WP6, focusing on “Demonstration of Digital Twinning for grid management, operation and monitoring”. Insights and findings from WP2, “Digital Twins EU-level cross-stakeholder use-case capitalization and preparation”, are further analyzed in Task 6.1, to contextualize them within WP6.

Additional inputs are drawn from WP4, which aims to develop the federated infrastructure for TwinEU Digital Twins. Task 6.1 assesses the feasibility of integrating WP6 Digital Twins into the TwinEU framework.

Furthermore, for validation, exploitation and knowledge sharing purposes related to the contributions of WP6, this task has closely aligned with the consolidation efforts in T9.1, which has the aim of validating the technological developments of the TwinEU Digital Twins. The integration with Task 9.1 ensures that insights from the pilot are effectively validated, exploited, and disseminated, reinforcing the project’s alignment with the overarching goal of establishing a federated digital twin ecosystem. These pilots are not isolated initiatives but part of a coordinated effort to enable data and model exchange through standardized interfaces and open APIs, paving the way for scalable, cross-border collaboration.

A summary of T6.1 interactions is provided in Figure 1-1, while the methodology is described in detail in Chapter 2.

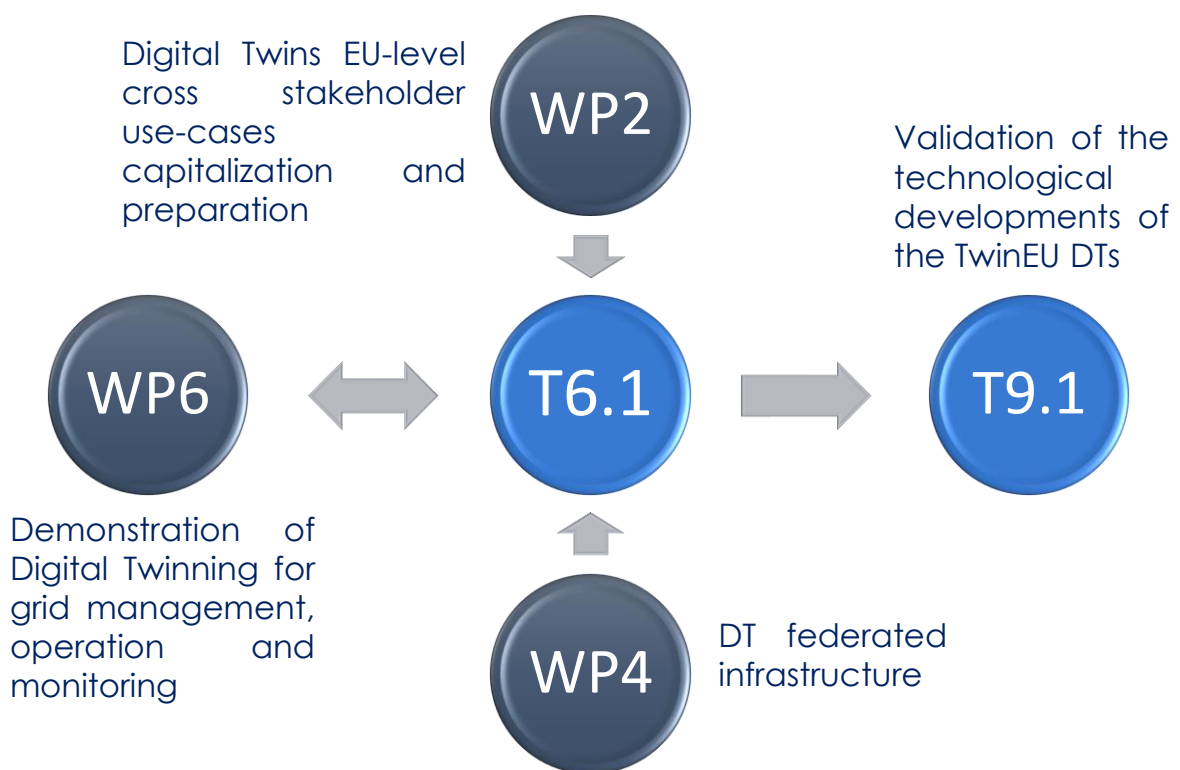


Figure 1-1 - Interactions of T6.1 with other TwinEU packages and tasks

1.2 Objectives of the Work Reported in this Deliverable

The primary objective of this deliverable is to report the homogenization analysis conducted to identify similarities and differences among Digital Twin platforms designed for specific applications in grid management, operations, and monitoring. The detailed description of implemented platforms can be found in dedicated pilots’ deliverables: D6.2 “Validation over digital twinning”, D6.3 “The defence system use case”, D6.4 “End-2-end-flexibility and dynamic grid monitoring”, D6.5 “Grid planning with digital twinning”, D6.6 “Slovenian demo”, D6.7 “Digital Twin for Power Line Monitoring”.

The deliverable aims to:

- **Collect the procedures** used in DT platforms, particularly those related to communication flows, data models, and architectures, while outlining best practices for digital twinning for grid management, operation, and monitoring
- **Propose recommendations** for improving external communications, interfaces, and adapters to enhance interoperability within a pan-European Digital Twin framework.

1.3 Outline of the Deliverable

This deliverable is structured into the following chapters:

- Chapter 2 describes the methodology employed for the homogenization of WP6 pilots.
- Chapter 3 reports the homogenization results, focusing on the general features of WP6 pilots: testbeds, requirements, and methodologies are described in Chapter 3.1; communication flows, data models, and architectures are described in Chapter 3.2; digital twin validation topics are described in Chapter 3.3.
- Chapter 4 draws the conclusions.

2 Methodology

This chapter outlines the methodology employed to homogenize the WP6 pilots. A **structured data model** was developed to represent the pilots based on shared features and ensure consistency across the analysis. Using this model, information about the WP6 pilots was **extracted** from project documentation, project meetings and partner interviews. Partners also contributed to **validating the collected information**, ensuring accuracy and reliability. The resulting data was organized into a structured database, which was subsequently queried to address predefined **competency questions**.

2.1 Data Model Definition

A **structured data model** was developed to identify and extract key features relevant for homogenizing the WP6 pilots. To define these features within the data model, a set of competency questions was established. These **competency questions** were formalized around three key discussion topics: “Testbeds, requirements and methodologies” (Table 2-1), “Communication flows, data models and architectures” (Table 2-2) and “Digital Twin Validation” (Table 2-3).

Table 2-1 – Competency questions for the discussion topic “Testbeds, requirements and methodologies”

Competency questions – Testbeds, requirements and methodologies
What do you describe using a Digital Twin?
What geographical area are you covering with your pilot?
Considering the 3 sub-areas of grid management, operation and monitoring, which of them are you covering?
Which applications do you consider in each sub-area of grid management, operation and monitoring?
Which is the final strategic aim of the DT in the context of grid management, operation and monitoring?
Which are the parties/actors involved in the demonstration?
Which systems are involved in the demonstration?
Can you describe the algorithms you include? Do they exploit AI ?

Table 2-2 – Competency questions for the discussion topic “Communication flows, data models and architectures”

Competency questions – Communication flows, data models and architectures
Which kind of standard and data models are used?
Which are the main challenges you found related to the standard and data models you use?
Which are the communication flows between parties? What protocol is used for these exchanges between parties?
Can you provide a high-level DT architecture? (software used, internal communication flows, datastore, expected user interfaces) Which are the main challenges you found related to the architecture you developed?
Which are the main challenges you found for your pilot to promote interoperability within a pan-European DT?
Do you think your approach could provide valuable practices in terms of interoperability within a pan-European DT ?

Table 2-3 – Competency questions for the discussion topic “Digital Twin Validation”

Competency questions – Digital Twin validation
Which cross-pilot validation KPIs are considered?
Which use-case-specific KPIs are considered?
Which application or aim can each KPI be mapped to?
Is the pilot involved in any pan-European scenario ?

The defined data model is represented as a **graph** (Figure 2-1), where nodes denote individual entities, and edges illustrate the relationships between them. The relevant entity types are detailed in Table 2-4, while Table 2-5 defines the significant relationships between nodes. Each node and edge type are characterized by the attribute “name”, which uniquely identifies the represented entities. Additionally, some nodes and edges are further described using specific attributes introduced in the corresponding tables, providing a more comprehensive characterization.

During the phases of the project, the defined graph-based data structure has undergone changes and updates to accommodate additional topics of analysis or to reflect the increased maturity of the Digital Twin implementation. The graph structure offers greater flexibility in restructuring data compared to traditional tabular databases, making it well-suited for evolving requirements and expanding use cases.

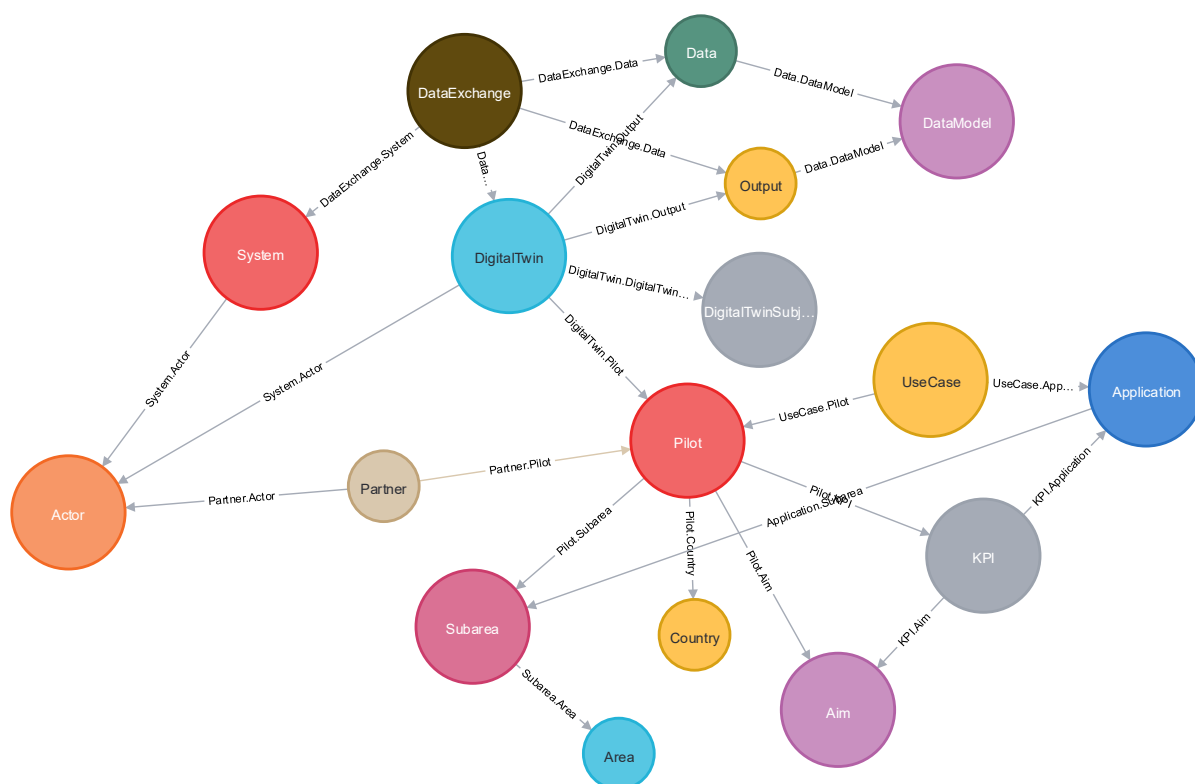


Figure 2-1 - Graph data model defined for the homogenization analysis

Table 2-4 - Node types and related definitions in the structured data model for the homogenization analysis

Node type	Definition
Actor	An entity that communicates and interacts within the identified use case for developing the Digital Twin platform
Aim	The intended strategic and business objective driving the development of the Digital Twin platform
Application	A specific task or function performed using the Digital Twin platform, belonging to the defined subareas of focus
Area	The primary domain or field of focus for the development of the Digital Twin platform. For example, in WP6, the relevant area is “Grid management, operation and monitoring”
Country	The European region or nation participating in the demonstration or implementation of the Digital Twin platform
Data	The information transmitted between the Digital Twin platform and other systems during the demonstration
DataExchange	The process of sharing information between the Digital Twin platform and other interconnected systems. The property “frequency” describes the occurrence of the data exchange
DataModel	An abstract representation or framework for structuring and organizing data
DigitalTwin	The Digital Twin platform specifically designed and developed for the demonstration
DigitalTwinSubject	The specific component or system being modelled or simulated using the Digital Twin platform. The property “type” details considered the network type (distribution_grid, transmission_grid, distribution_transmission_grid)
KPI	A measurable metric for evaluating DT platforms
Partner	Organizations, research institutes, or academic entities collaborating in the development of the Digital Twin platform
PanEuropeanScenario	Validation activity involving cross-pilot collaboration within TwinEU project
Pilot	A demonstration project aimed at developing the Digital Twin platform
Subarea	A more specialized domain within the overarching area of the Digital Twin platform. For instance, in WP6, subareas may include “Grid management”, “Grid operation”, or “Grid monitoring”

System	A component, such as a platform or sensor, owned by an actor and participating in the data exchange process within the Digital Twin platform
UseCase	A specific scenario or example illustrating how the Digital Twin platform is utilized

Table 2-5 - Edge types and related definitions in the structured data model for the homogenization analysis

Edge type	Definition
Application.Subarea	The specific subarea of development that the application is associated with
Data.DataModel	The data model used to structure and describe the data
DataExchange.Data	The data exchanged during the information-sharing process
DataExchange.System	The system participating in the information exchange. The property “direction” specifies the direction of exchange (start/end)
DigitalTwin.DigitalTwinSubject	The specific subject or component represented by the Digital Twin platform
DigitalTwin.Output	The output data generated by the Digital Twin platform
DigitalTwin.Pilot	The pilot project within which the Digital Twin platform is being developed
KPI.Aim	The strategic or business aim related to the Key Performance Indicator
KPI.Application	The application related to the Key Performance Indicator
Partner.Actor	The role of the partner as an actor within the formalized use case
Partner.Pilot	The pilot project that includes the partner’s involvement
Pilot.Aim	The strategic or business aim defined for the pilot demonstration
Pilot.Country	The country or region participating in the pilot demonstration
Pilot.KPI	The Key Performance Indicator considered by the pilot
Pilot.PanEuropeanScenario	The pan-European scenario involving the pilot
Subarea.Area	The broader area of development to which the subarea belongs
System.Actor	The actor responsible for owning or managing the specific system
UseCase.Application	The application associated with the specific use case
UseCase.Pilot	The pilot demonstration addressing the specific use case

The adoption of a structured data model ensures a shared understanding of information and provides several key benefits:

- **Data integration:** the model facilitates the linking and harmonization of data from diverse sources, encouraging data sharing and collaboration. For instance, the standardized structure can enable the exchange of similar information across different pilots.
- **Enhanced understanding:** by representing entities and their relationships, the data model provides context and improves comprehension of the information. Once data is structured according to the model, the graph can be explored to address research questions. As discussed in subsequent chapters, competency questions can be formalized as graph queries, allowing the extraction of comparable information across various pilots.
- **Improved search and discovery:** the model enhances the relevance, accuracy, and completeness of search results, facilitating the discovery of new knowledge and insights.
- **Inference and reasoning:** the model supports inference and reasoning tasks, enabling the discovery of new relationships, detection of inconsistencies, and validation of existing knowledge.

2.2 Information extraction and partner validation

Data were gathered according to the data model structure and were sourced from the following key documents:

- TwinEU Grant Agreement
- D2.2 Deliverable “Reporting outcomes of T2.3”
- T2.4 Use Cases
- T9.1 workbook.

Information shared during project meetings and general assemblies provided valuable input for populating the graph database. In addition, for sharing homogenization results, gaining more information about pilots and encouraging discussion, three T6.1 workshops have been organized.

The extracted data were then reviewed and validated by partners through ad hoc meetings and email exchanges. To facilitate this process, the data were shared in Excel format to ease of access and review.

2.3 Database population and querying

The validated data were converted into JSON format and imported into a graph database. Visualizing the data as a graph provides a clear understanding of the connections between entities, making relationships within the data both visible and actionable. Figure 2-2 illustrates a portion of the graph representing WP6 pilots, while Figure 2-3 represents the entire graph.



To analyze each discussion topic, the relevant competency questions were translated into graph database queries to enable structured information retrieval. For example, the competency question “*What do you describe using a Digital Twin?*”, associated with the discussion topic “Testbeds, requirements and methodologies” (Table 2-1), can be easily converted into a graph query. The query retrieves nodes of type DigitalTwin that are connected to nodes of type DigitalTwinSubject, along with all their associated attributes. The resulting pairs of nodes, along with their attributes, can be organized into a tabular format, as shown in Table 2-6.

Table 2-6 – Output of the graph query answering the competency question “What do you describe using a Digital Twin?” for WP6 Digital Twin platforms

DigitalTwin.name	DigitalTwinSubject.name	DigitalTwinSubject.type
Validation tool	New HV/MV power plant	distribution_transmission_grid
Defence System	Sardinia Island transmission and distribution grid	distribution_transmission_grid
(ANN)-based line monitoring sensor digital twin	Hungarian/Austrian distribution/transmission lines	distribution_transmission_grid
Intelligent Grid Platform 2.0	Westnetz distribution grid	distribution_grid
Transmission Grid DT	ELES transmission grid	transmission_grid

A detailed discussion of the results from the homogenization will be provided in the following chapters.

3 Description of WP6 pilots

In this chapter a description of WP6 pilots is provided focusing on the three discussion topics of testbeds, requirements and methodologies (Chapter 3.1), communication flows, data models and architecture (Chapter 3.2), and DT validation (Chapter 3.3).

3.1 Testbeds, requirements and methodologies

The first discussion topic focuses on a general description of WP6 pilots (Hungarian, German, Italian and Slovenian). Each testbed provides insights into different aspects of the energy transition, contributing to a more interconnected and sustainable European electricity system (Figure 3-1).

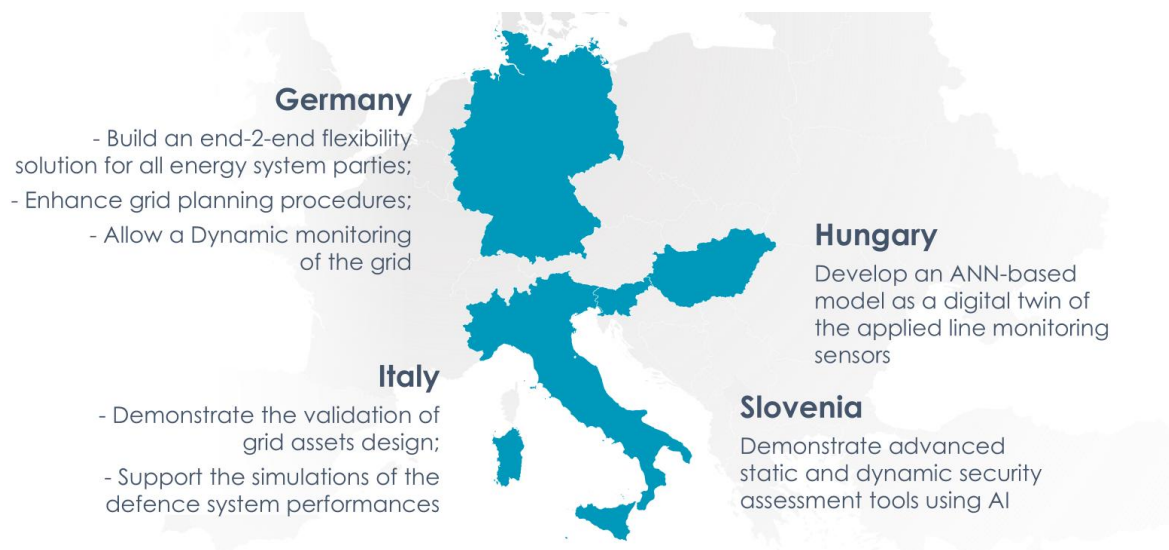


Figure 3-1 – WP6 Pilots overview

The analysis of the solutions adopted by the WP6 pilots reveals significant differences in **Digital Twin applications and functionalities**, as will be better explained in Chapter 3.1.2. Some pilots focus on **infrastructure validation**, while others emphasize **dynamic monitoring models** and **operational management**:

- The **Hungarian pilot** employs **virtual sensors for monitoring transmission lines**, collecting environmental and operational data to support **capacity optimization** and to create the possibility of building a **predictive maintenance system**
- The **German pilot** focuses on **flexible and dynamic distribution grid management**, using real-time data collection and analysis to improve **response capability to load variations**
- The **Slovenian pilot** uses Digital Twins to **assess the dynamic stability of the power system**, modelling demand and supply variations to ensure a more resilient network
- The **Italian Pilot - Digital twinning as a validation tool** employs Digital Twins for **infrastructure validation**, ensuring that new network elements are tested before their physical implementation
- The **Italian Pilot - Defence use case system** leverages simulations to **model emergency scenarios and develop proactive grid defence strategies**, reducing the risk of major system failures.

Hungarian Pilot Site

This pilot involves MAVIR (TSO), E.ON EED (DSO), F4STER (technology provider), and BME (academic partner). It aims at implementing a system that dynamically evaluates transmission line capacity by integrating **physical sensors measurements** (conductor temperature and environmental conditions) with **AI-driven virtual sensors** predicting capacity using weather and SCADA data. This predictive maintenance model is based on Artificial Neural Networks (ANNs), continuously analysing temperature, load, and weather conditions, to detect operational opportunities and risks. In this way, the system prevents overloads, enhances operational safety, and maximizes grid efficiency.

German Pilot Site

The German Demo Area involves the grid operators Amprion (TSO) and Westnetz (one of E.ON's DSOs). Within the Westnetz distribution grid, the pilot is conducted within the E.ON Lab (a testing area and project focusing on pre-scaling of smart assets and solutions in the low voltage (LV) grid and validation of added values from digitization) and focuses on testing an intelligent system for improving **real-time monitoring**, optimizing **market-based flexibility services**, and ensuring **grid reliability**. The system tracks power flows, detects network stress points, and optimizes energy distribution by estimating grid states under changing topologies. The pilot also focuses on optimizing flexibility management and market integration, ensuring efficient participation of Distributed Energy Resources (DERs), households, and businesses in the energy market. The utilized Digital Twin of the distribution grid (Intelligent Grid Platform – IGP) enables market aggregator integration, providing insights into market-based flexibility services, optimizing DER participation and enabling automated responses to grid conditions.

Italian Pilot Site

The Italian Demo Area within the TwinEU project focuses on **ensuring grid stability** and **validating new infrastructure designs** through the integration of Digital Twins at both the transmission (Terna) and distribution (ENEL) levels.

The **Defence System Digital Twin** simulates **dynamic responses to system disturbances**, and **test new defence system strategies** through Hardware-in-the-Loop (HIL) simulation, validating security measures before field deployment. This pilot includes two key use cases: Sardinia, where renewable energy capacity is rapidly expanding, requiring advanced stability and integration mechanisms, and the Rome metropolitan grid, a high-density urban area with growing energy demand that requires efficient grid management and long-term planning solutions. These areas provide a diverse testing ground for Digital Twins, demonstrating their ability to enhance system security, optimize flexibility, and support the transition to a fully renewable-based energy system.

The **Design Validation System** leverages **Building Information Modeling (BIM) methodology** and Digital Twins to facilitate **design validation** and **approval processes**. This initiative is being developed in parallel by Terna and ENEL and is based on automating project validation to ensure compliance with technical regulations and grid planning standards and on data model interoperability to create a framework for automated validation of power station designs and network expansions. By standardizing design validation processes, the system accelerates infrastructure development and support the efficient expansion of the Italian electricity network.

The Italian Demo Area contributes to the digitalization of Italy's energy system, integrating real-time stability management, infrastructure validation, and AI-driven simulations into a single, operational framework.

Slovenian Pilot Site

The Slovenian Demo Area within the TwinEU project uses Digital Twins to improve **grid observability, security, and flexibility management**, ensuring a more resilient and efficient transmission and distribution network. The pilot involves ELES (TSO), EG (DSO), HSE (Electricity Market Operator), and research institutions (UL, EIMV) and integrates **digital models of both the transmission and distribution networks** for real-time monitoring, predictive analytics, and optimized decision-making. A key focus is enhancing the security and stability of the transmission system through advanced stability simulations and security assessment tools. The ELES Transmission Grid Digital Twin simulates grid responses to disturbances to improve intervention strategies, develop a Static and Dynamic Security Assessment (SDSA) tool for real-time insights and remedial actions, and create a database of past steady-state conditions and stability indicators, analysed using AI to detect patterns and predict system behaviour. The integration of real-time data from SCADA/EMS and ADMS systems ensures continuous monitoring, preventing blackouts and optimizing grid operations. Key initiatives include upgrading the Dynamic Model of the Transmission Network to better forecast future grid challenges, developing a Transmission Network Harmonic Model to assess sources of harmonic distortion and their impact on grid stability, and defining security criteria for future grid development to ensure a reliable and resilient electricity infrastructure. By integrating AI-driven analysis of historical grid data, the pilot enables accurate scenario planning.

3.1.1 Digital Twin Subjects

This chapter describes the components represented by WP6 Digital Twin platforms, as summarized in Table 2-6. The German and Slovenian pilots aim to build a DT respectively of distribution (Westnetz distribution grid) and transmission grid (ELES transmission grid). With the Defence System the Italian pilot focuses on both Sardinian transmission and Rome distribution grids, while the validation tool DT describes new HV/MV power plants. Finally, the Hungarian Pilot describes distribution and transmission lines in Hungary and Austria.

3.1.2 Applications

As already mentioned, WP6 pilots focus on the following three main subareas (Table 3-1):

1. **Grid management** – Supporting network planning, capacity allocation, and asset management
2. **Grid monitoring** – Detecting congestion, analysing operating conditions, and forecasting critical issues
3. **Grid operation** – Managing stability, frequency regulation, and optimizing operational flexibility.

Table 3-1 - Pilots involved in each subarea of grid management, operation and monitoring

Subarea	Number of Pilots Involved	Pilots
Grid management	5	Italian Pilot - Validation Tool, Italian Pilot – Defence System, German Pilot, Hungarian Pilot, Slovenian Pilot
Grid monitoring	2	Hungarian Pilot, German Pilot
Grid operation	4	Hungarian Pilot, Italian Pilot - Defence Use Case System, German Pilot, Slovenian Pilot

In each Subarea, it was possible to identify specific applications, meaning tasks and functions performed using Digital Twin platforms. Table 3-2 provides a **structured overview of the different applications of Digital Twin technologies** across the WP6 pilots, highlighting their **subarea of focus, pilot involvement, and a description**.

Table 3-2 - Applications identified for each subarea

Subarea	Application	Pilots Involved	Description
Grid Management	Allocate grid hosting capacities	German Pilot	Optimize available grid resources for new connections
	Asset management	Hungarian Pilot	Evaluate line conditions for prioritizing asset maintenance
	Grid design and planning	Italian Pilot – Validation Tool, Italian Pilot – Defence System, German Pilot	Support future infrastructure expansion and modernization
	Promote standard data models and workflows	Italian Pilot – Validation Tool, Slovenian Pilot	Develop structured approaches for data integration
Grid Monitoring	Direct power line monitoring	Hungarian Pilot	Monitor line conditions in real-time using virtual sensors
	Enhance grid observability	German Pilot	Improve real-time situational awareness
	Identify grid states and potential bottlenecks	German Pilot	Assess power system vulnerabilities
Grid Operation	Alleviate and identify congestion	German Pilot, Hungarian Pilot	Improve load balancing and operational efficiency
	Data integration between DSOs and TSOs	Slovenian Pilot, German Pilot	Enhance coordination and data sharing between network operators

	Dynamic analysis of power system	Slovenian Pilot	Model system behaviour under varying conditions
	Dynamic Line Rating	Hungarian Pilot	Optimize grid utilization based on power line conditions
	Identify steering measures	German Pilot	Improve operational control strategies
	Implement envelope curves	German Pilot	Develop new control strategies for system optimization
	Manage system stability and security	Italian Pilot – Defence System	Strengthen resilience against system disruptions
	Provide grid services for frequency control	Slovenian Pilot	Improve stability in the energy system

Grid management applications focus on optimizing the planning and utilization of infrastructure, ensuring efficient allocation of resources.

- The **German Pilot** plays a crucial role in **allocating hosting capacities and network planning**, addressing the challenge of **optimizing spatial and temporal resources** to facilitate new grid connections. This ensures that the grid can integrate **renewable generation** and new demand sources without overloading the system.
- The **Hungarian Pilot** contributes to **asset management** by supporting condition-based maintenance and improving the monitoring of line health and performance.
- The **Italian Pilot – Validation Tool**, **Italian Pilot – Defence System** and **German Pilot** contribute to **grid design and planning**, ensuring infrastructure expansion and modernization. These pilots help TSOs and DSOs in **evaluating cost-effective infrastructure investments**.
- The **Italian Pilot – Validation Tool** and **Slovenian Pilot** also focus on **promoting standard data models and workflows**, addressing a key challenge in **data interoperability and integration** across different grid stakeholders. This is crucial for harmonizing grid operations across multiple actors.

Grid monitoring applications exploit Digital Twins to enhance real-time visibility into network conditions, enabling more proactive maintenance and operational decision-making.

- The **Hungarian Pilot** focuses on **direct power line monitoring**, using **virtual sensors** to improve **visibility of line conditions**. This approach reduces the risk of thermal overloads, makes it possible to fully utilize the power lines and can be integrated into an existing asset management system to prevent future failures in aging infrastructure
- The **German Pilot** focuses on **enhancing grid observability**, ensuring that operators receive **real-time data on network conditions**. Improved observability enhances **situational awareness**, enabling quicker responses to **congestion and instability**.

- Additionally, the **German Pilot** is responsible for **identifying grid states and potential bottlenecks**, helping operators anticipate and mitigate **vulnerabilities** in the power system before they lead to **major operational issues**.

Grid operation applications focus on real-time control, congestion management, and system stability, ensuring smooth and efficient energy flow.

- **Congestion management and identification** is a shared focus of the **German and Hungarian Pilots**, both working on **alleviating congestion** by optimizing **real-time load balancing and operational efficiency**. The **German Pilot** further enhances congestion relief by developing **steering measures and envelope curves**, which introduce **new control strategies** for **system optimization**.
- **TSO-DSO coordination** is addressed by the **Slovenian and German Pilots**, focusing on **data integration between DSOs and TSOs**. This effort seeks to improve **data sharing mechanisms**, ensuring a smoother exchange of **operational information** between grid operators.
- The **Slovenian Pilot** also integrates Digital Twins into **dynamic analysis of the power system**, allowing operators to **model system behaviour** under different conditions to **improve resilience and response strategies**.
- The **Hungarian Pilot** works on **Dynamic Line Rating (DLR)**, optimizing **grid utilization based on real-time data** about **temperature and loading conditions**. This allows for **more flexible grid operation**, reducing bottlenecks caused by conservative line rating methods.
- **System security and stability** are key concerns for the **Italian Pilot – Defence System**, which uses Digital Twins to **simulate grid emergencies and develop automated response strategies**. This enhances the **resilience of the power system**, ensuring **fast and efficient interventions** in case of disruptions.
- Lastly, the **Slovenian Pilot** extends its focus to **grid frequency control**, ensuring that Digital Twins help **balance power supply and demand fluctuations** to maintain **stability in the energy system**.

3.1.3 Aims

The Digital Twins implemented across WP6 pilots have **specific strategic objectives**. These aims are reported in Table 3-3.

Table 3-3 – Aims of WP6 pilots' implementations

Aim	Pilots Involved	Description
Cost optimization	Hungarian Pilot	Improve economic efficiency and reduce operational costs
Enable exchange of network models in a standardized and interoperable way	Slovenian Pilot	Improve data harmonization and system integration
Enhance grid resilience and reliability	Hungarian Pilot	Enable more flexible and secure operating states through thermal state simulation and DLR data

Enhance TSO-DSO interactions	Slovenian Pilot, Italian Pilot – Defence system, German Pilot	Improve cooperation between grid operators
Facilitate dynamic modelling of transmission networks	Slovenian Pilot	Develop real-time stability assessment
Increase consumer involvement	German Pilot	Improve demand-side participation in grid operations
Increase efficiency of grid operation/management	German Pilot	Optimize network resource utilization
Increase the implementation of RES	Hungarian Pilot, German Pilot	Improve grid adaptability to intermittent renewable sources
Increase security and observability of system stability in real-time	Slovenian Pilot	Reduce response time to critical events
Perform sensitivity analysis by considering the evolution of system parameters	Italian Pilot – Defence Use Case	Model various operational scenarios for better decision-making
Prevent bottlenecks and congestions	Hungarian Pilot	Improve power flow management
Prevent large-scale disturbances (cascading effects, blackouts)	Italian Pilot – Defence Use Case	Develop emergency mitigation strategies
Promote standard models and guidelines	Italian Pilot – Validation Tool, German Pilot	Facilitate Digital Twin interoperability and utilize models during the handover phase towards asset management
Propose price-optimized charging	German Pilot	Improve economic efficiency of energy distribution
Reduce grid expansion cost	Italian Pilot – Validation Tool, German Pilot	Optimize grid investment strategies
Reduce grid planning cost	German Pilot	Optimize grid investment strategies
Test physical devices in a safe way	Italian Pilot – Defence Use Case	Validate hardware integration before deployment
Time saving	Italian Pilot – Validation Tool	Reduce delays in infrastructure validation and reduce design errors

A **major objective** is enhancing **TSO-DSO coordination**, as will be better discussed in Chapter 3.1.4.

Moreover, the Italian pilot focuses on infrastructure validation, ensuring that new components are tested before deployment to minimize risks and reduce operational costs. The **Hungarian and German pilots** focus on **grid flexibility and cost efficiency**, aiming to **improve economic viability through optimized energy distribution and predictive maintenance**. The **Italian Defence Use Case Pilot**

uniquely focuses on **security and blackout prevention**, using Digital Twins to **model large-scale disturbances and design preventive countermeasures**.

3.1.4 TSO-DSO interactions

As already mentioned, all pilots present as applications or aims the enhancement of **TSO-DSO collaboration**. Across the WP6 pilots, the **level of coordination varies significantly**, with some pilots implementing **automated data exchange and redispatch mechanisms**, while others are still defining frameworks for **real-time grid balancing and flexibility optimization**.

Hungarian Pilot – Strengthening TSO-DSO Coordination for Improved Flexibility Management: The Hungarian pilot plans to implement a **unified data exchange framework**, improving electricity flows and grid monitoring through **synchronized analytics**. The flexibility allocation is optimized to balance local distribution needs with national grid stability, supporting a **more proactive and data-driven network management approach**.

Italian Pilot – Defence System for Grid Stability: The **Defence System** in Sardinia is designed to ensure **transmission grid security** and **operational stability**. Currently, **TSO-DSO interactions rely on periodic manual updates**, within the project the pilot aims at implementing **automated threshold adjustments**, allowing real-time defence updates based on DSO inputs.

Italian Pilot – Design Validation System for Grid Expansion: The **Design Validation System** is standardizing the infrastructure development by integrating **Digital Twins, Industry Foundation Classes (IFC), and automated validation processes**. The project has worked to close interoperability gaps between **TSO and DSO infrastructure models**, while also automating the validation processes to accelerate network expansion approvals. The project leverages **IFC-based descriptions of transmission and distribution infrastructure** to standardize the validation framework and map a set of generalizable rules. BIM methodologies are introduced to automate project validation, ensuring the compliance with technical regulations and planning standards.

German Pilot – Real-Time TSO-DSO Collaboration for Market-Based Redispatch: Germany is advancing **TSO-DSO coordination** through Redispatch 3.0 (RD 3.0), which facilitates market-driven congestion management. The pilot integrates **prosumers, including electric vehicles (EVs), into flexibility markets**, ensuring optimized load balancing. Developments have focused on **enhancing real-time dispatch, expanding data-sharing mechanisms, and increasing DSO-driven flexibility services** to ensure more efficient grid management.

Slovenian Pilot – Standardizing TSO-DSO Data Exchange for Grid Stability: Slovenia is developing **TSO-DSO interoperability** through the dynamic modelling of transmission and distribution networks. Currently, **data exchange between ELES (TSO) and EG (DSO) occurs on request**, limiting real-time monitoring capabilities. The pilot is implementing a standardized data exchange framework to **integrate SCADA data into TSO-DSO models and automate data-sharing methodologies for real-time grid stability**.

An overview of TSO-DSO interactions across WP6 pilots is reported in Table 3-4.

Table 3-4 - Overview of TSO-DSO interactions across WP6 pilots

Pilot	Interaction Type	Current State	Future Developments
Hungarian Pilot	Limited coordination in DLR systems	Seasonal rating and generation/consumption data are shared, separate DLR systems, minimal real-time exchange.	Development of a unified framework for data exchange.
Italian Pilot – Defence Use Case	Periodic manual updates	Load disconnecter relay (EAC) data shared twice per year , TSO manually modifies thresholds.	Automation of defence strategy updates based on real-time data.
Italian Pilot – Digital Twinning as a Validation Tool	Not yet fully developed	BIM files are exchanged in IFC standard open format	Future alignment with TSO-DSO validation frameworks .
German Pilot	Market-based redispatch	Uses Redispatch 3.0 (RD 3.0) for congestion management , DSOs play a role in redispatch.	Enhanced real-time monitoring and redispatch flexibility .
Slovenian Pilot	CIM-based dynamic modelling	Dynamic distribution model integrated into transmission grid model via CIM standards.	Improved automation of TSO-DSO data merging for real-time stability analysis.

The **WP6 pilots** highlight several key challenges and necessary improvements for the integration between **transmission and distribution networks**, as shown in Table 3-5.

Table 3-5 - Common challenges and proposed solutions for TSO-DSO interactions

Challenge	Impact	Proposed Solution
Limited real-time data sharing	Reduces TSO-DSO coordination efficiency	Automation of real-time exchange
Different data formats & models	Reduces system interoperability	Adoption of standardized models
Regulatory and market constraints	Slows DSO involvement in flexibility services	Policy alignment for market-driven redispatch
Manual updates in critical systems	Slows response times	Transition to automated grid adjustments

As proposed solutions, the following key areas emerged as **priorities for strengthening TSO-DSO collaboration** across all pilots:

- **Enhancing Real-Time Data Exchange:** the transition from manual or periodic updates to automated, real-time data flows is essential to improve the TSO-DSO coordination.
- **Standardizing models:** the lack of standard data formats and models reduces system interoperability between TSOs and DSOs, leading to inefficiencies in grid operations and flexibility management. The adoption of standards is critical for ensuring uniform data exchange, allowing different system operators to integrate their processes more effectively.
- **Strengthening Market-Based Integration:** regulatory and market constraints currently slow DSO involvement in flexibility services, preventing full utilization of distributed energy resources (DERs) for grid balancing. Including congestion management strategies is essential to improve market-driven grid operations. Additionally, the development of incentive models for DSOs to actively participate in flexibility markets will ensure an effective involvement.
- **Automated Critical Grid Adjustments:** the transition to automated grid adjustments will allow for faster and more efficient responses to system events, ensuring a more resilient and adaptive integrated electricity grid.

3.2 Communication flows, data models and architectures

The second discussion topic focuses on **communication flows** established between the Digital Twin platforms and other systems involved in the demonstration. Understanding how individual DT platforms connect with external systems is crucial for creating a federation of DT platforms, the primary goal of the TwinEU project. According to the project's Grant Agreement, the TwinEU consortium envisions *"enabling new technologies to foster an advanced concept of DT while determining the conditions for interoperability, **data and model exchanges through standard interfaces and open APIs to external actors**"*.

In the current WP6 pilots' implementations, **23 communication flows** have been identified, as detailed in Table 3-6.

Table 3-6 – Data exchanges in the actual WP6 pilots' implementation

DataExchange.frequency	DataExchange.name	DataExchange.data.name	DataExchange.data.datamodel.name
soft real-time	System Operator (SO)-SO phase conductor temperature	phase conductor temperature	/
soft real-time	SO-SO line load	line loading data	/
soft real-time	Weather Data Supplier (WDS) -SO weather data	weather data	/
real-time/scheduled syncs	Metering Point Operator (MPO)-Distribution System Operator (DSO) grid states	grid states (P,Q,V,I)	/
15_minutes	House Energy Management	intraday charging schedule	/

	System Service Provider (HEMSSP)-customer charging schedule		
once a day	DSO-MPO load limits	load limits - steering measures	/
once a day	MPO-HEMSSP load limits	load limits - steering measures	/
once a day	DSO- Flexibility Service Provider (FSP) envelope curve	envelope curves	/
once a day	FSP-HEMSSP envelope curve	envelope curves	/
once a day	FSP-HEMSSP disaggregated customer level	disaggregated customer level	/
in_advance	WDS-DSO weather data	weather data	/
according_to_schedule	design supplier-Transmission System Operator (TSO) project data	Building Information Model (BIM) project data (object data Level of Information Need (LOIN))	BIM model
according_to_schedule	TSO-design supplier outcome of project validation	Outcome of project validation	/
upon_request	customer-HEMSSP specifications	customer specifications	/
upon_request	FSP-Market Operator secured power data	secured power for redispatch	/
upon_request	TSO-Market Operator needed power data	needed power for or redispatch	/
upon_request	Market Operator-TSO purchased power data	purchased power	/
upon_request	TSO-FSP purchased power data	purchased power	/
upon_request	HEMSSP-customer steering of assets	steering of assets	/
upon_request	DSO-TSO dynamic grid model	Dynamic model of distribution network (grid model + metering data)	IEC Common Information Model (CIM)

2 times a year	DSO-TSO grid data	Distribution grid data (amount of power/load)	Matlab/Simulink
2 times a year	TSO-DSO frequency thresholds	Frequency thresholds	/
one time	HEMSSP-FSP customer data	individual customer data	/

The first notable observation concerns the **frequency of data exchanges**, as only three of these flows operate in real-time. This is significant because DT platforms are generally defined as virtual representations of devices or systems, continuously updated with real-time data throughout their lifecycle. The approaches for implementing real-time data exchanges in the WP6 pilots, along with the challenges encountered, are further elaborated in Chapter 3.2.1.

The second observation highlights the **limited use of defined data models** in these interactions; only three of the 23 data exchanges include detailed data models. This issue, along with its implications, is explored in Chapter 3.2.2.

3.2.1 Real-time data exchanges

The implementation of real-time data exchanges is essential for Digital Twin (DT) platforms, as these platforms provide real-time digital representations of physical objects or activities. So far, only three flows operate in real time, but the WP6 pilots have reasoned about the approaches to achieve real-time data exchanges, such as:

- **Soft real-time data exchanges:** aggregating and exchanging sampled information at a frequency aligned with the next processing steps (e.g., every 15 minutes).
- **Standard protocols:** utilizing protocols such as IEC 61850-8-1 (MMS or GOOSE), IEC 61850-9-2, IEC 60870-5-104, IEC 62056, IEC C37.118, SFTP, and MQTT.
- **Shared storage solutions:** employing shared databases or network storage, such as Network-Attached Storage (NAS).

The challenges that pilots have faced for the implementation of real-time data exchanges are mainly the following:

- **Scalability issues:** large-scale demonstrations involving massive datasets, such as those spanning entire countries, require significant server capacity, robust synchronization strategies, and solutions to interoperability problems.
- **Data access and security constraints:** strict regulations often govern access to data owned by network operators, complicating integration.
- **Interoperability challenges:** compatibility issues arise due to varying formats supported by different platforms, such as SCADA (Supervisory Control And Data Acquisition) and Energy Management Systems (EMSs).

3.2.2 Data models

The actual WP6 pilots' implementations utilize only three specified data models for their data exchanges. However, some pilots have already identified possible data models to be exploited. The data models gathered are the following:

- **Common Grid Model Exchange Standard (CGMES):** CGMES is a specification defining the interface between Transmission System Operators (TSO) software in order to exchange power system modelling information as required by the European Network of Transmission System Operators for Electricity (ENTSO-E) and TSO business processes [1]. CGMES is defined based on the Common Information Model (CIM) family of standards. Within WP6 pilots, CGMES is already used for modelling distribution and transmission grids. While no IEC CIM extensions are recognized for the necessary implementations in WP6, the limited dynamic modelling of generators is identified as a drawback.
- **Matlab Simulink modelling language:** Simulink is a block diagram environment for multidomain simulation and Model-Based Design, where physical systems can be modelled using block diagrams [2]. Therefore, the modelling language is not a standard model. Within WP6 pilots, it is utilized for modeling distribution grid data and conducting real-time simulations on the OPAL-RT real-time simulator [3]. This model is preferred due to the integration of OPAL-RT's real-time simulation software platform with Matlab/Simulink, unlike other commercial software widely used by DSOs and TSOs, which do not support real-time studies.
- **UCTE-DEF (UCTE Data Exchange Format):** it is an exchange format specified by the UCTE for the exchange of grid model among its members [4]. Data refer to load flow and three-phase short-circuit studies and describe the interconnected extra high-voltage network. Within WP6 pilots, it is used for operational planning purposes and for modelling Individual Grid Models (IGMs).
- **Hungary operators' data format:** it is an agreed data format used for data exchanges between network operators in Hungary. It is used by the Hungarian pilot within WP6.
- **Industry Foundation Classes (IFC):** it is the standard model used by the Building Information Modelling (BIM) methodology for the digital description of the built environment, including buildings and civil infrastructure [5]. Within WP6 pilots, it is used for describing information about the design of new network infrastructures, such as HV/MV primary substations. Moreover, the **Information Delivery Specification (IDS)** standard has been identified for specifying and checking information requirements from IFC models [6]. Moreover, IDS is used for identifying potential design issues, conflicts or inconsistencies in the model and resolving them before they become a problem in the real constructed structure.

During discussions, the pilots emphasize the necessity of adherence to internationally accepted standards to ensure compatibility and interoperability across systems. Standards provide indeed a comprehensive framework for data exchange and modelling in the energy sector, enabling communication between various applications and ensuring stakeholders can effectively share and use data.

To further strengthen standardization efforts within WP6 pilots, it is recommended to:

1. Review existing standards that could be applied to data exchanges in Digital Twin implementations;

2. Propose any gaps or new requirements identified to international standardization bodies to enhance interoperability and create unified frameworks across the energy sector.

By leveraging established protocols and proactively contributing to standardization, the project can ensure that Digital Twin solutions are robust, reliable, and secure, fostering effective collaboration across the European energy landscape.

3.3 Digital Twin validation

3.3.1 Digital Twin features of WP6 pilots

During the last phases of the project, WP6 pilots have been validated against the TwinEU architecture and the TwinEU Digital Twin federation framework. The findings from Task 6.1's homogenization analysis could contribute to shaping this architecture and refining the federation framework by leveraging the features identified across the pilots (Figure 3-2).

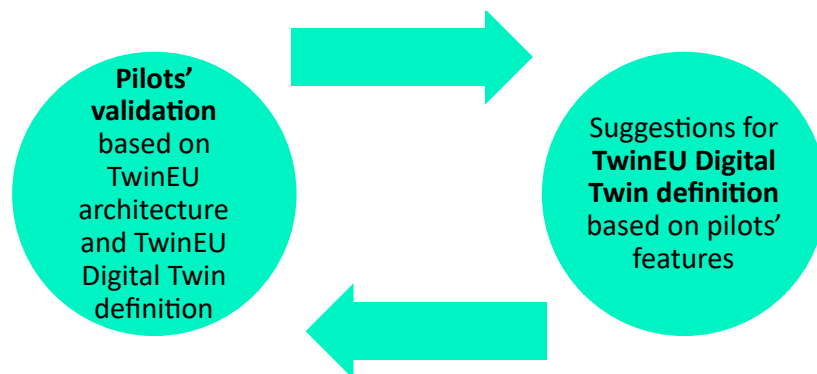


Figure 3-2 – Exchanges between WP6 pilots' features and TwinEU Digital Twin definition

The following features highlight the core capabilities of WP6 platforms that define them as Digital Twins and contribute to shaping the TwinEU Digital Twin framework:

- **Real-time data monitoring and visualization:** some platforms continuously retrieve operational data from SCADA systems or gather real-time field measurements. These capabilities enable efficient monitoring and support effective system management.
- **Prediction capabilities:** some platforms incorporate algorithms to predict the potential dynamic behaviour of system or network measurements. These predictions increase the possibility of a higher level of utilization without decreasing the level of operational safety, reducing the reliance on constant sensor readings. In particular, some predictive algorithms are based on artificial intelligence techniques, such as Artificial Neural Networks (ANNs).
- **Simulation capabilities:** WP6 platforms provide results in a virtual environment that can inform real-world actions, enabling feedback loops between the virtual and physical worlds. Digital Twins allow critical scenarios to be tested safely. Additionally, real-time simulators with time synchronization kits, employing hardware-in-the-loop (HIL) approaches, are utilized. WP6 pilots exploit two simulation tools: Simulink [7] and PowerFactory [8].
- **Connection to other systems:** WP6 platforms connect themselves to other platforms and systems, such as systems providing environmental data. Moreover, they explore the possibility of connecting with other similar platforms and constituting a network of DTs, which is in line with the objectives of TwinEU project of creating a federation on DTs. In particular,

the possibility of connection of real-time simulators exploiting the VILLAS framework [9] is explored, which uses the remote model as a black box without directly impact on the laboratory facilities.

- **Improved network models over the time:** WP6 platforms include network models evolving over the time, making the DT grow, so that the tool becomes more complex and accurate during the time.
- **Support for planning:** some WP6 platforms relate to something under construction, and not actually operating. In this way, the digital shadow or digital model is implemented, which is preliminary for the further development of the related digital twin, once the system is implemented.

3.3.2 WP6 KPIs

Within WP9, and in particular Task 9.1, the technological developments implemented across the pilot demonstrations have been consolidated and homogenized, and their outcomes have been cross evaluated to assess transferability and replicability. In this context, Task 9.1 has defined a **KPI catalogue** that gathers the key performance indicators collected from the pilots. These KPIs are organized according to four evaluation levels (component, DT system, use case, cross-pilot levels) and five dimensions (technical performance, operational impact, market and business relevance, data and federation aspects, transferability and scalability).

The final KPI catalogue includes 15 project-wide Grant Agreement KPIs (GA_KPI01-15) and 15 cross-pilot validation metrics (VAL_KPI01-15). Several of these validation metrics are common to multiple WP6 pilots, as shown in Table 3-7.

Table 3-7 – Cross-pilot validation metrics identified in T9.1

KPI_ID	KPI name	German Pilot	Hungarian Pilot	Italian Pilot	Slovenian Pilot
VAL_KPI01	DT model output accuracy	YES	YES	YES	YES
VAL_KPI02	DT computational performance and latency	YES	YES	YES	YES
VAL_KPI03	Impact on congestion and constraint violations	YES	YES		
VAL_KPI04	Cyberattack detection and mitigation effectiveness				
VAL_KPI05	Forecasting quality for DT-enabled decision support				

VAL_KPI06	Operational decision lead time gained by DT	YES			YES
VAL_KPI07	Market and flexibility value unlocked by DT		YES		
VAL_KPI08	Data quality index for DT input data	YES		YES	YES
VAL_KPI09	Data federation and interoperability coverage	YES	YES	YES	YES
VAL_KPI10	Transferability and replication potential score	YES	YES	YES	YES
VAL_KPI11	Open-source compliance and transparency	YES			
VAL_KPI12	Stakeholder usability and acceptance	YES	YES	YES	YES
VAL_KPI13	Frequency response effectiveness				
VAL_KPI14	DER aggregation model accuracy			YES	
VAL_KPI15	DT validation completeness score			YES	

The table shows that the following KPIs are common to all pilots:

- **DT model output accuracy:** measures how accurately the DT reproduces key grid variables against reference values, which may include field measurements, historical records, or validated simulation results, depending on the pilot.
- **DT computational performance and latency:** measures the DT execution time across real-time, near-real-time, and offline operations, such as forecasting, and may also include scalability under different load conditions.
- **Data federation and interoperability coverage:** measures the extent of data federation and interoperability among DT instances.
- **Transferability and replication potential score:** assesses the potential to replicate DT solutions in other contexts.

- **Stakeholder usability and acceptance:** measures end-user satisfaction and the perceived usefulness of DT tools.

In addition to these common metrics, the pilots identified more specific KPIs during the definition of their use cases. These indicators are closely linked to the distinctive features of the implemented DT platforms. In this work, such pilot-specific KPIs have been mapped to the applications and aims identified for the WP6 platforms in order to highlight common areas of interest and support a more structured comparison across the pilots.

Table 3-8 and Table 3-9 present the mapping of KPIs to WP6 applications and aims.

Table 3-8 - KPIs identified by WP6 pilots, mapped to WP6 applications

Application	KPI
Allocate grid hosting capacities	Increase in visibility of connected assets
	OCC processes
	automated CR processes
	automated CR processes and OCC
Asset management	Potential substitutions
Data integration between DSOs and TSOs	Equivalent dynamic network model is merged with dynamic transmission network model
	Number Data Streams
Direct power line monitoring	Over 3 physical sensors used
	Number of trained virtual sensors
	Over 1 of successfully trained models
	Virtual sensor accuracy (max & mean)
	Virtual sensor accuracy (outliers)
	Power lines covered with virtual sensor
Dynamic analysis of power system	Successful run of dynamic RMS analysis with included equivalent distribution model
	Dynamic network model of the transmission grid with observability area is developed
	Run dynamic network analysis on the extended network model with operational data retrieved from SCADA

	Operational data are successfully retrieved and imported in the simulation tool
Enhance grid observability	Increase in Grid Observability accuracy
Grid design and planning	Decrease in time needed to establish network capacities
	Reference profiles
	Automatization pipeline model building
	Characterization of flexibility sources
Identify and alleviate congestions	Achieved aggregation of EVs in the algorithm
	Increase in Response Time
Identify steering measures	Increased successfully steered charging events
Implement envelope curves	Increase in envelope curves implemented
Manage system stability and security	Creation of a dashboard
Promote standard data models and workflows	Rules analysis
	Translation of standard
	Data model development
	Objects in model production
	Extension of data model
	Dynamic network models exchange

Table 3-9 - KPIs identified by WP6 pilots, mapped to WP6 aims

Aim	KPI
Enable exchange of network models in a standardized and interoperable way	Operational data are successfully retrieved and imported in the simulation tool
	Dynamic network models exchange
Enhance TSO-DSO interactions	Number Data Streams
Facilitate more accurate and dynamic modeling of the transmission network	Successful run of dynamic RMS analysis with included equivalent distribution model
Increase consumer involvement	Increased successfully steered charging events

Increase efficiency of grid operation/management	Increase in Grid Observability accuracy
	Achieved aggregation of EVs in the algorithm
	Increase in Response Time
	Increase in envelope curves implemented
Increased security and observability of system stability in real time	Dynamic network model of the transmission grid with observability area is developed
	Run dynamic network analysis on the extended network model with operational data retrieved from SCADA
Performing sensitivity analysis by considering the evolution of system parameters	EMT component models
Reduce grid planning costs	Increase in visibility of connected assets
	OCC processes
	automated CR processes
	automated CR processes and OCC
	Decrease in time needed to establish network capacities
Test physical devices in a safe way	HIL tests for protection purpose
Test TSO-DSO interactions	Equivalent dynamic network model is merged with dynamic transmission network model
Time saving	Reduction of documents
	Efficiency of design validation

3.3.3 Feasibility of integration in TwinEU federated architecture

Within the TwinEU project, and in particular in WP4, a federated Digital Twin (DT) architecture has been developed to interconnect the DT technologies implemented and demonstrated in pilots across Europe. The core component of this architecture is the **TwinEU DT Federator**, designed to enable interoperable, secure, and sovereign exchange of data and models across heterogeneous energy systems and stakeholders.

The TwinEU DT Federator has been developed to operate within a **data space**–compliant environment, and therefore it is called Data Space Protocol (DSP) connector. Data spaces represent a promising class of decentralized infrastructures for innovative, secure, and trustworthy data exchange

among heterogeneous actors, helping to reduce fragmentation, enhance interoperability, and support the integration of diverse renewable energy and sensor data sources within the energy sector.

To validate the TwinEU architecture and demonstrate its broad applicability, the sharing of specific DT models and data structures originating from different pilots has been implemented and tested. This validation activity enabled cross-pilot collaboration to address selected challenges using the federated TwinEU architecture and is referred to, within the project, as **pan-European scenarios**.

Pan-European scenarios were identified and validated within WP2 and WP4. Furthermore, DT platforms developed in WP6 participated in several of these scenarios. Through this process, WP6 partners were able to test the main IT architecture by exchanging data and/or models, and to identify strengths, limitations, and open issues related to the TwinEU federated architecture. The pan-European scenarios considered in this context, which involve WP6 partners, are listed below.

- **Scenario 0 - Data Exchange**

The data exchange scenario involves all partners and is about a common data exchange using TwinEU DSP connector. All WP6 partners are onboarding for this scenario, but some issues and criticalities have been identified for the effective deployment. For example, some partners are experimenting with cybersecurity issues.

- **Scenario 1 - Pan-European distribution grids hosting capacity map**

This scenario has been proposed by the German pilot, which defined and developed an advanced grid hosting capacity map. From this concept, an implementation supporting cross-operators views have been developed, in order to provide a harmonized, real-time digital interface for visualizing grid hosting capacity across Europe, combining advanced grid data simulations and APIs that support DSOs and TSOs in the grid connection process for new distributed energy resources. TwinEU's Hosting Capacity Maps address the transparent and harmonised data on available capacity at both transmission and distribution level by proposing a standard for the publication of capacity data and reducing connection delays, which is a key bottleneck in renewable energy deployment.

Within this scenario, the pan-European Data Space interface has been successfully tested and implemented, and hosting capacity data are published to TwinEU pan-European connector

- **Scenario 2 - Co-optimization of the energy and balancing capacity market coupling with dynamic flow-based auction**

This scenario has been proposed by the Hungarian pilot within WP7 and regards the development of a unified auction platform enhanced by dynamic, flow-based capacity calculation for co-optimising energy and balancing capacity markets. This scenario involves also the Hungarian pilot in WP6, as the platform takes as input the Dynamic Line Rating (DLR) result produced as output by the ANN algorithm.

This data exchange is successfully based on connector-based sharing through the TwinEU data space

- **Scenario 5 - System security and stability**

This scenario represents the core of the Slovenian pilot and focuses on the development of a dynamic model for Dynamic Security Assessment (DSA). It involves the definition of a transmission network dynamic model based on cross-border dynamic data exchange among different TSOs. The model relies on a comprehensive and reliable set of static and dynamic parameters, including data required for observability area modelling (electrically close partners) as well as for outer equivalent parametrization (electrically distant partners). These parameters cover network topology, generation sources, and load characteristics.

From a technological perspective, the TwinEU dataspace connector was successfully tested within this scenario. However, its deployment in a real operational environment revealed cybersecurity-related issues, consistently identified by all TSOs involved in the demonstration. Inter-TSO data exchange is inherently sensitive and subject to strict, standardized, and well-established rules that are widely recognized by the TSO community as secure and trustworthy. As a result, a decision was made to execute this scenario without using the dataspace connector.

- **Scenario 6 - Digital twin for power line monitoring**

This scenario constitutes the core of the Hungarian pilot within WP6 and focuses on the training of artificial neural network (ANN) models for the real-time estimation of Dynamic Line Rating (DLR) and conductor temperature. Other pilots may contribute to this scenario by preparing and sharing the datasets required for model training and validation. Required data are overhead lines data, SCADA data, weather data and sensor measurements.

Within the German pilot, the TwinEU connector was also tested to support TSO–DSO coordination, including the involvement of an aggregator. The results indicate that Digital Twins and standardized Data Spaces can represent a viable building block for a pan-European redispatch mechanism; however, this technological foundation must be complemented by appropriate regulatory frameworks, market design choices, and alignment of TSO/DSO operational processes. In addition, the stringent cybersecurity requirements associated with software installed at TSO and DSO premises need to be carefully addressed.

By contrast, the Italian pilot did not implement the TwinEU connector. For the Design Validation use case, priority was given to a Common Data Environment (CDE), reflecting a pragmatic approach that leverages existing infrastructure and established data-ownership practices. Similarly, for the Defence System use case, the TwinEU connector was not adopted; instead, a functionally equivalent solution was implemented using standard communication protocols.

Finally, all WP6 partners were able to install and test TwinEU connector, but some criticalities should still be fixed for the implementation in real environment.

4 Conclusions

This deliverable presents the **homogenization analysis** conducted to identify similarities and differences among the WP6 Digital Twin platforms developed for specific applications in **grid management, operations, and monitoring**. The key outcomes of this work are here summarized:

- WP6 pilots address complementary aspects of grid management, operation, and monitoring, with Digital Twin development driven by **different objectives**, including cost optimisation, customer engagement, and grid security (see Chapters 3.1.1-3.1.3).
- All pilots focus on **TSO–DSO interactions**, highlighting common challenges such as limited real-time data sharing, interoperability issues due to heterogeneous data models, and regulatory and operational constraints (see Chapter 3.1.4). **Real-time data exchange** approaches remain limited by scalability, data access restrictions, and security concerns, while the adoption of standard data models is still insufficient to ensure interoperability across systems (see Chapter 3.2).
- **WP6 Digital Twins** provide key functionalities such as real-time monitoring, predictive analytics, and simulation capabilities, supporting both operational decision-making and asset planning (see Chapter 3.3.1).
- **Cross-pilot evaluation** based on KPIs confirms the performance and transferability potential of the developed solutions, while also highlighting pilot-specific validation needs (see Chapter 3.3.2).
- **Integration into the TwinEU federated architecture** is feasible and promising, as demonstrated through pan-European scenarios, but open challenges remain related to cybersecurity, operational constraints, and real-world deployment (see Chapter 3.3.3).

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