



From conceptual use cases to real demonstration - DT for smart coordinated planning of the grid

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List of Abbreviations and Acronyms

Acronym	Meaning
AGC	Automatic Generation Control
AI	Artificial Intelligence
AMQP	Advanced Message Queuing Protocol
API	Application Programming Interface
CRoF	Control Room of the Future
DG	Distribution Grid
DMS	Distribution Management System
DSO	Distribution System Operator
DT	Digital Twin
EHV	Extra High Voltage
EMT	Electromagnetic Transient
ENTSO-E	European Network of Transmission System Operators for Electricity
EV	Electric Vehicle
FCA	Flexible Connection Agreement
FFR	Fast Frequency Response
GIS	Geographic Information System
GUI	Graphical User Interface
HV	High Voltage
IEC	International Electrotechnical Commission
IoT	Internet of Things
KPI	Key Performance Indicator
LFM	Local Flexibility Market
LFMO	Local Flexibility Market Operator
LTS	Local Trading Solution
LV	Low Voltage
MVA	Mega Volt-Ampere
MV	Medium Voltage
NEMO	Nominated Electricity Market Operator
PLC	Programmable Logic Controller
P2P	Peer-to-Peer
p.u.	Per Unit

RES	Renewable Energy Sources
RMSE	Root Mean Square Error
RoCoF	Rate of Change of Frequency
RMS	Root Mean Square (simulation/modeling domain)
RTDS	Real-Time Digital Simulator
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SIOM	Sistema de Información del Operador de Mercado (Market Operator Information System)
TSO	Transmission System Operator
TYNDP	Ten-Year Network Development Plan
UC	Use Case

Executive Summary

This deliverable reports the activities carried out within Work Package 8 of the TwinEU project, dedicated to the demonstration of Digital Twins for smart coordinated grid planning. The work brings together transmission system operators, distribution system operators, market operators, research organisations and technology providers from the Iberian Peninsula and the Netherlands to demonstrate how Digital Twins can support planning and operational decision-making across multiple layers of the electricity system.

The demonstrations cover a broad range of use cases, including dynamic stability assessment of high-renewable power systems, AI-supported transmission system operation, synthetic renewable generation scenario creation, hosting capacity assessment, flexibility-based grid planning, maintenance planning, probabilistic cross-border capacity allocation, grid-equivalent modelling, short-circuit assessment, and market integration through local flexibility markets. Together, these use cases illustrate the value of Digital Twins as decision-support instruments capable of combining real operational data, advanced simulations, predictive analytics and interoperability mechanisms.

The results demonstrate that Digital Twins significantly enhance situational awareness and planning accuracy across both transmission and distribution networks. At transmission level, they enable operators to evaluate future low-inertia scenarios, automate dynamic stability assessments, identify remedial actions through AI-assisted approaches, and improve cross-border coordination. At distribution level, Digital Twins provide more accurate hosting-capacity calculations, facilitate N-1 and N-k security assessments, support maintenance planning, and unlock flexibility-based solutions capable of delaying or avoiding conventional network reinforcement.

Overall, the WP8 demonstrations confirm that Digital Twins can become a strategic capability for European grid operators. Through the TwinEU federated framework, they create a pathway towards more coordinated, transparent and efficient grid planning practices that support the energy transition while preserving network security, resilience and affordability.

1 Introduction

The power sector is undergoing a transformation from a bulk-based generation systems to a distributed multidirectional environment. This new ecosystem requires increased intelligence in grid planning activities. In this sense, Digital Twin technology has emerged as one of the most promising solutions to address the challenge. Digital Twins enable operators to move beyond static network models towards continuously evolving decision-support environments capable of assessing present and future system conditions.

Particularly relevant is the role of Digital Twins in smart coordinated planning of the grid. Future power systems require stronger coordination among Transmission System Operators (TSOs), Distribution System Operators (DSOs), market operators, flexibility service providers and other stakeholders. The increasing interaction between transmission and distribution networks, together with growing cross-border exchanges and local flexibility markets, calls for planning approaches that can simultaneously consider multiple actors, multiple time horizons and multiple layers of the electricity system.

1.1 Scope of Task 8.1

The aim of T8.1, the task that D8.3 reports, was to transfer and adapt the TwinEU concept from WP2 to the pilots involved in WP8 (Iberian and Dutch Pilots). T8.1 focused on transferring the concept applicable to the smart coordinated planning of the grid. The task was conceived to provide a consolidated conceptual framework for efficient management and operation of the pilot DTs.

In addition to the insights that WP2 offered, T8.1 was also the dedicated activity that coordinated the bidirectional communication and information exchange between the involved DTs in WP8 and WPs 3 and 4, dedicated to building the whole central architecture of the TwinEU Federation of DTs.

A summary of T8.1 interactions is provided in Figure 1-1, while the methodology is described in detail in Chapter 2.

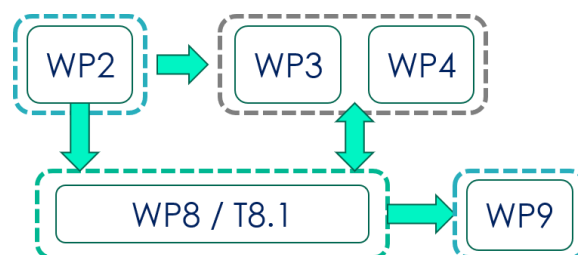


Figure 1-1 - . T8.1 integration within the TwinEU workplan

1.2 Objectives of D8.3

D8.3 aims at reporting the methodological homogenization conducted to drive the developments in the context of a smart coordinated planning of the grid so that they are fully compliant with the TwinEU approach towards a Federated Digital Twin Continuum.

D8.3 describes the conceptualisation process and the activities undertaken to monitor progress in the development and configuration of the Digital Twins involved. D8.3 draws a set of conclusions based on the results of the demonstration activities to enhance the capacities of European grid

operators in the field of grid planning through the use of Digital Twins, and especially within the pan-European Digital Twin federated framework proposed by the project.

1.3 Outline of the Deliverable

After the introduction to WP8 and T8.1 provided in Chapter 1, Chapter 2 provides a general overview of the WP objectives and describes the involved DTs in each one of the pilot sites involved, the Dutch and the Iberian Pilot Sites.

Chapter 3 summarises the use cases developed and demonstrated in the scope of the WP and matches them with the overall WP objectives.

Chapter 4 specifies the relation between the local use cases that were developed in WP8 with the pan-European scenarios validated in the framework of T4.6.

Chapter 5 takes the TwinEU reference architecture and identifies which parts of the total framework were integrated into the UCs developments and used in the validation and demonstration activities.

Chapter 6 reports the methodologies followed per DT for the development and demonstration of the associated UCs.

Chapter 7 presents the main takeaways per DT coming from the results of the UC demonstration activities.

Finally, Chapter 8 merges these into a comprehensive set of conclusions for the use of Digital Twins for the smart coordinated plan of the grid.

1.4 How to read this document

D8.3 presents the overall picture of the activities undertaken in the framework of WP8, including all pilots and all DT uses comprehended in each one of the WP tasks. D8.3 gives a general overview of (i) the technologies and systems involved in the WP, (ii) how the proposed use cases match the WP objectives, (iii) how the WP partners leverage the work done to participate in panEU scenarios, (iv) how the WP use cases implement the reference architecture, (v) the methodology and results employed for the development and demonstration of the proposed use cases, and (vi) a set of final conclusions for the use of DTs in the smart coordinated planning of the grid.

2 General overview of the WP objectives and involved DTs per pilot site

The aim of WP8 is to instantiate and demonstrate the digital twin continuum investigated in TwinEU for smart coordinated planning of the grid. WP8 demonstrates, in two different EU regions (The Netherlands and the Iberian Peninsula), how the services provided in WP4 can facilitate the coordinated planning by different stakeholders, such as TSO, DSOs and market operators.

Each regional implementation of the TwinEU continuum is demonstrated with a series of DTs that make use of the enhanced technological possibilities that the digital twinning technology and the federation concept provide to go beyond the state of the art in terms of grid planning and subsequent operation.

2.1 Digital twins in smart coordinated planning of the grid

Power Systems Digital Twins (DTs) have moved well beyond static planning models. Today's digital twins emphasize closed-loop, data-driven planning across design, operation, maintenance, resilience, and security. The technology is especially interesting in grids with high shares of renewables, distributed energy resources, storage, EV charging, and active prosumers. Such an ecosystem presents the new energy system model given after the latest energy transition.

Electricity systems digital twins are the digital copy of a physical system with the ability to simulate scenarios in the grid with high accuracy and perform supervised control actions when needed. DTs running for grid planning are no longer a one-time exercise around deterministic load growth, but a continuous coordination tool to manage uncertain demand, variable generation, congestions and voltage constraints, among other challenges.

2.2 Involved Digital Twins in the Iberian Pilot Site

2.2.1 Transmission Systems DTs

At transmission level, two different Digital Twins are involved in the demonstration activities, owned and operated by the two TSO in the Iberian Peninsula. REE is the TSO demo partner in the Spanish side of the Pilot, operating its TS DT as end-user and is supported by CIRCE for some of the technical developments required for the demonstration of TwinEU's DT-based Use cases. In the case of the Portuguese side of the Pilot, REN is the TSO demo partner and DT end-user and operator, supported by R&D NESTER on the IT side concerning their DT.

2.2.1.1 REE's transmission grid DT

Two use cases of the Digital Twin were developed and tested in the framework of T8.3 for the power transmission system using information and expertise for Spanish TSO Red Eléctrica. The first use case focuses on simulation of synthetic renewable resources profiles for power system studies application, and the second use case is to develop AI based algorithms to support the control centre decision for power system operation.

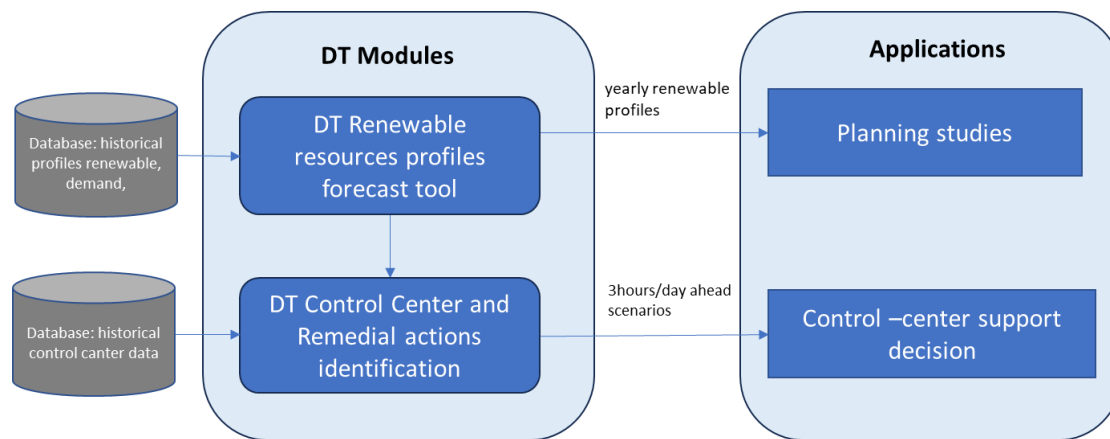


Figure 2.1. DT Modules and Applications for REE's transmission grid DT

DT module: Renewable resources profiles tool

This digital twin module aims to emulate and generate different profiles of renewable resources relevant for power system planning and operation. Based on historical data of the power system, the digital twin is able to generate different synthetic profiles of renewable power such as wind, solar radiation and hydropower.

Operation application: The scenarios generation digital twin module is also able to create probabilistic generation scenarios and profiles for power system operation in day-ahead timeframe. These profiles generated are used as input data historical records from the control centre, creating different probabilistic scenarios of the power system and generation. The probabilistic scenarios obtained could be used as an input for the DT control centre and remedial actions identification described below.

DT control centre and remedial actions identification

This DT module faces challenges in power system operation from control centre and identification of effective remedial actions (if required) typically proposed by control centre operators to preserve power system security. For that purpose, an advanced tool was developed, combining AI-based algorithms with optimisation methods.

The key component of the methodology is the integration of an optimization system that uses the forecasting grid scenarios and the historical data for real-time to find optimal actions for the system operation in different hours-ahead scenarios. This approach was designed to enable control centre operators to make faster and more effective decisions, as is the case of high penetration of variable renewable power. The validation indicated benefits including improved operational efficiency, efficient management of renewable energy, reduced operating costs, and increased resilience of the power system to unforeseen variations.

Ultimately, this approach aims not only to optimise the operation of the Spanish electricity system, but also to establish a framework for adaptive and sustainable decision-making in the electricity sector, promoting the transition towards a smarter and more efficient grid.

2.2.1.2 REN's transmission grid DT

The DT of REN's Transmission Grid encompasses several key features and capabilities to effectively model, simulate and optimize the operation of the Portuguese transmission grid and interface with neighbor TSO and internal DSO. The DT can be divided into two different frameworks: one stationary and another dynamic.

The stationary DT transmission grid model details comprehensively a representation of the entire Portuguese transmission network, including substations, transformers, transmission lines, and other grid components. It accurately captures the physical and operational characteristics of each asset regarding steady-state. The DT involved in the Pilot Site Ecosystem supports scenario analysis capabilities, allowing grid operators to simulate and evaluate different operating scenarios, such as changes in demand, renewable energy integration, or network contingencies. This helps in assessing the impact of various factors on grid stability and reliability. The DT incorporates predictive analytics capabilities that enables the digital twin to forecast grid behavior, identify potential congestion, and optimize grid performance. The DT can feature different functionalities and in the specific case of the pilot site environment is relevant for doing a probabilistic cross-border capacity allocation analysis, cross-border flexibility assessment and short-circuit calculations. Related to the cross-border capacity analysis, the horizontal network identifications method is applied to guarantee that the relevant grid assets are in the DT model.

Regarding the dynamic DT, the main objective is to create a model that represents in a reliable way the distribution grid behavior to disturbances seen from the TSO perspective. The role that distributed generation units connected to these parts of the network have in the overall system performance must be taken into account with respect to different phenomena and planning/operation strategies, once it may represent an important percentage of the total generated power in a given region. Therefore, in order to achieve relevant results within the scope of networks' stability studies, the distribution networks modelling strategies should be revised – from a classical passive lumped loads approach to a dynamic model able to capture the whole active behavior of the grid. However, even assuming the availability of data to fully characterize distribution grids and generation assets connected to it – traditionally difficult since transmission and distribution systems are operated and managed by different companies – a detailed modelling approach would raise increased computational burdens with respect to overall system studies. To maintain data discretion and simulation computational burden within reasonable limits, this DT intends to derive an equivalent, reduced dynamic model able to capture the transient response of the distribution network when facing large disturbances occurring at the transmission side.

REN's Transmission Grid DT also incorporated a communication layer that enabled integration with existing grid-management systems, market platforms, operational tools, and other project DTs., enabling interoperability, data exchange and coordination across different systems, facilitating more efficient grid operation and management.

2.2.2 Electricity Markets DTs

At market level, OMIE is the NEMO, DT operator and end-user, as well as its own IT provider. OMIE makes available two digital twins for the TwinEU project implementation. On the one hand the DT of the wholesale electricity markets is available for studying the collaborative ecosystem, although it was finally neither used nor further developed in the project, and the Local Flexibility Market DT.

2.2.2.1 OMIE's wholesale markets DT

The Digital Twin of the Iberian Electricity Market is based on the architecture of the trading platforms owned by OMIE, which are **fully integrated with** the information exchange systems necessary for compliance with the **European regulation** of the internal energy market, and specifically, the market rules of the Spanish and Portuguese systems.

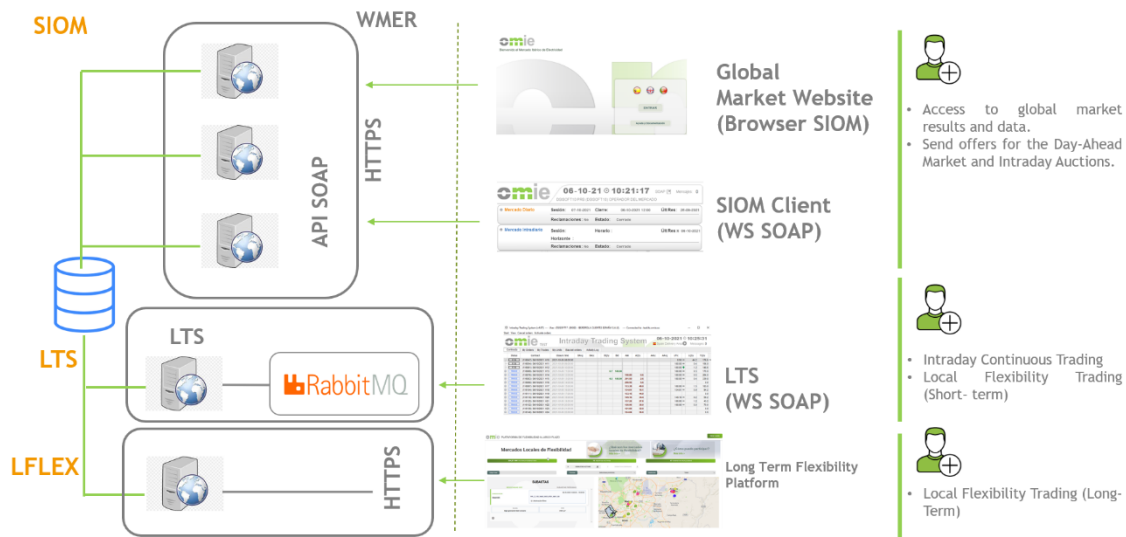


Figure 2.2. OMIE's Market Operator Information System (SIOM) architecture

SIOM: Market Operator Information System

For the negotiation of daily and intraday auctions, **SIOM** incorporates access to the Market Web through “Web Service” technology that complements access through browser, providing an application interface.

LTS (Local Trading Solution) for continuous trading developed by OMIE.

On the other hand, for continuous intraday trading, the connection to OMIE's systems is carried out through the **LTS**. Each NEMO has their own LTS platform to integrate energy transactions among different Members States in the common XBID system.

AMQP messages to communicate with the intraday continuous market through LTS (Local Trade System).

AMQP messages are based on message queues to carry out its communications. An LTS module is made available to market participants as a tool owned by OMIE that facilitates their access without having to carry out any type of external development or integration.

These **types of messages allow to communicate with the trading platform** of the continuous intraday market, being able to perform the following functionalities:

- Presentation of the contracts that are negotiated.
- Sending, cancellation, modification, and activation orders to contracts under negotiation.
- Consult information related to offers, transactions, and units.
- Other information query and update operations

2.2.2.2 OMIE's LFM DT

OMIE is developed two market **platforms for procuring local flexibility markets**. There is one for the local short-term negotiations, with the same technology as the LTS system to provide grouping functionalities in the same market tool.

On the other hand, for the long-term flexibility negotiation, a new market platform has been developed seeking the objective of achieving a more attractive and easier-to-use tool, focused on new roles such as aggregators, DSOs or active consumers with renewable energy resources that have manageable capacity. This long-term flexibility platform has been designed to cover all the processes related to local flexibility procurement to demonstrate this type of negotiation.

This market platform is based on a web application where users, both flexibility-providing markets participants and DSOs, can register themselves using a username and password. Once registered, users are able to participate in long-term flexibility auctions through the GUI to integrate their energy flexibility into the markets.

2.2.3 Distribution Systems DTs

At distribution level ETRA is the main developer of ÉTER, which is the core of ANELL's DT. ADAION took part, along with Cuerva, as main developers of their DT.

2.2.3.1 ANELL's distribution grid DT

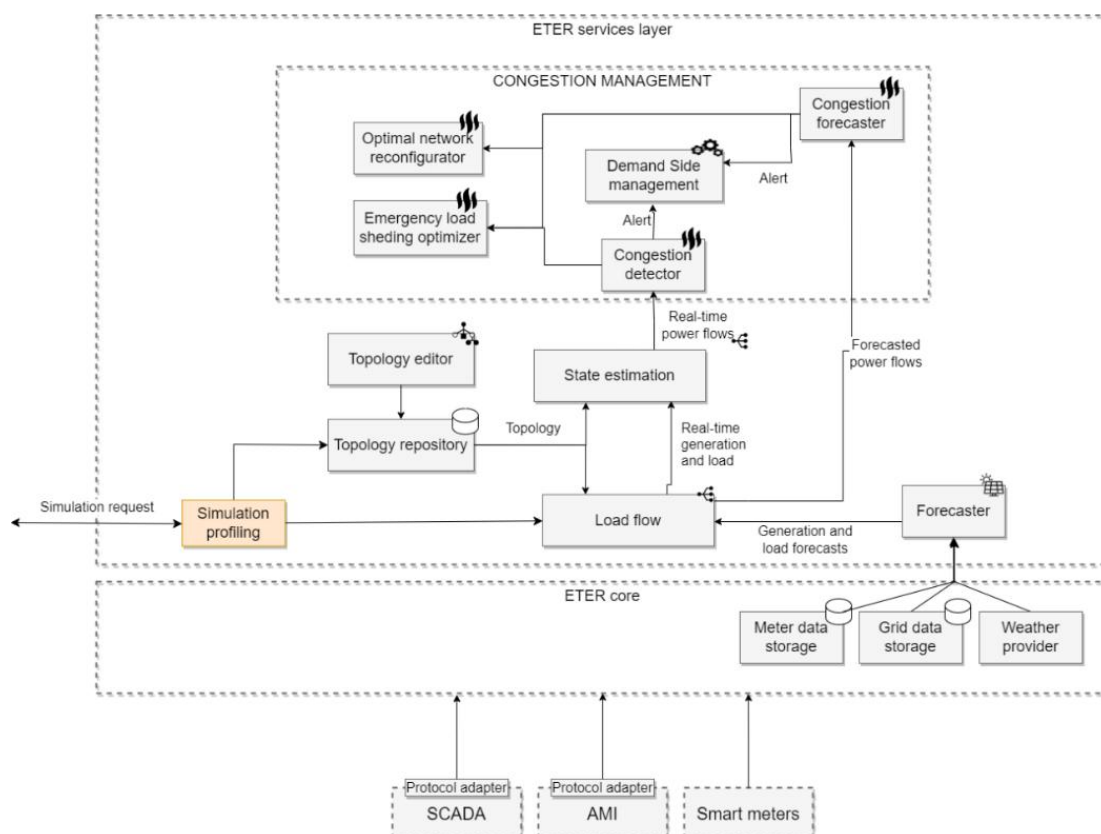


Figure 2.3. ÉTER product architecture with the new Simulation profiling module.

ÉTER is the product within ETRA's portfolio targeting distribution system operators, aiming at facilitating the monitoring, control and planning activities of modern distribution grids efficiently. The application can be categorized as a DMS (Distribution Management System), and as such, it features

several specialized functionalities. The main components or services of ETER are depicted in Figure 2.3.

The functionalities are designed in ETER as independent software modules and subsystems that communicate and coordinate with each other to build the complete platform and fulfil its requirements. This approach is commonly known as micro-service-based architecture and, in comparison to traditional monolithic architectures, it facilitates maintenance of the software modules, minimizes the impact of failures, avoids vendor lock-in or increases reusability of the developments from the design phase. Additionally, ETER is equipped with an additional module to be referenced as Digital Twin, the Simulation Profiling module.

The ESTEBANELL network topology is included in ETER network topology repository following a pre-defined structure. In this way, all the functionalities previously described were used to obtain a distribution network digital twin.

ANELL's Digital Twin was completed with the integration of ETRA's ETER with the local systems currently running in ANELL's premises, with a special focus on the network model in Digsilent. Estabanell (ANELL) currently operates several control hardware (PLCs and RTUs) and software to monitor their network with different monitorization, simulation and control capabilities. The system in use right now is TedisNet, a SCADA software developed by SITEL, a software provider that implements SCADA systems. This system runs locally and uninterruptedly at Estabanell's control centre within its headquarters in Granollers. The features of this embedded Multiprotocol (IEC 870-5-101/104 , Modbus TCP, Prosa, ICCP) platform are listed below:

- Real time information on the status of all the elements and devices of the system both on High Voltage and Medium Voltage
- Historical data analysis and graphic representation
- Generation of tailored feedback
- Alarm management
- Technical calculations and limited simulations
- Automatizations
- Real time power flow calculations
- Distribution quality ratings

Even though TedisNet is not a Digital Twin *per se*, it has some of the DT functionalities such as power flow calculations and limited simulation capabilities which prove the usefulness of a DT in Anell's network. Nevertheless, its limited use and the risk of using a control system to run simulations and tests has highlighted the need for an independent Digital Twin. Therefore, the combination of these systems with ETER set up a fully functional DT aimed at demonstrating the Use Cases and scenarios (both local and pan-European) defined within the project.

2.2.3.2 Cuerva's distribution grid DT

Cuerva's network DT is based on the Adaion Platform. Adaion is a Data driven platform to support Grid Operations and Planning with focus on the LV Network. In a nutshell Adaion transforms the Power Grid into a Digital Asset to help DSOs gain visibility, predictability, and control by gathering data and generating valuable insights and tools.

This is an interoperable and modular platform, with high analytics capabilities and tools for the design, planning, operation, and maintenance of MV and LV grids. It's based on advanced algorithms, AI, third party Digital Twins integration, and a Data Integration Platform.

Adaion integrates multiple sources of data with different formats into a single, unified model. It generates the digital twin of the grid (HV, MV and LV), based on the real data from the measurements and the topology, which is created from the inventory info of the DSO typically provided by the GIS. Based on this digital twin, the platform offers different features that served as a solid basis for developing the project use cases. The most relevant features related to the DT for this project are listed below.

- Power flow capability
- Node Capacity calculation over all the nodes in a grid
- Technical feasibility of new access and connection requirements
- Optimal planner for EV charger massive deployment

From the physical infrastructure side, Cuerva has a highly digitized network included in the DT with the following measuring equipment:

- +5500 users (residential, commercial, and industrial)
- 2 substations
- 220/132 kV 1x160 MVA connected to REE
- 132/66/20 kV
- 31 km of HT lines
- 292 km of MT lines
- 315 km of LT lines
- 100% penetration of Smart Meters, both residential and industrial level
- High-resolution measuring devices in MV
- High-resolution measuring devices in LV

The structure illustrating the measurement map can be viewed in the following image.

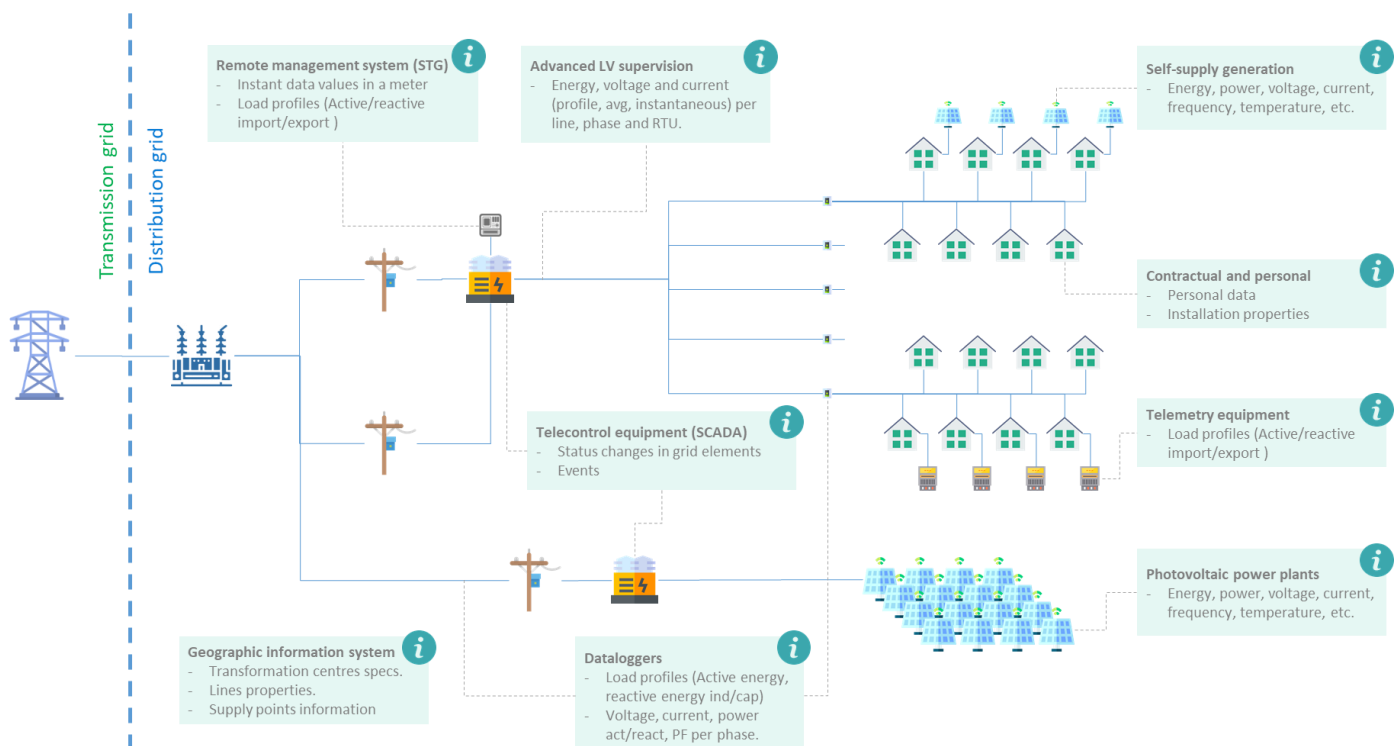


Figure 2.4. Measurement map for the Cuerva's living lab

This setup ensures the availability of reliable datasets concerning the network infrastructure (smart meters, transformers, lines, etc.). However, it's imperative that all this data is processed through a platform capable of aggregating diverse data sources and protocols. This fosters the development of proprietary tools such as APIs, Notebooks, IoT platforms, as well as planning and simulation tools.

2.2.4 High-level Iberian electricity system DT

Additionally, INESC-TEC implements an upper-level DT of the Iberian electricity system in connection with the Central-European System.

The progressive integration of electronic converter based Renewable Energy Sources lead to a reduction of the system synchronous inertia that can endanger the system frequency stability behavior, especially in poorly interconnected systems, such as the case of Iberian system. A Digital Twin representing the dynamic behavior of Iberian system interconnected with the central European system is therefore needed to assess the stability of the Iberian grid when facing large disturbances such as a sudden loss of a large amount of generation. Figure 2.5 describes the dynamic model associated to the DT.

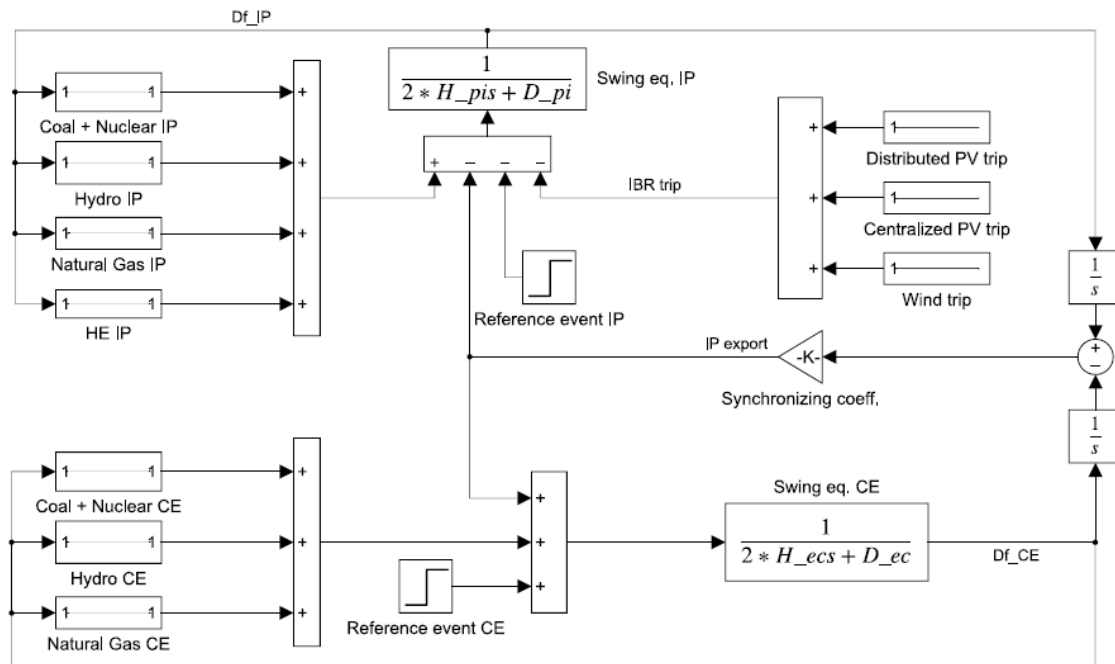


Figure 2.5. DT of the Iberian system interconnected with central Europe

The DT needs to be calibrated using a parameter estimation methodology that tunes the model frequency response to the real system frequency response when facing large disturbances. An initial parameter identification, that involves the identification of the values for system inertia, system damping, generator droops, and synchronization coefficients, was performed by solving an optimization problem, which corresponds to the minimization of the quadratic error summation between the model frequency response and the real system frequency response using in this case a metaheuristic approach based on a particle swarm algorithm. The real data exploited corresponds to the frequency behavior during a disturbance related to the sudden loss of 1 GW of Active Power, due to the Almaraz II Nuclear plant unit disconnection in October 2011. The inertia parameters were subsequently adjusted using engineering judgement to evaluate future-year scenarios. Further calibration was done using data from frequency behaviors following large disturbances obtained from

system operators records. Assessing this data is an important requirement for the quality of the results obtained when using this DT.

The DT can be further expanded to include the AGC operation and control loops as described in Figure 2.6.

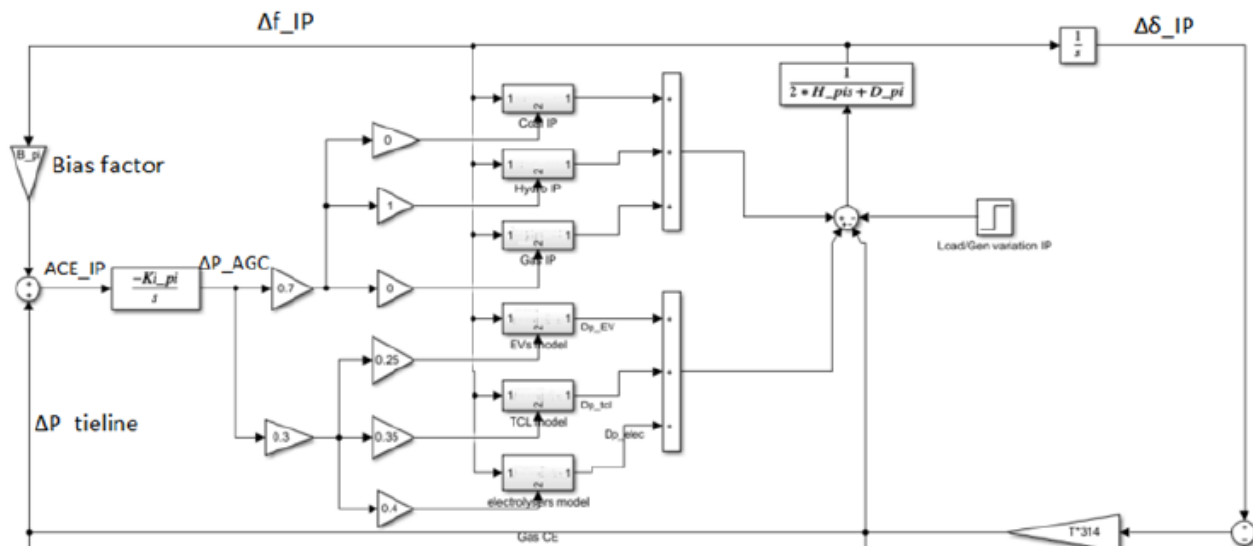


Figure 2.6. Dynamic model of the DT including the AGC control loops and load response

This DT allows modelling different generation technologies, including the ones using electronic power converters related to Renewable Energy Sources and their frequency sensitive modes. It is also possible to include blocks representing the dynamic response from demand like thermal loads, electric mobility and electrolyzers when responding to frequency excursions.

With this DT, and when properly calibrated, it was possible to evaluate the dynamic behavior of the Iberian system when facing active power disturbances, identifying the type, volume and characterization of frequency ancillary services (including innovative ones like FFR, virtual inertia) needed by the system and to be provided by both generation power converters (synchronous and non-synchronous), storage units (hydro pumps or batteries) and responsive demand.

2.3 Involved Digital Twins in the Dutch Pilot Site

The Dutch pilot involved the development of two distinct models: a digital twin and a synthetic data generator consisting of a steady-state model that produces time responses resembling data from actual power systems. The combination of both systems enables the implementation of the DT usability for the grid stability studies in Task 8.2.

The practical demonstrations of these capabilities were conducted within the innovative environment of the Control Room of the Future (CRoF) located at the TU Delft campus. In the CRoF, the demonstration also included a communication layer and tools to simulate interactions with typical SCADA systems. This setting provides a real-world context for evaluating the digital twin's effectiveness in simulating complex scenarios and devising proactive strategies to mitigate potential risks.

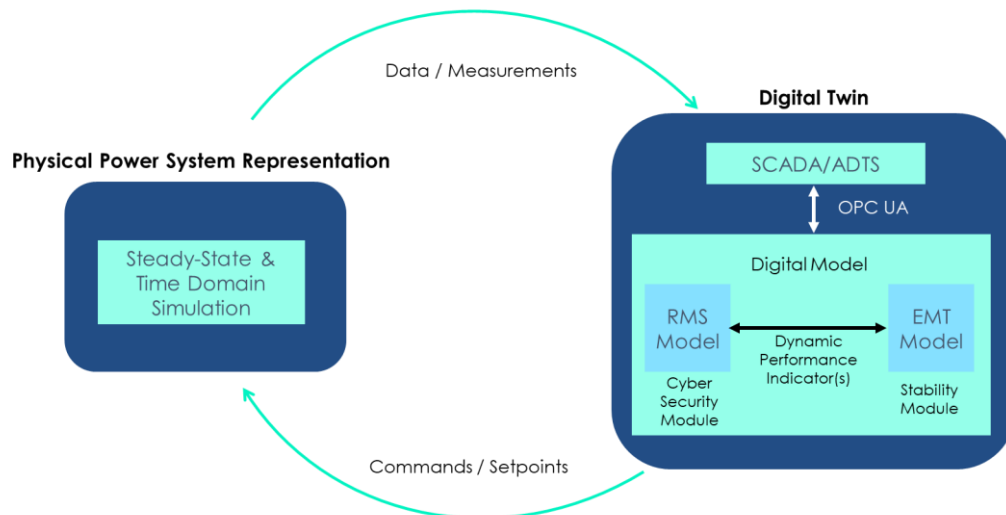


Figure 2.7. Overview of Dutch Integrated DT

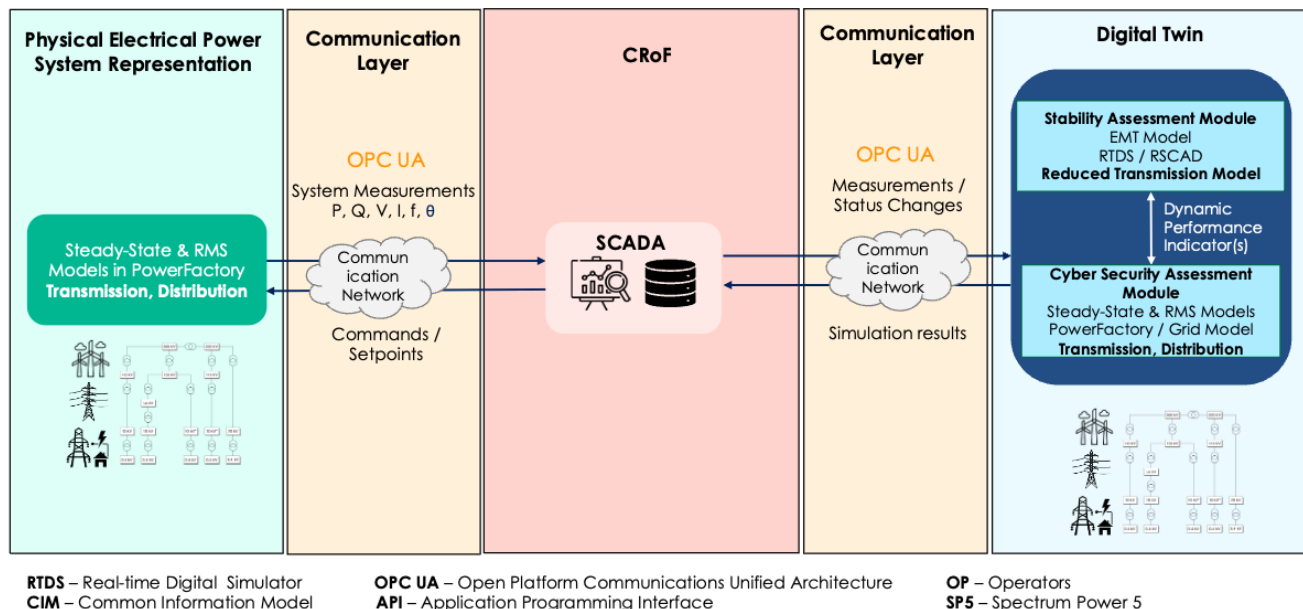


Figure 2.8. Architecture of Dutch Integrated DT

The digital twin incorporates an RMS model for cybersecurity assessment and slow dynamic simulations, and an EMT model for detailed analysis of specific instability issues and fast dynamic simulations. The RMS module consists of a complete model of the transmission network, some sections of the distribution network and equivalent models for the rest of the network. The EMT model includes only the extra-high-voltage transmission network and equivalent models for the rest of the network, since the computational requirements for the EMT real-time simulations are more demanding.

The transmission grid constitutes the backbone of the compound digital twin. TUD's research focused on algorithms and techniques to automate the setup and initialization of parameters of power system components. TenneT, as the transmission operator, advised in the development of the algorithms and validation of the results.

To account for the distribution grid, TU Delft's research is centred on assembling dynamic models that capture essential characteristics for accurate simulation of the system's variables. Alliander and Stedin play a critical role in reviewing and validating the assumptions of model development and its parameters and results against their proprietary distribution models and empirical data.

It is also important to mention that equivalent reduced models were employed whenever possible. However, specific sections of the distribution network with high penetration of renewables or dynamic phenomena of interest were modeled in greater detail. This is because, already today, the energy flows bidirectionally, and the distribution network becomes critical for dynamic studies.

3 Use cases summary and mapping into meeting the WP objectives

A set of 13 use cases was defined and demonstrated across the WP8 pilot activities to demonstrate the use of digital twins for the smart coordinated plan of the grid.

The use cases range from Business Use Cases/Scenarios to actual System Use Cases.

T8.2 – Digital twin for stability of power systems with high penetration of renewable energy sources:

- UC NL02: DT-based dynamic stability assessment under active power flow changing events.

Within T8.2, TwinEU (1) developed a Digital Twin (DT) capable of simulating the dynamic behaviour of the Dutch power systems during active power flow disturbances; (2) calibrated the DT using generated signal records from simulations, accessible published databases, and parameter estimation techniques to obtain a numerically acceptable representation of real-time system dynamics; (3) analysed the impact of various disturbance scenarios on system stability, focusing on frequency deviations, voltage stability, and power oscillations; and (4) evaluated and proposed control and mitigation strategies that enhance the coordination between DSOs and TSOs during disturbance events.

T8.3 – Analysis of digital twin application for control centre support, technical restrictions resolution and operational planning

- UC Ib01: AI Agent for probabilistic grid status forecast and remedial actions identification for the TSO's control centre Operator
- UC Ib02: DT for generation of synthetic series of renewable resources
- UC Ib05: DT-based N-1 contingency analysis
- UC Ib06: DT-enabled new RES integration validated plan in the MV grid
- UC Ib07: DT-based grid maintenance planning activities
- UC Ib08: Long term flexibility in MV
- UC Ib09: Flex Connections
- UC 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.

T8.3 worked in an integrated manner in all voltage levels of the grid. At transmission level, AI-assisted DTs were used to enhance system operation and planning for increased RES penetration. At distribution level, the common key point identified as most benefited from the use of DT technologies is the boost of flexibility-related scenarios for advanced grid planning purposes.

T8.4 – Probabilistic-based cross-border capacity calculations and Cross-border assessment of flexibility and pre-qualification

- UC Ib03: DT-enabled multi-area system dynamic behaviour assessment
- UC Ib10: Probabilistic cross-border capacity allocation
- UC Ib11: Cross-border assessment of flexibility and pre-qualification

- UC Ib13: Enhancement of short-circuit models and TSO/DSO information exchange for operational planning

T8.4 focused on the use of DTs at transmission level for cross-border operations. In this case, there were two different layers of simulation, one with REN's TG DT that also embedded a Distribution Grid digital model for the TSO-DSO collaboration, and another one as a high-level DT of the Iberian electricity transmission system developed by INESC TEC.

The aim of WP8 is to instantiate and demonstrate the digital twin continuum investigated in TwinEU for smart coordinated planning of the grid. WP8 demonstrated in two different EU regions (The Netherlands and the Iberian Peninsula) how the services provided in WP4 can facilitate the coordinated planning by different stakeholders, such as TSO, DSOs and market operators.

WP8 implemented a set of use cases at transmission and distribution level that compile encapsulated scenarios and multi-actor integrated tests to demonstrate this enhanced coordination planning of the grids.

4 Relation of the WP to the pan-European scenarios

Among the activities enabled by the WP8 use cases, the one most closely aligned with a strong business case was the coordination of DSO DTs for participating in the pan-EU hosting capacity map through the TwinEU interoperable data space. This initiative strongly supports the goals of the EU Action Plan for Grids (COM/2023/757), particularly Action 6, which calls for transparent and harmonised data on available capacity at both transmission and distribution levels.

TwinEU's Hosting Capacity Map addresses this by proposing a standard for the publication of capacity data and reducing connection delays, which is a key bottleneck in renewable energy deployment.

The two participating DSOs in the Iberian Pilot showed strong interest in leveraging the simulation results performed by their DTs in the framework of UCs Ib 06, 08 and 14. This way the Pilot contributed with the enhanced results that the DTs offer through the architecture proposed at project level with the data space in its core.

5 Digital twinning for smart coordinated planning of the grid and its application in the DTs federation and the TwinEU reference architecture

Most of the use cases and involved digital twins in WP8, no matter whether they perform 1-actor assessments or whether they use the DTs federation framework, are self-contained in terms of functionalities and services related to the DT per se. This means that one piece of software embeds both the DT and the services required to undertake the demonstration activities.

The Red Eléctrica DT use cases used a slightly different configuration, where the DT is an independent module that is connected to the set or independent services that offer the necessary functionalities to undertake the use cases demonstration activities. In this case, Figure 5.1 represents the relation with the overall TwinEU architecture.

Figure 5.1 represents the sub-section of the TwinEU reference architecture in which these configurations are embedded.

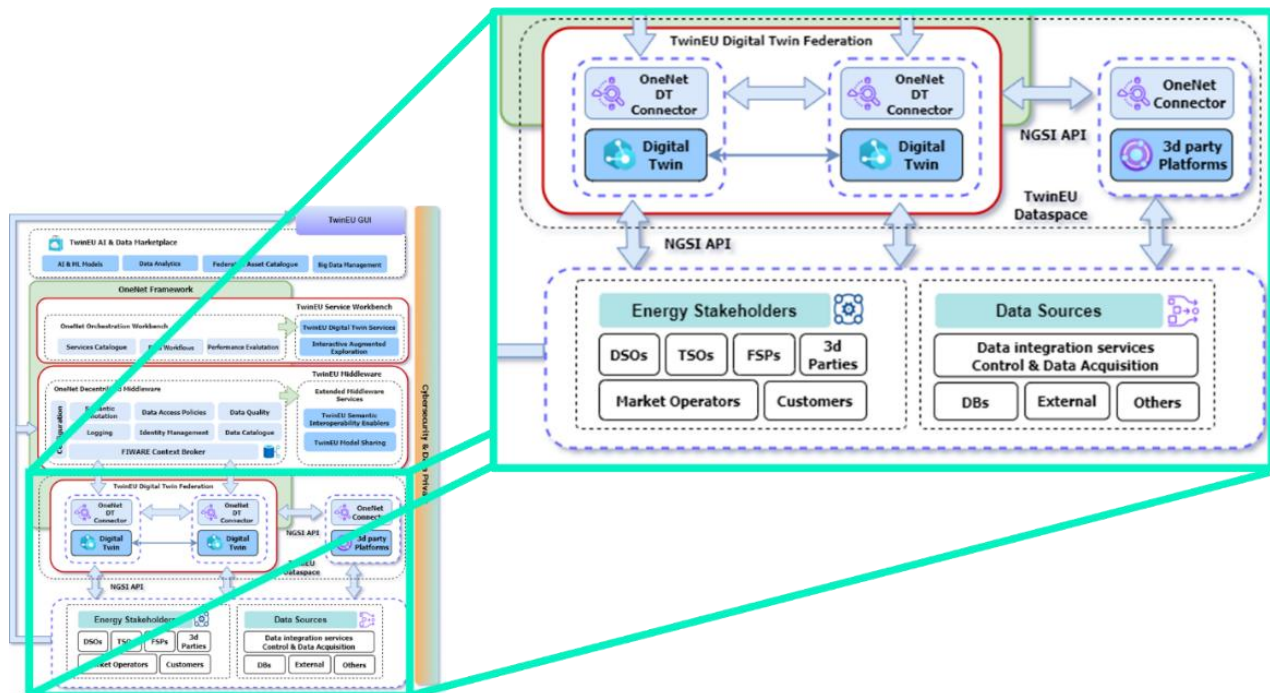


Figure 5.1. Main applicability of the smart coordinated plan of the grid UCs into TwinEU's reference architecture

6 General overview of the WP8 development and demonstration plan

All tasks and the involved Digital Twin-based use cases created detailed development and demonstration plans that helped structure the necessary steps to reach the expected WP outcomes.

6.1 T8.2 Digital twin for stability of power systems with high penetration of renewable energy sources

The implementation of Use Case NL-02 followed a progressive development and demonstration plan, moving from use-case definition and scenario construction to regional and national-scale real-time stability assessment. The resulting demonstrator combines two complementary components: a synthetic model for generating representative future operating conditions and a real-time EMT simulation core for evaluating the dynamic response of the Dutch transmission system.

The first development stage consisted of constructing a synthetic model of the Dutch EHV transmission network in PowerFactory using publicly available grid information and technical reports. The model represents the projected 2030 network and was used to assess operating conditions combining different levels of wind and solar generation, electrolyser demand, and transmission-network contingencies. These studies provided a controlled basis for examining how renewable generation patterns and Power-to-X demand placement affect power flows, voltage profiles, and component loading.

The work then progressed to real-time EMT modelling in RSCAD/RTDS at TU Delft's Control Room of the Future. A regional model of the Randstad network was developed first, incorporating conventional synchronous generation, detailed converter-interfaced offshore wind generation, dynamic network components, and the BritNed interconnection. Its behaviour was assessed under steady-state conditions and representative faults while maintaining continuous real-time execution.

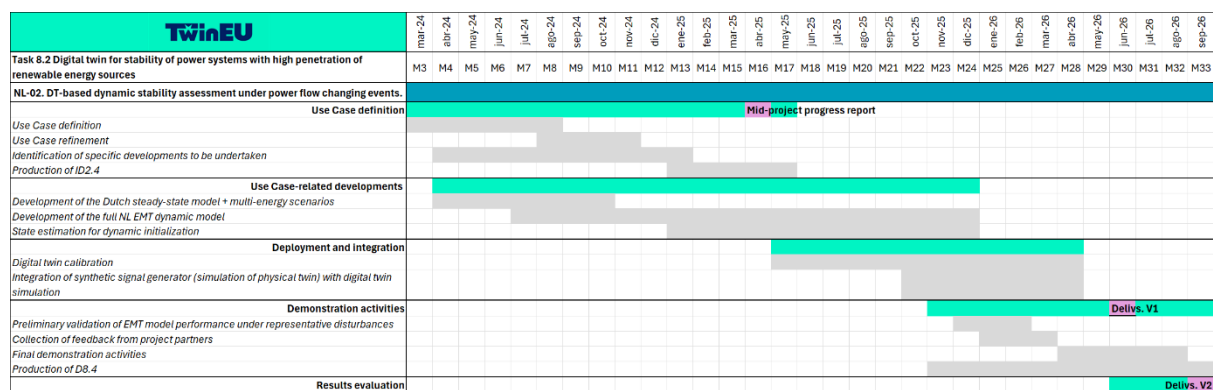


Figure 6.1. UC NL-02 development and demonstration plan

Building on the regional implementation, the demonstrator was extended to a national-scale EMT model covering the Dutch 380, 220, 150, and 110 kV transmission networks. The final model represents the dynamics of conventional synchronous generation, converter-interfaced renewable sources, transformers, transmission lines, dynamic loads, and equivalent neighbouring systems while preserving real-time execution. In the final demonstration stage, the model was applied to high-renewable operating scenarios, and voltage, frequency, RoCoF, and recovery indicators were extracted from the simulated disturbance responses. This established an integrated and scalable DT-

based environment for stability screening, scenario comparison, and further development of operator- and controller-oriented applications, as documented in Deliverable D8.4.

6.2 T8.3 Analysis of digital twin application for control centre support, technical restrictions resolution and operational planning

6.2.1 REE's Transmission Grid DT

Use Cases Ib01 and Ib02 were implemented following a structured process encompassing definition, development, deployment, and validation activities. Throughout the implementation period, weekly coordination meetings between CIRCE and REE enabled continuous monitoring of progress and facilitated agile adjustments whenever required.

For Ib01, the implementation began with the definition of the AI agent's scope, objectives, and functional capabilities, providing the foundation for the subsequent development phase. During development and training, the system architecture and supporting tools were continuously refined, leading to measurable improvements in performance and resilience under a wide range of operating conditions. Once development was completed, the AI agent underwent an extensive validation process in which it was exposed to a broad set of imbalance scenarios representative of real-world grid operation challenges. The validation phase concluded with a comparative assessment between the remedial actions recommended by the AI agent and those traditionally adopted by system operators, enabling a comprehensive evaluation of the tool's effectiveness and operational value.

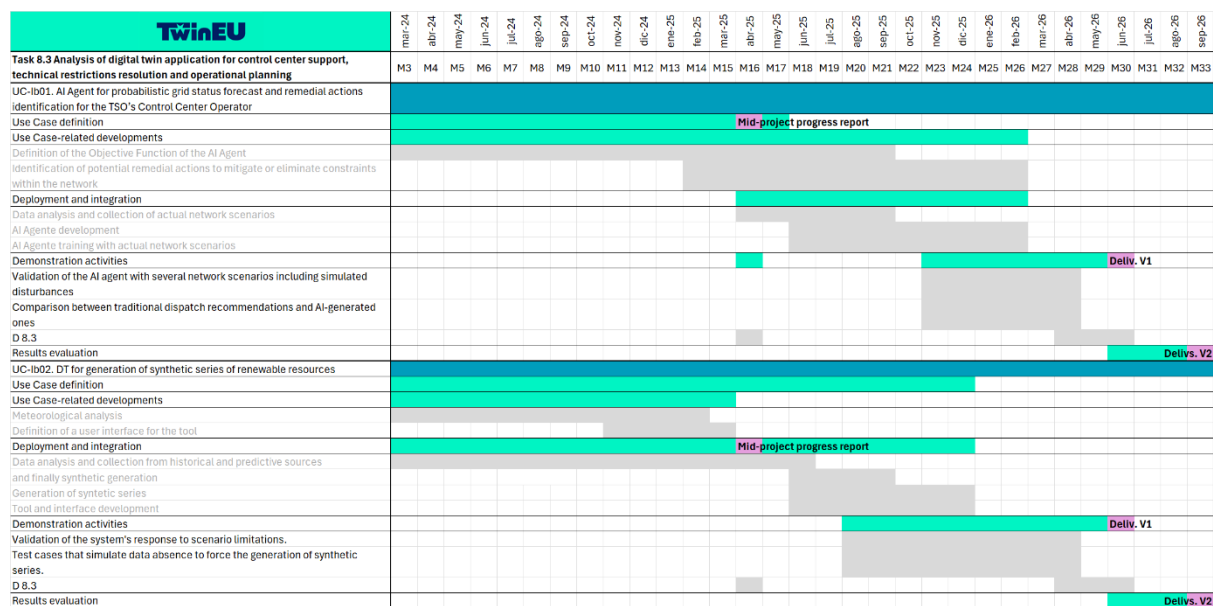


Figure 6.2. REE's TG DT development and demonstration plan

For Ib02, implementation followed an incremental approach, beginning with the development of a minimum viable product that was progressively enhanced with additional functionalities. The first stage focused on the creation of data homogenisation modules capable of integrating heterogeneous datasets from multiple sources, thereby expanding the range of scenarios available for simulation. Insights gained during dataset analysis informed the definition of data segmentation strategies and contributed to the design of the user interface. Once the data integration framework and core

platform functionalities were established, the generation of synthetic scenarios was undertaken. The resulting datasets and functionalities were subsequently subjected to a progressive validation process, which served as a quality assurance mechanism by identifying inconsistencies, assessing limitations, and supporting the continuous refinement of the tool.

6.2.2 ANELL's Distribution Grid DT

The implementation of Use Cases Ib 05, 06, 07 and 14 was monitored through the follow-up of a detailed development, configuration and demonstration plan that evolved during the project phases, reflecting the updated planning status.

The plan followed a coherent methodology where baseline use cases (i.e., 05 and 06) were developed prior to advanced implementations of their functionalities (i.e., implementations proposed for UCs 07, 14 and the participation in the Pan-European Scenario #1 on hosting capacity maps at distribution level).

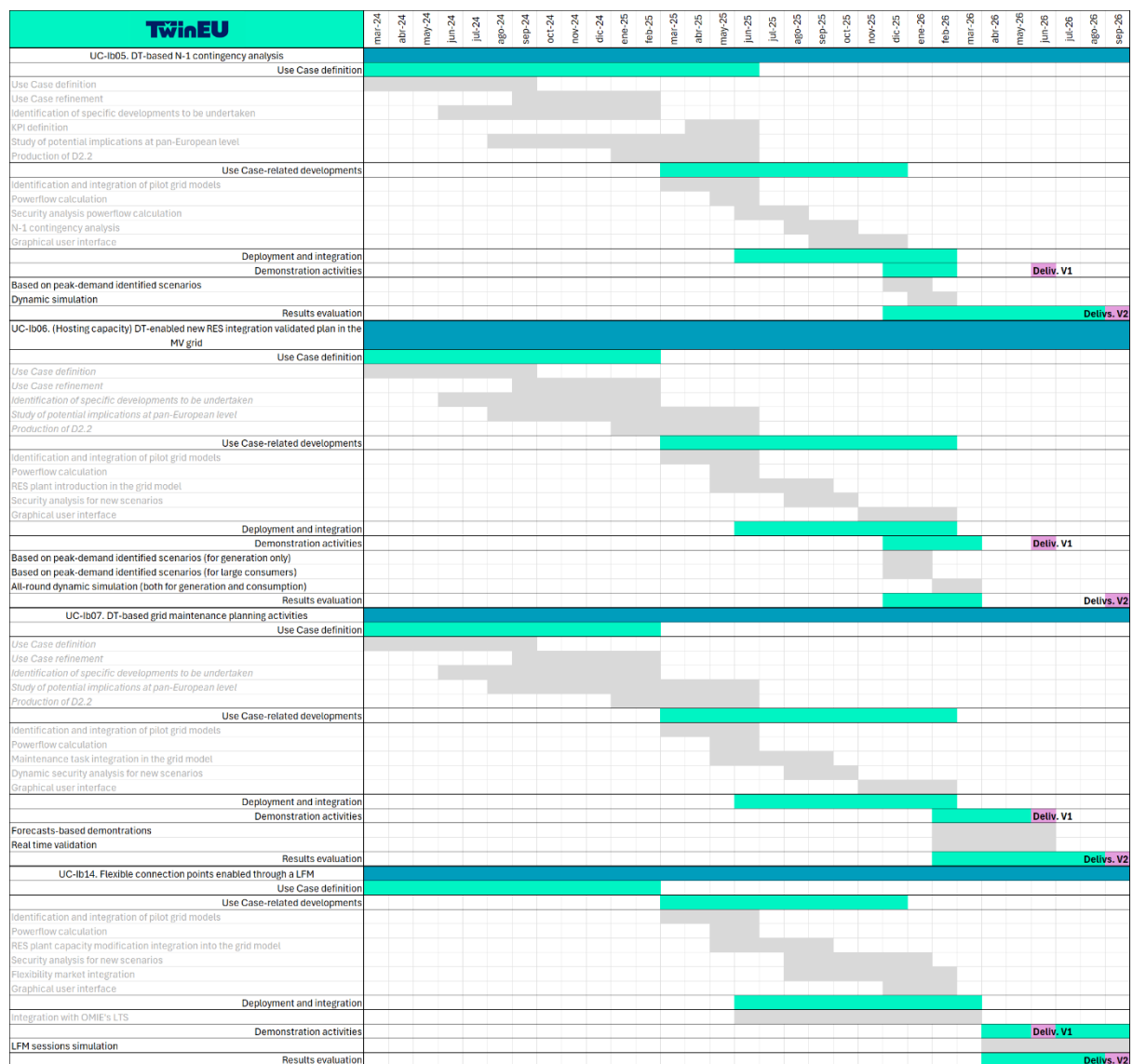


Figure 6.3. ANELL's DG DT development and demonstration plan

A gradual validation and demonstration of the baseline functionalities in offline operations of the DT (without real-time integration) in UCs Ib05 and Ib06 allowed the finetune of the results for the advanced demonstration activities involving validation of real maintenance activities scheduled by the DSO (UC Ib07) and validation of actual capacity available to be consumed in the local grid (UC Ib14).

For the implementation of UC Ib14, a DTs collaboration was established with the LFMO systems. This implied the integration of ÉTER with their LTS and the configuration of the P2P market service to meet the requirements for the use case execution. For the specific case of UC Ib14, there was a direct integration proposed, while the use of the central architecture of TwinEU was conceptually left for the implementation of UC Ib04 in WP5 (T5.4).

6.2.3 Cuerva's Distribution Grid DT

The implementation of Cuerva's Distribution Grid DT, developed on the Adaion Platform, progressed through platform deployment, consumption segmentation, and a full-year power flow baseline used to validate flexibility-based solutions for UC Ib08 (Long-term flexibility in MV) and UC Ib09 (Flex Connections).

To support UC Ib09, a segmentation approach was developed to classify consumption profiles in a way that is both interpretable and directly translatable into flexible connection contracts, based on five business-oriented criteria: intra-period variability, homogeneity across networks, differentiation of peak consumption ranges, temporal fragmentation, and interpretability.



Figure 6.4. 127 simultaneous voltage violations at hour of the annual demand peak (20 July 2026, 12:00, 4.0 MW).

Using telemetry data, K-means clustering showed that telemetry-derived consumption magnitude, rather than temporal behaviour, is the dominant driver of segmentation quality, particularly for intermittent (agricultural/industrial) loads. Aggregating consumption at substation level, rather than per transformer, proved substantially more effective at exposing available capacity: full theoretical capacity was released for more than 30% of the time.

A full-year (8,760-hour) power flow simulation was run on Cuerva's grid using consumption data per secondary substation (CT), converging for 100% of the hours analysed with no computational errors. No line overload was recorded in any hour of the year. In contrast, 24 hours across the year showed voltage violations, concentrated exclusively in December, January and July, and occurring almost entirely between 10:00 and 18:00. Minimum voltage and total demand were strongly negatively correlated, indicating a demand-driven undervoltage pattern. The most severe event of the year, 127 simultaneous voltage violations, with minimum voltage dropping to 0.9395 p.u. (below the minimal voltage: 0.95), occurred at the hour of the annual demand peak (20 July 2026, 12:00, 4.0 MW).

This confirms that the binding technical constraint on Cuerva's grid is voltage quality, not thermal capacity: a capacity assessment based purely on the line/transformer loading would understate the true limiting factor for accepting new flexible connections during peak-demand periods.

A nodal voltage-sensitivity analysis was performed at the network's worst-case hour to test whether demand-side flexibility could resolve the identified undervoltage. No single node in isolation was sufficient to bring the network's minimum voltage back above the 0.95 p.u. threshold; grouping electrically related nodes was required.

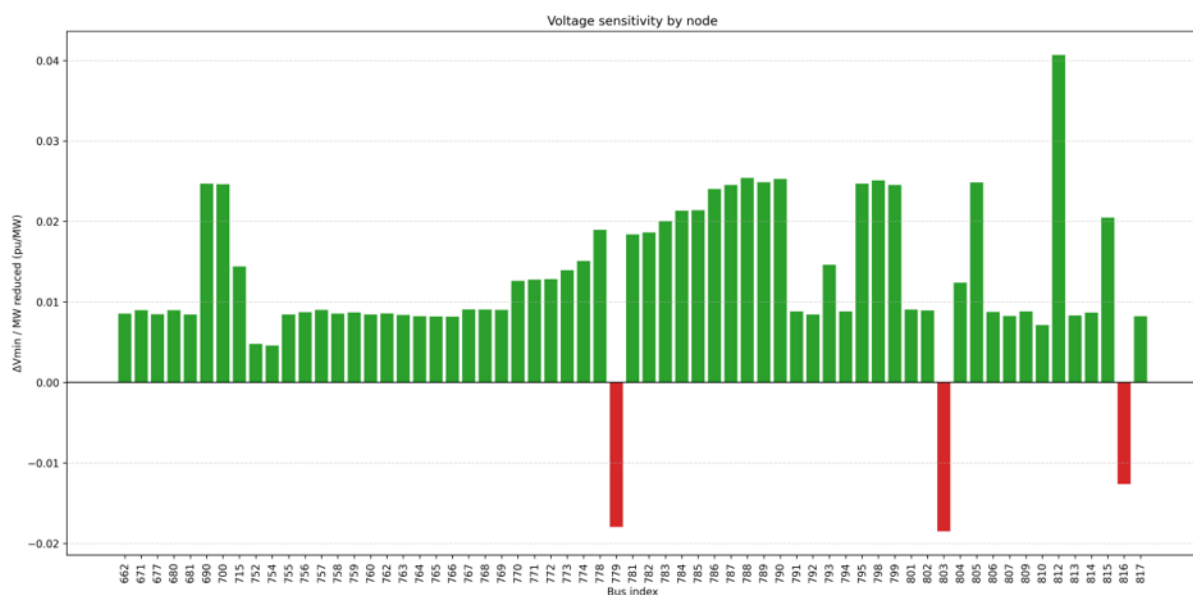


Figure 6.5. Voltage sensitivity by node at the network's worst hour (current demand). (EV charger) shows the highest sensitivity in the network

An EV-charging point (617 kW of instantaneous demand at the critical hour) and a small adjacent secondary substation (67 kW) were found to jointly resolve 100% of the worst-hour undervoltage event when combined, 325.6 kW of combined curtailment, 8.1% of the hour's peak demand, raising the network's minimum voltage from 0.9395 to 0.9506 p.u. Individually, the EV charger alone (41.9% curtailment of its instantaneous load) reduced network-wide voltage violations from 127 to just 3, demonstrating that a single, moderately-sized flexible resource resolves the substantial majority of

the identified voltage-quality issue. Ten alternative node groupings of increasing size (2–5 nodes) were validated as equivalent options, giving Cuerva a choice of flexibility configurations depending on contractual or operational preference.

To assess whether this flexibility-based solution scales with anticipated grid electrification, the same worst-case hour was re-evaluated under a uniform +30% increase in demand across all loads, including the EV charger. The critical hour remained the same (20 July, 12:00), but its severity increased substantially: minimum voltage fell to 0.918 p.u. (from 0.9395 p.u. in the current-demand case), with 306 simultaneous violations (versus 127 today). No line thermal overload appeared even at this elevated demand level (maximum line loading 75.3%, versus 56.5% today), confirming that voltage quality remains the binding constraint even under significant electrification.

The EV-charger-centred flexibility group, even fully exhausted (100% curtailment of all five CTs, 938.2 kW), fell just short of the 0.95 p.u. target (0.9494 p.u.). Extending progressively to 8 nodes across two electrically adjacent clusters (962.9 kW) narrowed the shortfall to a negligible 0.00002 p.u. A ninth resource then closed the gap decisively (1.77 MW, 0.965 p.u.), though this significantly overshoots what is strictly necessary, a fine-grained partial activation of that ninth resource (estimated under 1 kW based on nodal sensitivity) would likely suffice.

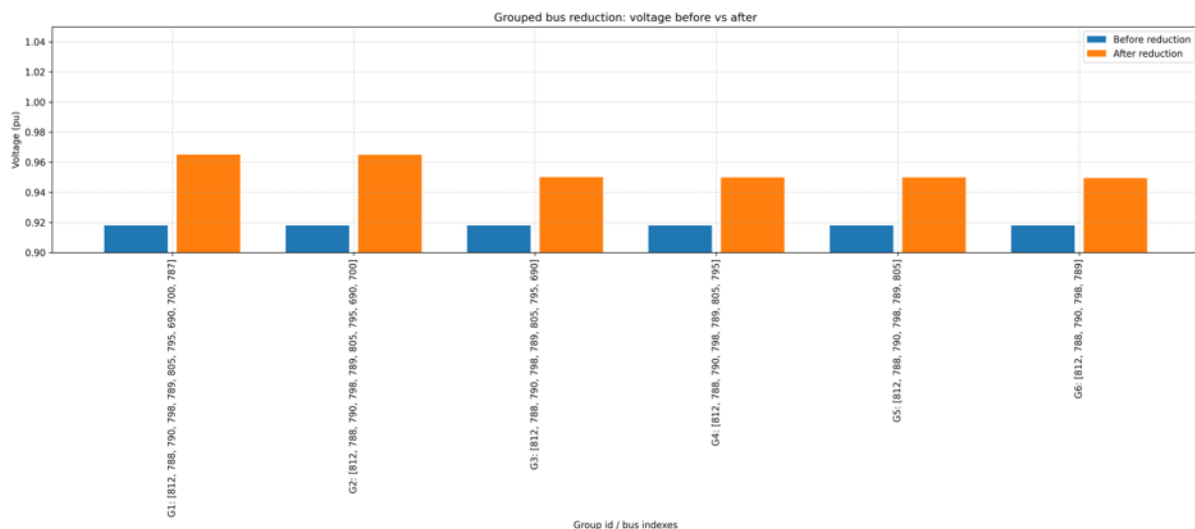
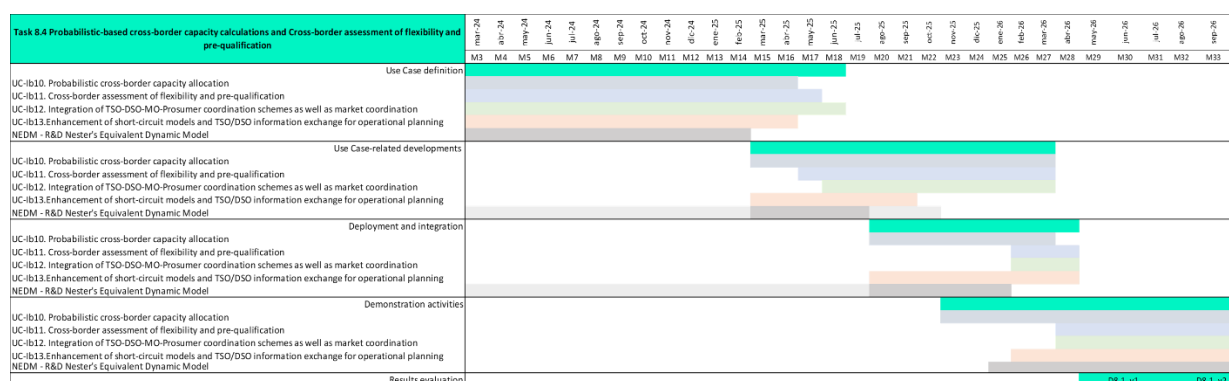
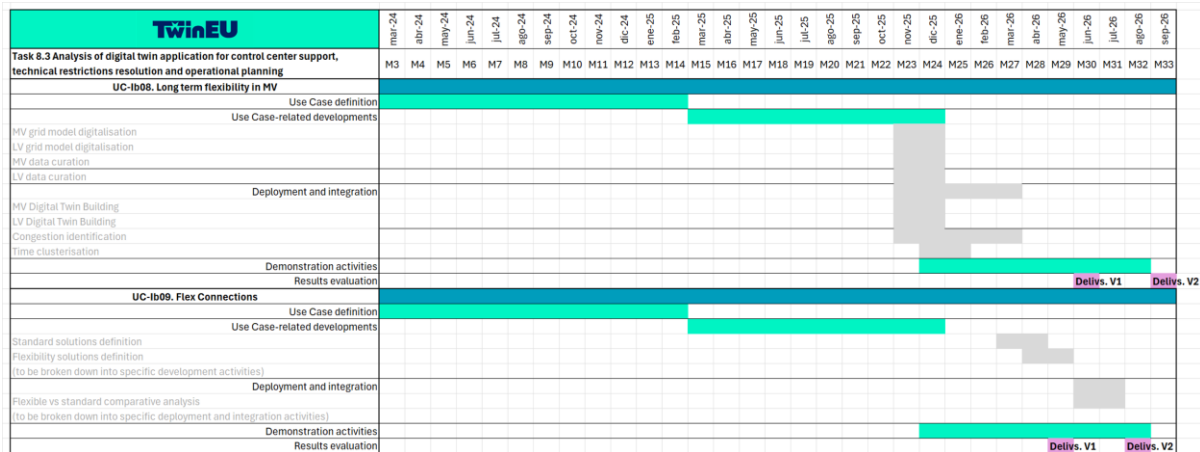


Figure 6.6. Grouped node curtailment (5–10 nodes) under the +30% demand scenario. Voltage before/after reduction, showing the sharp improvement once a ninth resource is added

This confirms that the flexibility-based solution validated at current demand does not scale indefinitely: at approximately +30% electrification, the immediate EV-charger flexibility cluster becomes insufficient on its own, requiring a small additional contribution from a further part of the network.



Iberian power system and supporting the identification of solutions for future low-inertia operating conditions. The methodology combines real and prospective system data, reduced-order dynamic modelling for different generation technologies, simulation-based assessment and validation against system behaviour, covering both operational and planning applications of the DT.

The first stage consisted of the development and calibration of the multi-area dynamic model, representing the Iberian Peninsula system and its dynamic interaction with the Continental European system following a large disturbance like the loss of large generation unit. The approach followed exploits the concept of an equivalent electromechanical model, where the mechanical power depends on the frequency response of the generation technologies in each area and was then calibrated against measurements from the loss of a nuclear generation unit of 1GW, through parameter estimation based on Particle Swarm Optimisation. System inertia, damping, generation-technology droops and synchronisation coefficients were adjusted by minimising the difference between the real measured and simulated frequency responses given by the simulation model. This established a representative baseline DT that could subsequently be adapted to different operating conditions.

Building on this model, an automated DT workflow was implemented to connect actual system conditions with dynamic simulations. Operational generation and demand data are collected from the ENTSO-E Transparency Platform and transformed into the parameters required by the dynamic model, including generation capacities by technology, equivalent inertia, damping and governor characteristics. The parameterised model is automatically executed and relevant dynamic-security indicators — particularly the frequency nadir and the RoCoF—are calculated and stored or presented to the dispatch operators. The results and generation-mix evolution are made available through a monitoring dashboard, thereby creating an integrated chain from operational data acquisition to model parameterisation, simulation, assessment and visualisation, capable of providing measures of the robustness of the Iberian system under the dispatch centre environment.

The DT was then extended from present operating conditions towards scenario-based planning assessment. Future configurations for 2030 and 2040 were constructed using the ENTSO-E TYNDP National Trends scenarios, considering the expected evolution of generation portfolios, demand and interconnection capacities. Critical operating conditions were selected with emphasis on periods of high converter-interfaced renewable generation and low synchronous generation. For these scenarios, system inertia and frequency response were systematically evaluated following a reference large generation loss in the Iberian system, allowing the evolution of frequency nadir and RoCoF and the corresponding need for additional system support on ancillary services to be quantified.

Based on the identified stability needs, the methodology proceeded with the design, sizing and comparative assessment regarding the adoption of new ancillary services. Alternative solutions — including Fast Frequency Response, synchronous condensers and battery energy storage systems equipped with Grid-Forming controls — were parameterised and progressively tested through dynamic simulations. Their characteristics and required volumes of services were iteratively adjusted according to their impact on frequency nadir and RoCoF, enabling technically suitable combinations of frequency-support resources to be identified for future system operating conditions.

Finally, the methodology was complemented by a more detailed transient-stability assessment for the optimum sizing and location of Grid-Forming resources. A detailed Portuguese transmission-system model was developed for the purpose, using public data from the Portuguese TSO, and representative operating scenarios were generated from historical data. Clustering and severity-based filtering techniques were applied to reduce the scenario and disturbance space while preserving

representative and critical system conditions, making extensive dynamic simulation computationally tractable.

Overall, UC-Ib03 therefore follows a methodology in which real-system validation, automated DT operation, future-scenario analysis, new frequency ancillary services solution design and simulation-based demonstration are progressively integrated. This enables the same DT framework to support both near-real-time monitoring of dynamic robustness and forward-looking planning studies for the identification of the volumes of new frequency ancillary services capable to maintain frequency stability of the future Iberian power system.

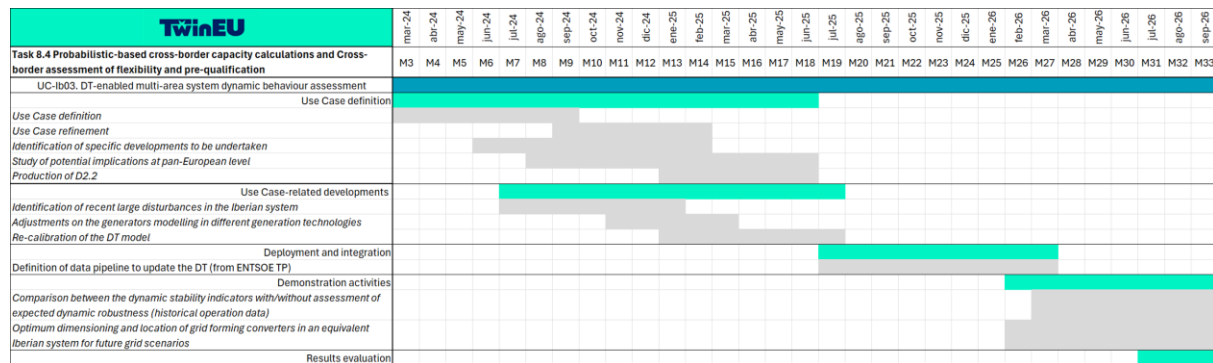


Figure 6.9. UC Ib03's HL DT development and demonstration plan

7 Takeaways from the DT for smart coordinated planning of the grid

7.1 T8.2 Digital twin for stability of power systems with high penetration of renewable energy sources

The implementation and assessment of Use Case NL-02 demonstrated a coherent DT-based workflow combining synthetic steady-state scenario analysis with regional and national-scale real-time EMT simulation. The resulting demonstrator enables representative future operating conditions to be constructed, dynamically simulated, and assessed through voltage- and frequency-based stability indicators within a controlled research environment.

The synthetic PowerFactory model provided the planning foundation for assessing 2030 operating conditions with high renewable generation and electrolyser demand. The studies identified voltage and transformer-loading constraints in selected scenarios, including regional undervoltages of approximately 0.9 p.u. under solar-dominated, low-demand conditions and critical EHV/HV transformer loadings following contingencies. The results also showed that the location and distribution of electrolyser demand can materially affect network loading and contingency performance.

The regional RSCAD model demonstrated continuous real-time EMT execution and represented the dynamic behaviour of conventional synchronous generation, detailed converter-interfaced offshore wind generation, and the BritNed interconnection. Its assessment under representative faults showed the capability of the demonstrator to reveal location-dependent interactions, reactive-power support, and post-fault oscillations that cannot be captured through steady-state analysis alone. The subsequent national-scale implementation extended this capability to the Dutch 380, 220, 150, and 110 kV transmission networks while preserving real-time execution and representing the dynamics of both conventional and renewable sources.

For the assessed national scenarios, frequency behaviour became increasingly severe as renewable penetration increased. Maximum absolute RoCoF rose from 2.04 Hz/s at 50% RES to 14.54 Hz/s at 80% RES, making it the indicator most sensitive to renewable penetration, while voltage-sag duration remained primarily determined by fault-clearance time. The demonstrator therefore provides a scalable real-time simulation core for stability screening, comparison of future operating scenarios, and identification of emerging voltage and frequency stability trends. It also establishes a technical basis for the further development of operator-training, controller-oriented, and decision-support applications for high-renewable power systems.

7.2 T8.3 Analysis of digital twin application for control centre support, technical restrictions resolution and operational planning

7.2.1 REE's Transmission Grid DT

The work presented in this deliverable demonstrates that the development and demonstration of Use Cases Ib01 and Ib02 followed a coherent and structured methodology, progressing from the initial

definition of objectives and scope through iterative development cycles to comprehensive validation activities. The results obtained confirm the potential of both AI-assisted operational support tools and synthetic climate data generation methodologies to enhance decision-making processes in control centres and improve the quality and representativeness of planning studies.

The validation activities carried out throughout the project highlighted the ability of these solutions to address complex operational and analytical challenges while providing valuable decision support to system operators and planners. In particular, the use of AI-based recommendations and synthetic scenario generation techniques has shown significant potential to increase operational awareness, broaden the range of situations that can be analysed, and support more informed and robust decision-making processes.

However, the successful adoption and integration of these technologies into real-world operational environments requires the parallel implementation of appropriate governance frameworks, safeguard mechanisms, and controlled testing environments. Elements such as guardrails, sandbox platforms, latency management, cybersecurity provisions, and clear accountability frameworks are essential to ensure that operators retain full ownership of critical decisions while benefiting from the enhanced analytical capabilities provided by the developed tools. Achieving this balance between human supervision and technological support will be a key enabler for the effective deployment of AI-driven solutions in future control and planning centres.

7.2.2 ANELL's Distribution Grid DT

The methodology proposed for the implementation of WP8's use cases in the distribution grid of ANELL has been key for a successful validation of the two workstreams proposed, one focused on hosting capacity calculation and maximization (UCs Ib06, 14, and Pan-EU Scenario #1) and the other one focused on N-k contingency analysis with DT simulations (UCs Ib 05 and 07).

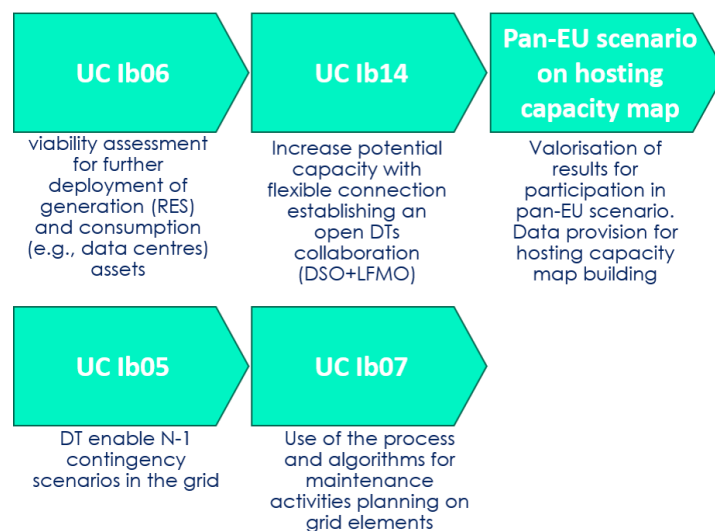


Figure 7.1. ANELL's DG UCs development and demonstration sequence

UC Ib06 provided a much more accurate limit on actual hosting capacities in the current distribution grid, based on dynamic simulations instead of static simultaneity coefficients. UC Ib14 took that baton to offer industrial consumers the possibility of extending their generation or consumption power limits with FCAs when the grid was able to host that extra power. Additionally,

the updated calculations of the grid's hosting capacities were leveraged into building a pan-European distribution grid hosting capacity map for project developers to have simplified access to the data.

In the meantime, UC Ib05 provided a DT-validated assessment on the N-1 contingent character of the grid, while UC Ib07 made use of that functionality to take programmed maintenance activities on the grid and validate that they were not going to disrupt the operation, considering an N-k contingency requirement.

7.2.3 Cuerva's Distribution Grid DT

The combination of the full-year power flow baseline and the nodal flexibility analysis allows several of the KPIs defined for UC Ib08 and UC Ib09 to be updated with concrete, traceable results:

Table 7-1. KPI results for UC Ib08 (Long-term flexibility in MV) and UC Ib09 (Flex Connections), current demand vs. +30% electrification scenario

KPI	UC	Results
Voltage Quality Improvement	Ib09	Current demand: Minimum voltage raised 0.9395→0.9506 p.u. (+0.0111 p.u.) using 325.6 kW (EV charger + 1 MV consumer, 8.1% of peak demand). Violations: 127→0. +30% electrification: Minimum voltage raised 0.9180→0.9500 p.u. (+0.0320 p.u.) using 962.9 kW across 8 resources (99.998% of target). Full compliance (0.9650 p.u.) reached by extending to a 9th resource (1.77 MW, overshoots requirement).
Flexibility Utilization Rate (EV charger)	Ib09	Current demand: 258.4 of 617 kW activated = 41.9% of the EV charger's instantaneous demand (paired with 1 MV consumer at 100%). +30% electrification: 802.1 of 802.1 kW activated = 100% of the EV charger's instantaneous demand (fully exhausted as part of the 8-resource solution).
Grid Stability	Ib09	Current demand: Violations reduced 127→3 (97.6%) with the EV charger acting alone; 127→0 (100%) with the 2-resource combination. +30% electrification: Violations reduced to a residual gap of 0.00002 p.u. below target with the 8-resource combination; fully eliminated with the 9-resource combination.
Load Balancing Efficiency	Ib09	Current demand: Critical-hour peak reduced 4.005→3.679 MW; peak-to-average ratio improves from 2.03 to 1.87 (8.1% peak shave). +30% electrification: Critical-hour peak reduced 5.207→4.244 MW (8-resource solution); peak-to-average ratio improves from 2.03 to 1.66 (18.5% peak shave).
Overload reduction	Ib08	Current demand: 0 line overloads across all 8,760 h; max. line loading 56.5%. +30% electrification: 0 line overloads across all 8,760 h; max. line loading 75.3%.

Availability and Reliability of Flexibility Service	Ib08	Current demand: Flexibility needed 24 h/year (0.27% of the year). 100% reliability at the year's most severe event (worst hour tested). +30% electrification: Flexibility needed 459 h/year (5.24% of the year, $\approx 19\times$ more often). Reliability reaches 99.998% with the immediate cluster; 100% once extended to a 9th resource.
Utilization of Flexible Resources	Ib08	Current demand: 47.6% utilisation of the 2-resource pool (325.6 of 684.2 kW available) – comfortable headroom remains. +30% electrification: 100% utilisation of the 8-resource pool (962.9 of 962.9 kW available) – full exhaustion, still marginally short of target alone.
Implementation Cost vs Savings	Ib08	Current demand: The 2-resource solution (47.6% utilised) fully avoids conventional reinforcement at current demand. +30% electrification: Near total exhaustion of 8 resources (100% utilised) is required and still marginally insufficient alone – reinforcement costs may become comparable to flexibility costs beyond this electrification level.

Across every technical KPI, the same pattern holds: the current-demand solution operates with comfortable headroom (partial resource utilisation, e.g. 41.9–47.6%), while the +30% electrification scenario pushes the same resource pool to full exhaustion (100% utilisation) and still falls marginally short, requiring a small additional contribution from outside the immediate cluster. This provides a concrete, quantified boundary condition for Cuerva's long-term flexibility planning under UC Ib08, complementing the current-demand demonstration under UC Ib09.

7.3 T8.4 Probabilistic-based cross-border capacity calculations and Cross-border assessment of flexibility and pre-qualification

7.3.1 REN's Transmission Grid DT

The implementation and assessment UC-IB10 and UC-Ib11 showed the use of DTs for cross-border probabilistic capacity allocation and assessment of flexibility and pre-qualification [1].

The implementation and assessment of UC-Ib13 showed the use of DTs to forecast short-circuit currents at the TSO-DSO given the day-ahead market results.

The development and application of the Equivalent Dynamic Model of distribution grids shows that the methodology creates accurate equivalent distribution grid models, measured by the RMSE between the model's voltage, active and reactive power transient response and the corresponding response of the reference grid overcoming the need of a comprehensive representation of the distribution network.

Results and final KPI assessment can be seen in the Deliverable D8.1 of the TwinEU project.

UC-Ib12 concerns market integration. The results from the implementation and assessment of this use-case are depicted in the TwinEU Deliverable D5.4. It showed how the process of bid forwarding from the Local Flexibility Market can decrease costs of the balancing market while increasing revenues for flexibility service providers at the distribution grid.

7.3.2 High-level Iberian electricity system DT

UC-Ib03 demonstrates the value of Digital Twin approaches for anticipating and managing the dynamic stability challenges of future low-inertia power systems, as it is the case of the Iberian power system in the future. The work confirms that the progressive replacement of synchronous generation by converter-interfaced renewable generation changes the dynamic behaviour of the Iberian power system and increases the importance of systematically assessing stability, and namely frequency stability, across different operating conditions.

A key takeaway is that dynamic security cannot be adequately addressed through a single predefined operating scenario or a set of mitigation measures. Instead, the required system support depends on the generation mix, system inertia, natural damping evolution, interconnection with neighbouring areas and the characterization of the reference disturbances used to assess robustness of the system. By linking system data with automatically parameterised dynamic models, the DT provides a framework through which these changing conditions can be continuously translated into indicators of system robustness, like the nadir of the frequency excursions and the RoCoF values. This establishes a bridge between traditional offline dynamic studies and more adaptive, data-informed assessment approaches, as proposed.

The analyses of future scenarios further highlight that maintaining system stability will require a portfolio of complementary flexibility and stability resources rather than reliance on a single technology. Fast Frequency Response, synchronous resources and Grid-Forming converter-based solutions can contribute in different and complementary ways, with their effectiveness depending on their response characteristics and on the underlying system conditions. The results particularly reinforce the relevance of combining converter-based solutions with resources providing inherent system-strength characteristics, pointing towards coordinated and potentially hybrid approaches for future system operation. Apart from this, this dynamic simulation platform can be used to evaluate the contributions from the demand (EV, large industrial loads like electrolyzers or thermal loads) in providing frequency ancillary services.

Finally, UC-Ib03 shows that the DT concept can support both operational awareness and long-term planning: from monitoring how the current generation mix affects dynamic robustness to assessing future scenarios and supporting decisions on the type and volume of the new ancillary services. A more complete assessment is needed when the grid location of the new frequency ancillary services is required. In this case other types of stability problems, like transient stability or even new converter driven stability problems can also be addressed. The broader takeaway is therefore that Digital Twins can evolve from being primarily simulation environments into decision-support instruments for system operators, helping translate the increasingly variable characteristics of converter-dominated power systems into actionable information for secure grid operation and planning.

8 Conclusions

The demonstrations carried out in WP8 confirm that Digital Twins are becoming a key enabling technology for the future planning and operation of European electricity networks. Across transmission systems, distribution systems, electricity markets and cross-border coordination activities, the demonstrated use cases have shown that DTs provide a significant improvement in the ability of grid operators to understand system behaviour, anticipate future challenges, evaluate alternative solutions and support decision-making under increasingly uncertain conditions.

One of the main conclusions of the work is that Digital Twins enable a shift from static and largely deterministic planning approaches towards continuous, data-driven and scenario-based planning processes. The demonstrations showed that Digital Twins can integrate operational measurements, historical datasets, synthetic data generation capabilities, dynamic simulations and advanced analytics into a common environment that supports both long-term planning and operational decision-making. This significantly increases the quality of planning studies while reducing uncertainty regarding future network developments.

The work carried out in the Dutch pilot demonstrated the value of Digital Twins for dynamic stability assessment in power systems with high penetration of renewable energy sources. The combination of synthetic future scenarios with real-time EMT simulations provided a scalable framework to evaluate the impact of changing generation mixes on frequency stability, voltage performance and system robustness. The results highlight the importance of Digital Twins as a planning tool for identifying emerging stability issues in low-inertia systems and for evaluating mitigation strategies before they become operational requirements.

The Iberian transmission-level demonstrations further confirmed the benefits of integrating artificial intelligence and advanced simulation capabilities into Digital Twin environments. The results obtained from AI-supported control centre applications and synthetic renewable resource generation demonstrate that DTs can increase operational awareness, improve forecast quality and support the identification of remedial actions under complex system conditions. At the same time, the demonstrations highlighted the importance of governance, cybersecurity, explainability and human oversight mechanisms to ensure trustworthy adoption of AI-enabled decision-support tools in critical infrastructures.

At distribution level, the demonstrations provided compelling evidence of the value of Digital Twins for hosting-capacity assessment, grid maintenance planning and flexibility-based network development. The results obtained in the grid of ANELL demonstrated that dynamic simulation approaches provide more realistic hosting-capacity calculations than conventional methods, creating opportunities for faster renewable integration and more efficient use of existing infrastructure. Similarly, the successful validation of maintenance activities through DT simulations confirmed their capability to support risk-informed operational planning.

The demonstrations hosted in the grid of Cuerva revealed that flexibility can become a powerful planning alternative to conventional network reinforcement. The analyses showed that voltage constraints, rather than thermal limits, are likely to become the dominant planning challenge in increasingly electrified distribution networks. The Digital Twin enabled the identification and quantification of specific flexibility resources capable of resolving voltage violations while deferring infrastructure investments. However, the results also showed that flexibility alone is not an all-powerful solution, as increasing electrification progressively exhausts available flexibility resources

and eventually requires complementary reinforcement measures. This demonstrates the value of DTs for identifying the optimal balance between flexibility procurement and network investments.

The cross-border and multi-area demonstrations highlighted another important conclusion: future grid planning cannot be performed effectively within organisational silos. The use cases involving probabilistic capacity calculations, flexibility pre-qualification, TSO-DSO coordination and system-wide dynamic stability assessments demonstrated the need for coordinated modelling and information exchange across multiple stakeholders. Digital Twins provide the technological means to support this collaboration while preserving the autonomy of the participating actors.

From a European perspective, the results of WP8 demonstrate that Digital Twins can support key policy objectives including accelerated renewable integration, improved hosting-capacity transparency, enhanced TSO-DSO coordination, increased utilisation of flexibility resources, strengthened cross-border cooperation and more resilient power systems. The ability to connect local, regional and system-wide Digital Twins within a common framework creates the foundation for a future European Digital Twin ecosystem capable of supporting the planning challenges associated with the energy transition.

References

- [1] Use of DTs for cross-border probabilistic capacity allocation and assessment of flexibility and pre-qualification, European Commission's Innovation Radar. Available : <https://innovation-radar.ec.europa.eu/innovation/65656>