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Building a Sustainable Future: The Role of Digital Twins in Transforming Europe's Energy Systems

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Abstract. In an era marked by an urgent need for sustainable energy solutions, digital twins have emerged as a pivotal innovation to address the challenges of modern power systems. Digital twins provide a real-time virtual model of physical energy systems, enabling enhanced monitoring, simulation, and optimization. This paper examines the TwinEU initiative, a cornerstone of the Horizon Europe program, which seeks to implement a pan-European digital twin ecosystem to revolutionize the management and operation of power grids. The study covers the development of digital twin technology, its architecture, and its application across transmission and distribution networks and energy markets. Results demonstrate how digital twins facilitate the integration of renewable energy, enhance grid flexibility, and ensure the reliability of Europe's energy systems. Furthermore, it explores the role of federated digital twin ecosystems in fostering cross-sectoral collaboration and innovation, paving the way for a unified and sustainable energy infrastructure.

Key words. Digital twin, TwinEU, Energy market, Power system operation, Power system planning

1. Introduction

The global transition to renewable energy sources is reshaping energy systems, introducing complexity into the management and operation of grids. With increasing penetration of intermittent energy sources like wind and solar, the European energy sector faces the dual challenges of maintaining reliability and achieving flexibility. Traditional grid management approaches struggle to cope with these demands, necessitating new technologies that can seamlessly integrate renewable energy while ensuring system stability.

Digital twins, a concept originating in aerospace and manufacturing, offer transformative potential in the energy sector. By creating a virtual replica of physical systems, digital twins enable continuous monitoring, predictive analysis, and decision support. The TwinEU project builds on this foundation, aiming to develop a scalable and federated digital twin ecosystem that spans the entirety of Europe's energy networks. This paper explores the evolution of digital twin technology, the architecture of the TwinEU system, and its practical applications across key areas of energy management.

2. Theoretical foundations and architecture of digital twins

A. The definition of digital twin

A digital twin is a dynamic virtual representation of a physical system, capable of real-time interaction with its counterpart through data synchronization. ([1],[2])

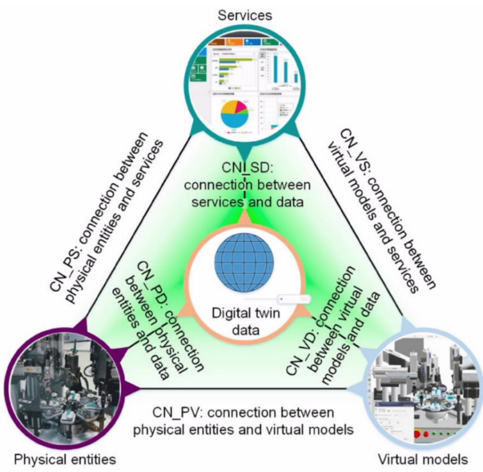

Fig.1. Five-dimension digital twin model ([1])

Defined by Grieves and popularized by NASA, the digital twin concept encompasses five key components:

1) *Physical Entity:* The real-world object or system being modelled.
2) *Virtual Model:* The digital counterpart replicating the physical entity's behaviour and attributes. When developing a virtual model, not only the initial state is relevant, but also the continuous monitoring is important.
3) *Data:* Information flows that connect the physical and virtual realms.
4) *Service Interface:* Applications and tools that extract insights from the digital twin.
5) *Connection:* The bidirectional communication

enabling synchronization between physical and digital systems. ([1],[2])

This five-dimensional framework (Figures 1) serves as the foundation for the TwinEU project, ensuring adaptability and scalability.

B. TwinEU Architecture

In the TwinEU architecture (Figures 2), the task is to implement a federated digital twin ecosystem, which is created by connecting, synchronizing, and coordinating several independent digital twins. The ecosystem is organized into three primary layers:

1) *Adaptive Twins:* These components provide real-time data acquisition and model synchronization. They enable advanced features like predictive maintenance, fault diagnosis, and real-time simulation. A part of the layer is the DT Federator, which provides a sophisticated background for the other layers and builds local digital twins into a common framework.
2) *Data Space Infrastructure:* An important part of the layer is the traceability of data to build trust between stakeholders. A secure and interoperable platform that facilitates data sharing and collaboration among diverse stakeholders, including TSOs, DSOs, and market participants. An essential part of this layer is the integration of the OneNet Connector, which provides the link between the digital twins and the physical world.
3) *Service Workbench:* A suite of analytical tools and applications that support grid planning, market analysis, and operational decision-making. ([3])

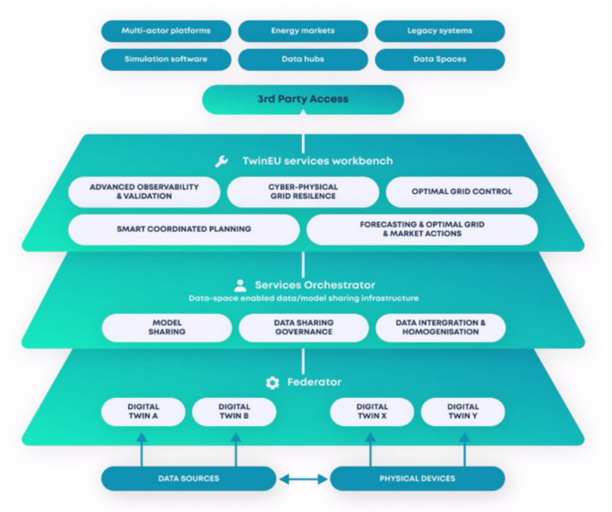

Fig. 2. TwinEU architecture ([3])

This layered architecture enables modular development and seamless integration of digital twins across different domains.

3. Case studies and demonstrations

Twin EU's demonstrations cover three application areas: the transmission grid, the distribution grid, and the energy market. Furthermore, pilots also demonstrate cross-sectoral applications, which deal with more than one area.

A. Transmission Network Applications

The number of transmission network twins is significant, as evidenced by the participation of numerous TSOs in TwinEU. The transmission network is characterized as a fully monitored network, equipped with an array of sensors and measuring units, and supported by substantial IT infrastructure, including condition estimation software. The primary objective in this field is to further develop active management strategies and to prepare the grid for the large-scale integration of renewable energy sources.

In case of network planning and renewable energy integration, the following technologies are relevant:

1) *Spanish Pilot:* Focused on optimizing renewable energy integration, the Spanish digital twin develops energy production profiles using meteorological and historical grid data. These profiles help identify optimal locations for renewable energy deployment, reducing strain on the existing grid.
2) *Italian Pilot:* The Italian project uses Building Information Modelling (BIM) to validate infrastructure upgrades, ensuring compliance with national standards and enhancing grid reliability.
3) *Bulgarian Pilot:* By simulating network reliability, the Bulgarian twin evaluates the impact of renewable integration on grid stability, employing advanced loss and load flow calculations. ([4])

The Spanish demonstration focuses on the utilisation of renewable energy sources and investigates potential scenarios from the deployment perspective. In contrast, the Bulgarian demonstration places greater emphasis on the testing of grid upgrades and the development of associated technologies. This demonstrates the potential value of a joint utilisation of the two digital twins, with the Bulgarian digital twin being capable of conducting a reliability analysis for the deployments delineated by the Spanish demo.

The Italian demonstration, on the other hand, supports infrastructure development for further deployments through the provision of a faster and more unified planning platform. The establishment of a federated digital twin ecosystem is predicated on the definition of identical validation steps at the system level, a prerequisite for the deployment of standardised units, and the enhancement of system interoperability.

Regarding the operation area, the role of the digital twins is to prepare the transmission network for threats and thus increase its resilience by incorporating network forecasts. In addition, their aim is to further enhance the active grid management and prepare for large-scale renewable energy integration. Main technologies in this section are:

1) *Spanish Pilot:* Design a digital twin-based control centre, which uses data from renewable energy profiles.
2) *Portuguese Pilot:* There are two implemented models: the stationary and the dynamic model. The stationary model has the capacity to simulate and analyse a variety of operational scenarios (e.g., network threats, demand variations) to forecast grid behaviour, and optimize grid performance, while the dynamic model is to calculate the transient response of the distribution network to transmission disturbances.
3) *Slovenian Pilot:* In this project, FFR (Fast Frequency Response) service requirements are defined, and the impact of the service is evaluated by simulations with the aim of creating a more stable network.
4) *Hungarian Pilot:* The objective is to develop a conductor temperature measurement system that utilizes artificial neural networks (ANNs). The implementation of this system is expected to result in a more cost-effective current calculation. ([4])

The Portuguese demonstration encompasses the transmission network and simulations to ascertain the performance conditions, thereby facilitating the creation of a capacity estimation model.

A fundamental aspect of network forecasting involves preparing for potential threats and outages, a key element in the Portuguese demonstration. This involves simulating the impact of major hazards (e.g., power plant shutdowns) to ensure the grid's resilience against such scenarios.

Frequency stability represents a significant concern for grid operation, a matter that is addressed in several demonstrations within TwinEU. The development of the FFR (Frequency Regulation) service is of particular importance, as it has the capacity to regulate faster than the current FCR (Frequency Containment Reserve) service.

B. Distribution Network Applications

As with the transmission network, several DSOs are also participating in TwinEU. The enhancement of the observability of distribution networks is a task of significant importance for DSOs, particularly considering the present static or semi-static network. In the medium-voltage segment, telemetry and tele-operated devices have already emerged, though in the low-voltage segment, their adoption remains limited in numerous countries. The integration of smart meters at low voltage facilitates the development of actively monitored networks, as the resulting data can be utilised to accurately determine consumption and production. The significance of state estimation and simulation is essential, particularly in scenarios where data availability is limited.

The optimal design of the network becomes even more crucial, particularly in the context of renewable power plants, such as solar or wind energy facilities, which are increasingly prevalent at medium and low voltage levels. The impact of these installations on the network's performance and stability must be analysed.

Relevant technologies in case of distribution networks are:

1) *Iberian Pilot:* The development of two Iberian digital twins is underway, with the objective of enhancing the distribution network. The first digital twin (Figures 3) is of relevance to the medium voltage network. Its functions include, in addition to operational control, elements dealing with network state estimation and network reconfiguration. It also creates a GIS model of the network for network transparency. Several system functions support fault protection. The second digital twin, in contrast, is a data-driven system that focuses on low-voltage operation and planning. The twin's primary functions are the support of power distribution and the calculation of power at connection points, and its role in planning is also significant.

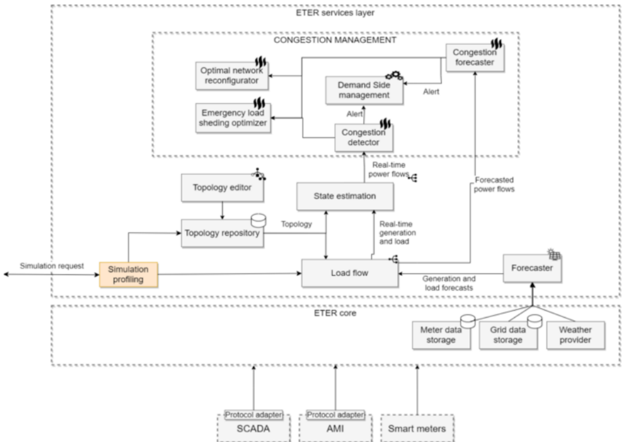

Fig. 3. Iberian digital twin architecture ([4])

2) *German Pilot:* The main objective is to enhance the observability of the network by developing an Envelios IGP (Intelligent Grid Platform). This platform will facilitate the integration of diverse data sources, thereby automating and standardising operational and planning processes. The platform's overarching objective is to establish a monitoring system that is predicated on real-time measurements. Beyond the indication of voltage, symmetry and power values, the platform is designed to signal when network limits are exceeded and to support plant management with status estimation. Furthermore, the platform can detect inaccuracies in the network

model.

3) *Italian Pilot:* The primary task to be completed will be the creation of a DER management system (DERMS) that will be capable of integrating DERs with the functions relevant to the DSO. ([4])

The Iberian and German digital twins both implement the same technology, building on existing operating platforms to create digital twins. In both cases, the functions of these platforms are utilized and developed further, thus achieving a similar purpose; namely, optimizing network operation and detecting faults using real-time data. Concurrently, the increased deployment of smart meters on distribution networks is a crucial factor in the technology's dissemination across Europe. The availability of data is fundamental to the development of digital twins; therefore, infrastructure development is essential to attract DSOs with smaller coverage and to spread the technology.

The German and Iberian digital twins are also exploring optimal connection points for renewable energy sources by testing grid stability. The German demonstration focuses on the automation of application acceptance and the visualisation of installable capacity on a map. In contrast, the Iberian demonstration prioritises the low-voltage grid upgrades necessary for installation.

In the context of the distribution network, the quantity of production and consumption constitutes essential information for ensuring operational security. Through the calculation of production and consumption, digital twins can provide data for both the market and load studies.

In the German demonstration, the significance of condition estimation is highlighted, as the digital twin aims to encompass less monitored areas to ensure comprehensive analysis. The development of a state estimation algorithm tailored to distribution networks is a priority, as it facilitates the construction of a digital model for less digitised network components.

C. Market Integration

The development of TwinEU is also followed by market aggregators and operators. The analysis was initiated with a focus on the day-ahead market, the intraday auction market, and the intraday continuous market, which offer the possibility of cross-border capacity transfer, thus laying the foundations for the creation of a European internal market. Furthermore, the flexibility markets, which are local markets, are also being explored in TwinEU. The final stage of this analysis will examine the balancing and ancillary markets to see how they contribute to network stability.

The essential technologies in the TwinEU are:

1) *Iberian Pilot*: The primary objective of the initiative is to enhance the efficiency of communication among market participants. A crucial aspect of this objective is the establishment of a unified market, facilitated by the creation of a designated trading platform.
2) *Hungarian Pilot:* The objective of the present undertaking is to optimize the line current with generation and demand, a process which can be dynamically scaled using DLR. Moreover, a web-based platform is to be developed for the purpose of presenting increased network limits, critical points, and simulation results, in addition to the possibility of data queries.
3) *German Pilot:* The utilisation of data from flexible prosumers is imperative for the technological design, encompassing data from resilient systems, smart meter consumption and production records, market intelligence, and envelope curves. This data is employed to delineate day-ahead flexibility steps that are mutually beneficial to the grid and the business.
4) *Greek Pilot:* The primary objective is the development of market simulators, with the day-ahead market simulator functioning as an agent for capacity allocation in accordance with regulatory frameworks and developmental expectations. Additionally, a balancing market simulator is in the planning stage, which will be based on the data provided by the day-ahead market simulator. This simulator will aggregate the options for providing balancing power and analyse power plant units from economic and technical perspectives to identify the most optimal solution. In the process, in addition to calculating the required balancing power, it also allocates the necessary reserves.
5) *Cypriot Pilot:* The provision of flexibility services is facilitated. Network congestion analysis is utilised to ensure the requisite flexibility service for each area. Coordination with these FSPs and these service providers is undertaken in the event of issues arising.
6) *Bulgarian Pilot:* The utilisation of a digital twin to monitor the cross-border energy market. This technology employs market analysis results to evaluate the technical costs and the reliability of the network. ([4])

The establishment of federated digital twins is also a prerequisite for the functioning of markets. Each of these demonstrations operates based on the data of the digital twins in the transmission network, with the operation of market interconnection based on the establishment of a link between national Market Operators and TSOs. The Greek, Hungarian and Bulgarian demonstrations analyse the different links between TSOs and digital twins in the markets. The Greek demonstration uses market simulators on the transmission network model to improve the existing capacity allocation algorithm. In contrast, the Hungarian and Bulgarian demos perform market analysis and make changes to the network as a result.

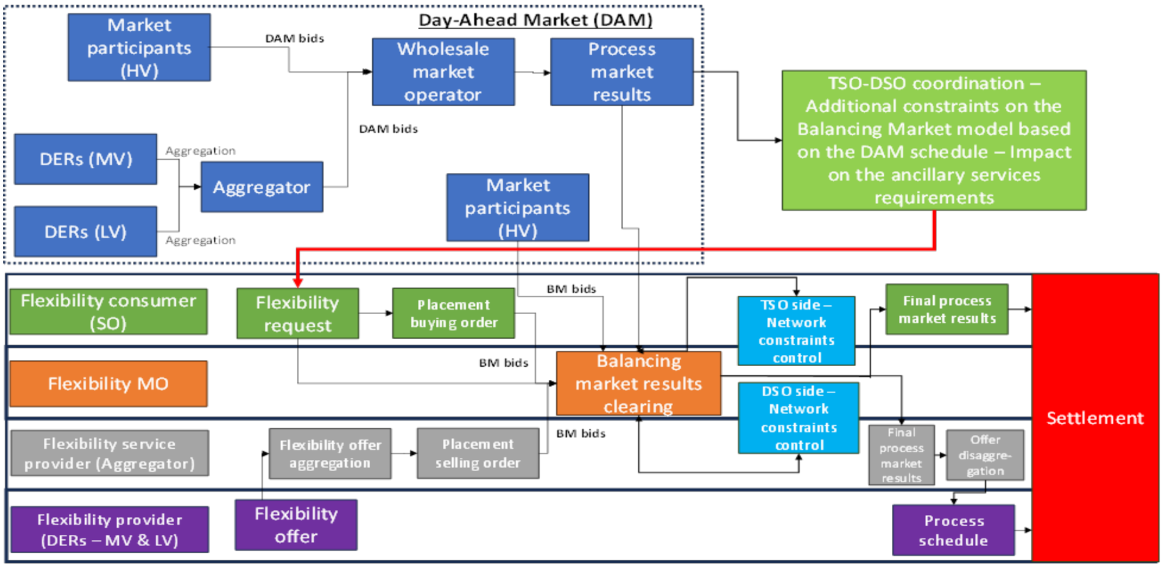

Fig. 4. TSO-DSO coordination market design ([4])

In addition to the standardisation appropriate communication channels, the Iberian demonstration will also focus on the European prequalification of FSPs. The applicability of the service will increase with the number of participating FSPs; therefore, it is vital to simplify the involvement of new FSPs and the inclusion of cross-border service provision.

The Greek demonstration will provide a comprehensive overview of the functionality of the two market simulators and their interconnectivity (Figure 4). Additionally, it will elucidate the procedural steps necessary to enable the utilisation of these simulators by other nations. The technological framework is predicated on the symbiotic coordination between the DSO and the TSO, along with the acquisition of data. This necessitates the integration of the market twins with the transmission network twins, facilitating the calculation of production data and the determination of network status.

D. *Cross-sectoral applications*

In this section, the implementation of digital twins necessitates the coordination of multiple stakeholders due to the comprehensive nature of the digital twins, which encompass the entire system by incorporating both the distribution and transmission networks, and occasionally market models. Utilising a comprehensive system model facilitates the investigation of numerous system elements in terms of analysing the grid's operational state.

Relevant technologies in case of cross-sectoral applications:

1) *Iberian Pilot:* The high-level digital twin of the Iberian system is employed to investigate the dynamic behaviour of the system in terms of frequency stability. Furthermore, the purpose of this study is to analyse the impact of large system outages on the network.
2) *Bulgarian Pilot:* The demonstration model is a digital twin representing the entire electricity system. It is an integration of three other Bulgarian digital twins and is based on the same technology. Its purpose is to represent the state of the whole system, with a focus on high-level assessments rather than detailed analyses, in order to facilitate rapid calculations that estimate the state of the grid.
3) *Cypriot Pilot:* The digital twin model is concerned with the modelling of both the high and medium voltage grids. It employs Phasor Measurement Units (PMUs), which are installed in substations, to obtain real-time data and utilise this information to demonstrate the functionality of the network.
4) *Dutch Pilot (Figures 5):* The digital twin under consideration is integrated, with the capacity to process the Dutch network system in its entirety. The transmission network serves as the basis for the model, with a reduced model of the distribution network and an equivalent model of the network in neighbouring countries incorporated. The development of a new dynamic model reduction is imperative for this purpose. ([4])

The Bulgarian demonstration model places significant emphasis on the importance of estimation, as its primary objective is not to provide exhaustive details, but rather to offer a representative overview of the overall network state. For TwinEU, it is imperative to have a model that is complementary to the detailed models, one that not only describes the relationship between the network components for individuals who are well-versed in the subject, but also serves as a foundational framework for those less familiar with the intricacies of the subject matter.

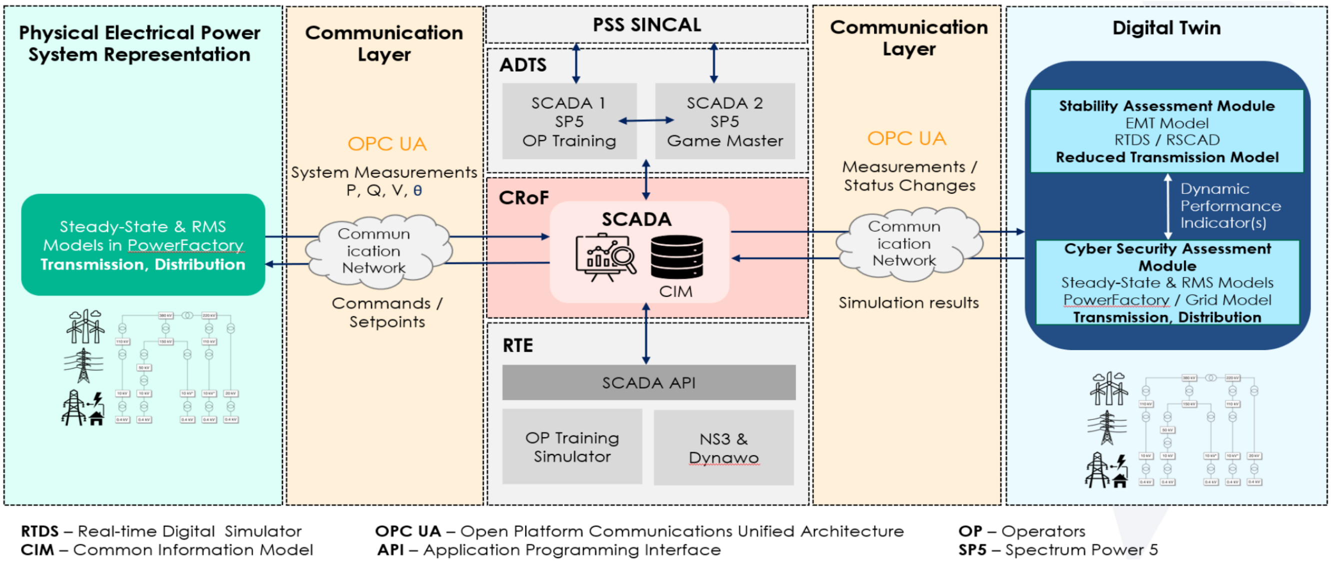

Fig. 5 The Dutch integrated digital twin architecture ([4])

The Cypriot digital twin system integrates data from substation meters and distribution network devices, resulting in a higher number of measurements and fewer estimates compared to transmission-only or distribution-only network twins. Nevertheless, it employs this data to address critical tasks, including the HVDC and FSPs efforts, which are significant to the overall project.

The Dutch and Iberian digital twins prioritise network security through the implementation of a comprehensive system model, which facilitates the analysis of outages and attacks on the entire system. This approach is crucial as these events can have far-reaching consequences for the interconnected components of the network, in addition to the network itself. The utilisation of a unified protection strategy can therefore be more effective. In the Dutch and Iberian digital twins, the impact of countries outside the system is also examined by setting up an equivalent model. This is an important element for the overall European system because it considers the impact outside the boundaries of the overall system for the calculations.

4. Conclusion

The TwinEU project exemplifies the transformative potential of digital twins in creating a sustainable, resilient, and adaptive energy system for Europe. By combining advanced modelling techniques with practical applications, TwinEU bridges the gap between innovation and implementation. The project's success highlights the importance of collaboration, standardization, and technological advancement in addressing the challenges of modern energy systems. With continued development and investment, digital twins could become the cornerstone of a unified European energy strategy.

5. Summary and outlook

Despite its success, the TwinEU project faces several challenges:

1) *Data interoperability:* Developing standardized protocols for data sharing across diverse systems and stakeholders remains a priority.
2) *Cybersecurity:* Ensuring secure data exchange and protecting critical infrastructure against cyber threats are critical for long-term adoption.
3) *Scalability:* Expanding the digital twin ecosystem to encompass all of Europe requires further investment and collaboration.

Future research should explore:

1) Integrating machine learning algorithms for advanced predictive analysis.
2) Developing decentralized data sharing frameworks to enhance resilience.
3) Expanding applications to include energy storage and electric vehicle integration.

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