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Analyzing Future Multi-Energy Scenarios

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***Abstract*—The integration of variable renewable energy sources (VRES) into the Dutch transmission network is imperative for transitioning to a sustainable energy future. However, incorporating large-scale VRES poses significant monitoring and control challenges, such as fluctuating power flows and grid stability concerns. This manuscript examines the role of digital twins as modern tools for supervising and controlling power systems. This work also presents the development of a synthetic digital model of the Dutch extra-high-voltage (EHV) network to analyze steady-state performance under high VRES penetration scenarios for 2030. Using DIgSILENT PowerFactory, automated by Python scripting, this study offers insights into the impacts of VRES and electrolyzers in power networks. By creating and analyzing various future scenarios, this research evaluates the effectiveness of digital models in scenario analysis, marking a significant step toward the implementation of comprehensive digital twins for future energy system planning and optimization.**

***Index Terms*—digital twin, extra-high-voltage (EHV) network, variable renewable energy sources (VRES), power system stability, multi-energy scenario analysis, electrolyzers, synthetic model.**

I. Introduction

As the Dutch energy sector aligns with the global shift toward sustainability, transforming the transmission network is both essential and challenging. The expected increase in variable renewable energy source (VRES) installations, critical for meeting the Paris Climate Agreement objectives [1], introduces new levels of variability and unpredictability in power flows, raising concerns about grid stability and reliability.

This study addresses these concerns by developing a digital model of the Dutch Extra-High Voltage (EHV) grid, serving as a foundational step toward creating a complete digital twin. Digital twins are modern tools that integrate real-time data and facilitate ongoing monitoring and control of power systems [2]. This paper aims to construct a robust synthetic model that paves the way for such advanced capabilities in the future.

The digital model was implemented and fine-tuned using publicly available data from credible sources [3], [4]. The model anticipates future challenges by thoroughly examining the integration of VRES and electrolyzers and provides strategic insights into renewable energy distribution. While real-time data integration and control are beyond the current scope, this study forms a critical first step and offers valuable perspectives for scenario analysis and system planning.

The remainder of this paper is organized as follows: Section II analyzes the applications of steady-state digital twins in power systems. Section III explains the methodology for constructing the synthetic digital model. Section IV presents the different multi-energy scenarios considered and their respective results. Section V evaluates the results and provides insights into the effectiveness of the proposed model. Finally, Section VI outlines future work toward the full digital twin.

II. Applications of Steady-State Digital Twins in Power Systems

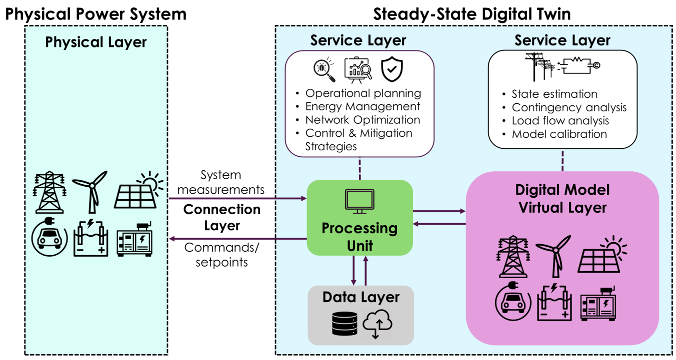


Fig. 1: Steady-state digital twin for monitoring and controlling power systems

According to [5], a digital twin is defined as a digital representation of a real-world target entity with data connections that enable convergence between physical and digital states at an appropriate rate of synchronization.

This bidirectional data connection allows a digital twin to monitor measurement signals and control the system by sending commands and setpoints, providing modern solutions for managing complex power systems with VRES generation and power electronic loads [6]–[8]. Furthermore, these digital replicas can be programmed to provide automatic services such as operational planning and energy management. Consequently, power system operators are increasingly considering these tools for operation, stability, control, and cybersecurity management [9].

Fig. 1 illustrates a comprehensive framework for utilizing steady-state digital twins in power systems. This framework includes the physical power system and the digital twin, connected through a layer for data exchange. The main components of each element are listed below.

Physical Power System: The real system that changes over time and must be monitored and controlled.

- *Physical Layer:* Represents the actual power system, including transmission lines, conventional and renewable generation sources, electrical transformers, loads, electric vehicles, batteries, etc. It provides real-time data and operational conditions to the digital twin.

Connection Channel: Constitutes the connection layer and facilitates data exchange between physical and digital systems.

- *Connection Layer:* Ensures the digital twin receives up-to-date information and can send control commands back to the physical system, promoting an integrated and responsive environment.

Digital Twin: Contains the components needed for the digital representation of the actual system.

- *Virtual Layer:* Consists of a digital model that replicates the physical system in a virtual environment, enabling detailed simulations. Tasks such as load flow analysis, state estimation, and contingency analysis can be performed over this digital representation. It can be calibrated with real-time system measurements.
- *Service Layer:* Focuses on high-level applications such as operational planning, control and mitigation strategies, and model calibration. It utilizes real-time data to predict issues and optimize operations.
- *Data Layer:* Manages data storage and retrieval for the digital twin.
- *Processing Unit:* Administrates communications between the real system and the digital model. It provides the computational power to execute tasks such as network optimization, predictive maintenance, control strategies, data storage, and model updates.

By integrating these layers and leveraging advanced modeling and simulation tools, steady-state digital twins provide a robust framework for proactive system management, ensuring a resilient and efficient power grid.

III. Development of the Synthetic Digital Model of the Dutch EHV Network for 2030

A. Methodology

This model has been developed based on data available from public sources such as [3]. The generation/demand profile is theoretically defined based on [10], where specific regional values and VRES installation capacities are the most extensive among various technical reports. The transmission lines and power transformer parameters were derived from previous research conducted at Delft University of Technology [11]. Additionally, supplemental network data was collected from public resources like [4], an independent website focusing on high-voltage networks in countries such as the Netherlands and Belgium.

The transmission system was modeled in PowerFactory, and Python scripting was used to automate data reading and perform scenario simulations. A flowchart illustrating the complete process of developing the synthetic digital model is shown in Fig. 2.

After constructing the base model, several verification steps were conducted. First, the model's results were compared to system performance data and studies available in [10] to verify consistency with historical and expected system behaviors. Second, the parameters of transmission lines, transformers, and generation capacities were cross-referenced with values reported in technical documents from different public data sources. Although real-time operational data was unavailable, these comparisons ensured that the synthetic model aligned with the expected performance of the Dutch EHV grid. Adjustments were made where discrepancies were found, particularly with respect to generator settings and regional demand values.

Subsequently, the model was updated with projections for 2030, including adjusted installed capacities and topology configurations. The dispatch configuration and testing for these future scenarios were conducted as part of the case studies described in Section IV.

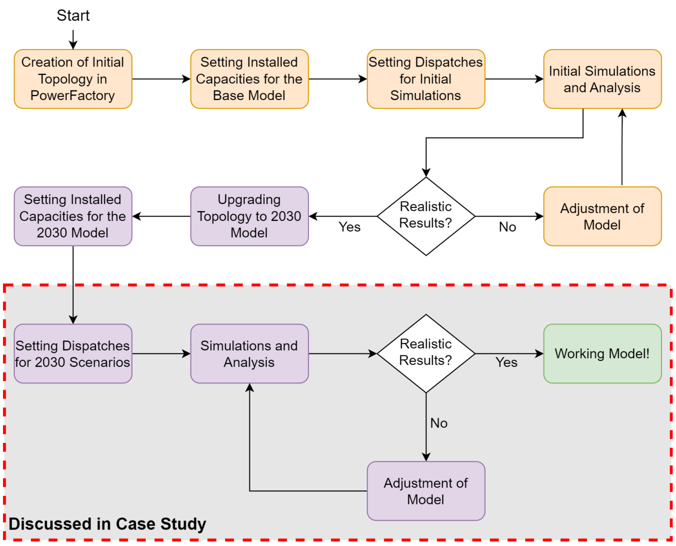


Fig. 2: Synthetic model development flowchart for the Dutch EHV network of 2030

B. Network Topology

The grid topology is based on [4], [12]. The network was expanded in compliance with different ongoing or planned projects mentioned in technical reports available at [10]. Various network configurations were tested, including both typical operating conditions and more extreme scenarios designed to push the system to its operational limits. These tests considered factors such as high demand, solar and wind renewable energy integration, installation of electrolyzers, and potential grid contingencies, allowing us to assess the network's resilience under diverse conditions.

The single-line diagram of the final system for 2030 is given in Fig. 3. The example diagram uses colors to indicate voltage levels and loading conditions: green indicates normal operating conditions, light blue to blue indicates increasingly lower voltage ranges, and yellow to red indicates increasingly higher levels of loading and potential overloads. Additionally, highly loaded components (in this case, transformers) are circled in pink, and a large area with undervoltages of around 0.95 p.u. is colored in light blue.

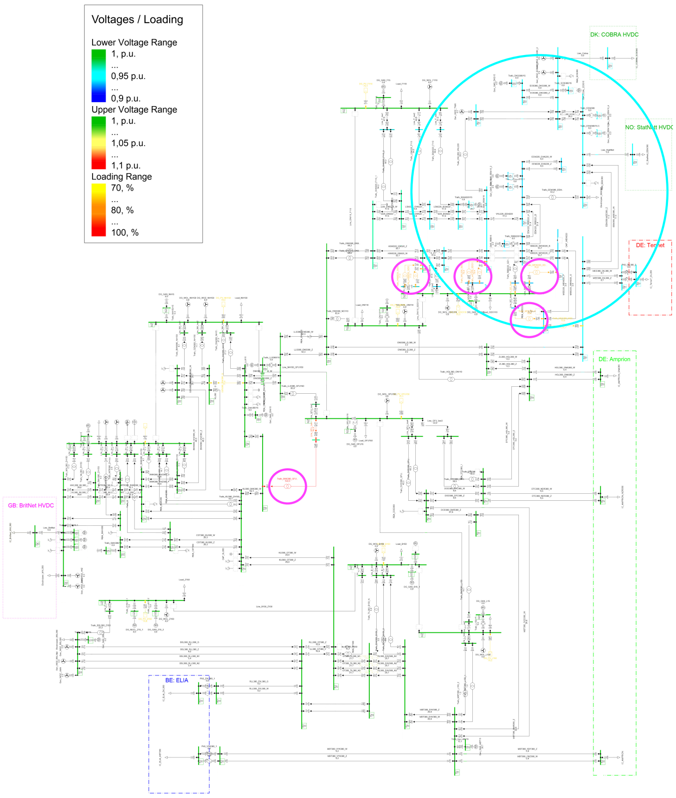


Fig. 3: Single-line diagram of the synthetic digital model of the Dutch EHV system. The diagram uses colors to indicate voltage levels and loading conditions.

IV. Multi-Energy Scenario Case Study

A. Description of cases

Simulations were performed for the 2030 scenario. This scenario was selected as a reference because it is based on installed capacities from the Dutch climate agreement [13].

For each scenario, the power flow within the transmission network was analyzed with the introduction of electrolyzers at locations near new offshore wind connections. The chosen locations are illustrated in Fig. 4.

Different distributions of the electrolyzers were assumed for different cases. Based on the maximum expected power outputs, the total installed capacity of the electrolyzers is set to 10 GW.

Fig. 4: Illustration of the electrolyzer locations. Grid map taken from [3]

Different combinations of VRES generation, demand, and electrolyzer distribution are considered for the operational scenarios. In all cases, the Netherlands is assumed to be self-sufficient. This assumption was made because it is expected that in the future, 70% of the main transmission network transfer capacity should become available for the market [14]. The different cases that were chosen to be investigated are the following:

- **Case A:** Wind energy as the only source of electricity generation for a high demand.
- **Case B:** Solar energy as the only source of electricity generation for a high demand.
- **Case C:** A mix of high wind and some solar generation during peak demand.

Three base cases were created where no electrolyzers are used, and the national system's generation and demand are balanced: A0 for only wind generation, B0 for only solar generation, and C0 for a mix of solar and wind generation. The Dutch transmission system is assumed to be self-sufficient, so interconnections are disabled.

Subsequently, 3 cases (A, B, and C) were created, each with seven scenarios in which different electrolyzer distributions are considered. This includes cases locating electrolyzers only at one location, in two locations and at all three locations. For these scenarios, the generation of VRES exceeds the demand, so electrolyzers are used for Power-to-X (P2x) generation. Table I and II present an overview of the different cases' characteristics.

For each of the scenarios (1-7) belonging to a case (A, B, and C), three different analyses were performed: power flow,

TABLE I: Summary of case scenarios with solar/wind capacity percentages and presence of conventional generation, interconnections, and electrolyzer demand.

Conv.Gen: Conventional Generation, IC: Interconnections, P2x Dem.: Electrolyzer Demand.

Case Type	Synthetic Case Description	Solar (%)	Wind (%)	Conv Gen	IC import	IC export	P2x. Demand
A0	base case, only wind, no IC	0	87	N	N	N	N
B0	base case, only solar, no IC	65.5	0	N	N	N	N
C0	base case, mix solar and wind, no IC	18	90	N	N	N	N
A1-7	electrolyzer cases, only wind, no IC	0	100	N	N	N	Y
B1-7	electrolyzer cases, only solar, no IC	91	0	N	N	N	Y
C1-7	electrolyzer cases, mix solar and wind, no IC	52	100	N	N	N	Y

TABLE II: Description of cases. Active power generation, demand, electrolyzer usage, and power surplus.

Conv.Gen: Conventional Generation, Import/Export: Interconnections, P2x Dem.: Electrolyzer Demand.

Case Type	Solar (GW)	Wind (GW)	Conv. Gen (GW)	Regional Demand (GW)	P2x. Dem. (GW)	Import (-) / Export (+) (GW)	Gen. - Dem. (GW)	Active Power Surplus (GW)
A0	0.0	16.2	0.0	16.0	0.0	0.0	0.2	0.2
A1-7	0.0	18.6	0.0	12.0	6.5	0.0	6.6	0.1
B0	16.2	0.0	0.0	16.0	0.0	0.0	0.2	0.2
B1-7	22.5	0.0	0.0	12.0	10.0	0.0	10.5	0.5
C0	4.5	16.7	0.0	21.0	0.0	0.0	0.2	0.2
C1-7	12.9	18.6	0.0	21.0	10.0	0.0	10.5	0.5

optimal power flow, and a contingency analysis.

B. Results of case study

The synthetic digital model proved to be a valuable tool for testing multi-energy scenarios, with several notable observations arising from the different cases.

1) Case A - Only Wind Generation: For scenarios A0-7, large electricity transport can be seen from offshore wind farms towards inland connections. Large exports can especially be seen from the regions of Zeeland to Brabant in the Netherlands. Large exports were particularly evident from the regions of Zeeland to Brabant. As most wind generation is concentrated at the $380\,\mathrm{kV}$ and $220\,\mathrm{kV}$ levels, considerable power flows were also directed toward the $150\,\mathrm{kV}$ and $110\,\mathrm{kV}$ regions. Contingency analysis revealed that the most effective distribution of electrolyzers occurs when they are evenly distributed across the three locations, with a total electrolyzer demand of $6.5\,\mathrm{GW}$.

2) Case B - Only Solar Generation: In the only-solar-generation scenarios B0-7, results differed notably from those in Case A. For the base scenario B0, significant power transport was observed from the northern to the southern regions of the Netherlands due to the higher installed solar generation capacity in the North. A total electrolyzer demand of $10\,\mathrm{GW}$ was considered. In these scenarios, the power exported from the HV to the EHV regions of Groningen and Drenthe led to undervoltages, reaching approximately $0.9\,\mathrm{p.u.}$ This issue arose due to the combination of high solar capacity, low demand, and insufficient transformer capacity between the HV and EHV sections of the network.

3) Case C - Mix of Solar and Wind: In this case, the optimal locations for electrolyzers were identified as Locations 1 and 3 (case C5) and Locations 1 and 2 (case C6), as only these two cases displayed no component loading above 70%. Results from the contingency analysis for cases C5 and C6 are shown in Fig. 5a and 5b. In both cases, transformers between the EHV and HV regions were critical for n-1 security in several areas, with some transformers showing loadings up to 100%.

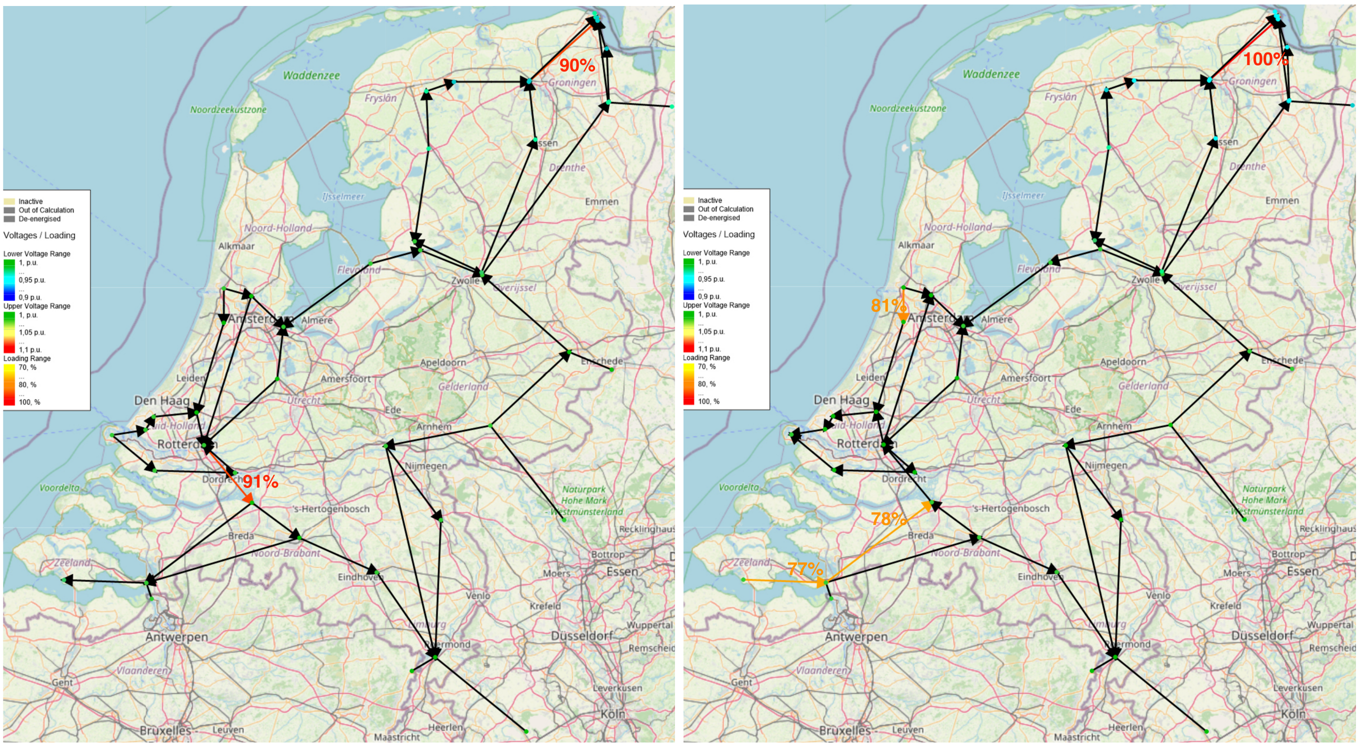
V. Conclusions

The steady-state digital twin framework developed in this study showcases its potential for enhanced monitoring and control of power systems. The synthetic model of the Dutch power system serves as a foundational layer for a future comprehensive digital twin. The digital model has provided valuable insights into key areas such as the integration of distributed generation and system flexibility measures. By enabling multi-energy scenario planning, the model contributes to a better understanding of future network challenges, particularly under varying configurations of VRES and electrolyzer deployments.

However, the model's reliance on publicly available data necessitated numerous assumptions, particularly regarding generator and transformer settings. This was a limitation of the study, but care was taken to validate the model by comparing its results to data from trusted sources, ensuring reasonable alignment with expected system behavior. Despite the absence of real-time data integration, this synthetic model accurately reflects projected system performance for 2030.

VI. Future Work

The ultimate goal of this research is to evolve the current synthetic model into a complete digital twin, enabling real-time data integration and dynamic monitoring. Future work will focus on incorporating transient stability analysis, which will allow the model to assess system responses to faults or sudden changes in operating conditions. Additionally, communication channels will be established with the physical system, enabling real-time synchronization between the digital and physical systems.



(a) Electrolyzers at Locations 1 and 3 - case C5

(b) Electrolyzers at Locations 1 and 2 - case C6

Fig. 5: Geographic diagram of contingency analysis for $n-1$ security

Further validation of the model with real-time operational data will be pursued to ensure its accuracy and applicability for practical use in network management.

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