FEATURE

VIRTUAL POWER PLANT DIGITAL TWINS

Ensuring Seamless Deployment via Standard Architectures

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DIGITALIZATION IS TRANSFORMING power systems in multiple ways, driving efficiency, flexibility, and sustainability to new levels. Examples of such transformations have been visible since the introduction of the supervisory control and data acquisition and energy management systems several decades ago, enhancing overall network stability and reliability and enabling better prediction of faults and more rapid response to disruptions. Since then, investments in new monitoring and communication technologies have resulted in an advanced metering infrastructure capable of collecting large amounts of data, ranging from assets and devices to the system level. Data availability leads to advanced digital models and platforms, helping to resolve open challenges in modern power systems, including handling increasing levels of renewable energy, controllability of large numbers of distributed energy resources (DERs), and the need for faster and more flexible operational decision-making models.

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In this context, the concept of virtual power plants (VPPs) has emerged, facilitating the decentralized dispatch and control of larger numbers of DERs, such as solar panels, wind turbines, battery storage systems, electric vehicles, and flexible loads, via a digital platform that enables a unified coordination. Building on top of this digital platform, digital twins (DTs) can facilitate VPP operation and planning.

Introduction

DTs emerged as a promising concept aimed at leveraging large amounts of data and advanced simulation and modeling capabilities. In 2010, NASA proposed the DT concept for space exploration using remote-controlled vehicles, and it was conceived as a simulation model primarily for monitoring purposes. The idea behind using DTs was to facilitate solving technical problems with space vehicles hundreds of kilometers away. Since this definition, the DT concept has evolved and adapted to multiple domains. In the power system domain, DTs have been mainly used to enhance the real-time monitoring capabilities of power systems infrastructure and devices. Nevertheless, most DT monitoring applications disregard one of the key DT features: a bidirectional and automated data exchange between a physical system and its digital counterpart. As a result, simulation models alone are misconceived as DTs (see Table 1). From this perspective, a digital model capable of simulating a physical system in real time is the base for any monitoring application, enabling observability of such a physical system. Nevertheless, most current power system DT applications disregard the fact that digital models can also be used for short-term decision making and long-term system upgrades, based, for instance, on scenario analysis aimed at considering uncertainty. Thus, there is a need to recognize key features of DTs that go beyond real-time monitoring. Despite power system DTs' potential, several challenges and questions remain open, as follows:

- ✔ What are the key features of a DT? Which features (beyond monitoring) must be recognized as integral parts of a VPP DT?
- ✔ How can we leverage the benefits of DTs in the context of VPPs?
- ✔ What should a standard DT architecture look like? Such architecture must enable seamless integration with new and already deployed tasks and applications for transmission and distribution and seamlessly extend to model DERs up to the VPP.
- ✔ How do we enable multiple DTs to cooperate and coordinate, especially in the context of VPPs, where resources can be geographically sparse?
- ✔ What role can artificial intelligence (AI) and machine learning (ML) play in the future development of VPP DTs?
- ✔ What can be learned from pilots who successfully deployed advanced VPP DTs?

This article aims to answer some of these questions, presenting a new perspective on power system DTs and their implementation, covering examples that go from DERs up to VPPs.

VPP DTs

A VPP can be defined as a collection of DERs, perhaps geographically spread, requiring advanced digital tools to ensure appropriate operational coordination as an integrated and unified power plan. VPPs are also part of large-scale electricity

Table 1. A comparison of key features of different DT definitions.

DT Definition	Modeling Approach	Data Exchange Between a Physical and a Digital System	Applications Beyond Monitoring (e.g., Control and Planning)
NASA	Multiphysics model representation of a real physical system.	From the physical system to its digital counterpart.	Disregarded.
Digital models			
Provided definition (see the "VPP DTs" section)		Bidirectional link: from the physical system to its digital counterpart and vice versa.	Scenario-based analysis can be deployed. Useful for short-term decision making considering uncertainty and long-term planning.

infrastructure that can comprise medium- and/or low-voltage networks organized as neighborhoods, cities, industrial parks, universities, hospital campuses, etc. DTs can provide a holistic approach to processing, modeling, simulating, and validating all DERs operations within a VPP, thereby playing an essential role in bridging the gap between the physical and digital worlds. In this sense, a VPP DT holds the potential to do the following:

- ✔ Enhance the VPP's controllability, stability, and resiliency by leveraging real-time monitoring and fast decision-making capabilities.
- ✔ Facilitate handling of uncertainty derived from renewable-based DERs via scenario analysis using risk-based decision-making models.
- ✔ Ensure scalability features to handle large numbers of DERs via proper aggregation and disaggregation models, integrated into operational models.
- ✔ Facilitate the VPP infrastructure maintenance and update by performing scenario-based analysis, helping to define investment decisions considering physical constraints of the electricity network.

In general, a power system DT can be defined as "a collection of modules integrated into a single software ecosystem with advanced data management capabilities, aimed at mirroring the real time operation of an electricity infrastructure and support its long-term planning" (see the "For Further Reading" section). This DT definition can also be extended to VPPs, as an electricity infrastructure composed of several (geographically spread) DERs and assets (e.g., transmission or distribution cables and transformers). This more comprehensive VPP DT definition recognizes multiple key features as fundamental. These key features are represented in Figure 1. A VPP DT encompasses a wide range of multiphysics models (e.g., dynamics and steady-state models used for thermal and electrical stimulation) at different scales (from assets/DERs to system-of-systems) and timescales (e.g., seconds or hours). These multiphysics models aim to represent in real time the operation of a physical asset or system via a bidirectional data exchange supported by advanced metering (e.g., smart measurement units and sensors) and control infrastructure deployed within the VPP infrastructure. To properly handle large amounts of data and information, a VPP DT must be able to process data to facilitate the operators' decision-making and planning process. This should be done based on modular functionalities, including specialized data storage, engineering, and analytics modules. Such VPP DT models are expected to properly integrate and interface with existing operational tools (e.g., those already deployed to perform DERs dispatch) and multiple measurement and control infrastructures (e.g., supervisory control and data acquisition and energy management systems). A key feature of advanced VPP DTs is enabling planning functionalities beyond real-time monitoring, including forecast-based dispatch of DERs, scenario-based analysis, and future investment planning. The above-described VPP DT features and capabilities can be enabled via proper standardization of the DT architecture.

Toward a Standard DT Architecture

Concepts from software development can be borrowed by conceiving a VPP DT as a comprehensive software ecosystem. A standard approach toward the development of a modular-based DT

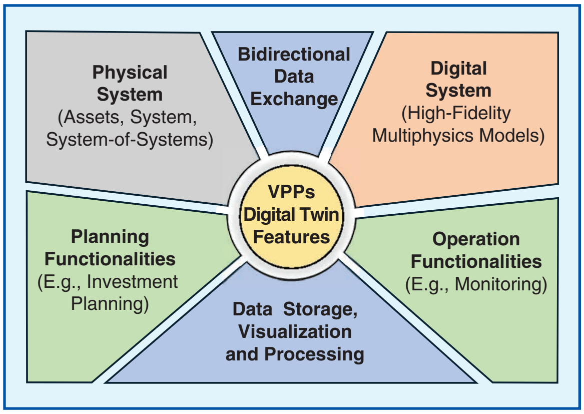

Figure 1. The recognized key features of a VPP DT, going beyond the monitoring application to more advanced functionalities, including infrastructure planning. The same color coding is used in other figures: gray indicates physical systems or devices, blue indicates data capabilities (measuring, storage, processing, and visualization), orange indicates the digital counterpart of the physical system, and green indicates functionalities.

architecture will enable VPP operators to work with a self-contained approach, ensuring a separation of concerns for processes related to the deployment of new functionalities, as well as those that support simultaneously multiple tasks via multiple models (e.g., data engineering and data analytics). Standardization and self-containment play a particular role in VPPs with DERs located geographically apart from each other. In this case, the expectation can be for multiple DTs to cooperate, composing an ensemble of DT models that ensures scalability without compromising the VPP unified operation and control approach.

Figure 2 presents a representation of a standard DT architecture for power system applications. This DT architecture can be deployed from DERs up to the VPP, and it is composed of four main components: 1) simulation models, 2) operation and planning models, 3) data engineering, and 4) data analytics. The former components aim to facilitate operation and planning by leveraging advanced modeling capabilities, enabling VPP operators to meet their objectives from everyday operation to long-term planning. In contrast, the latter components compose the backbone of multiple functionalities, allowing real-time automated data exchange between the digital and physical world and between the different components and models via proper data interfaces. A more detailed description of each of these components is presented as follows:

- ✔ *Simulation models*: Various multiphysics multiscale simulation models compose the core of the DT. These simulation models support the capabilities of different DT components. From an operational perspective, various models are expected to be leveraged depending on the type of DERs and infrastructure deployed. Some models may include power flow models for steady-state analysis, electromagnetic and transient models, thermal models for heat transfer analysis, and dynamic phasor models for analysis based on phasor measurement units. Due to the nonstationary environment of a large-scale electricity infrastructure, a continuous model update process is expected due to the adoption of new DERs or increased demand (see later the single source of information [SSI] approach). A simulation model management module can automate and handle this automated update process, orchestrating and synchronizing models with the actual system. Tasks such as model version control and

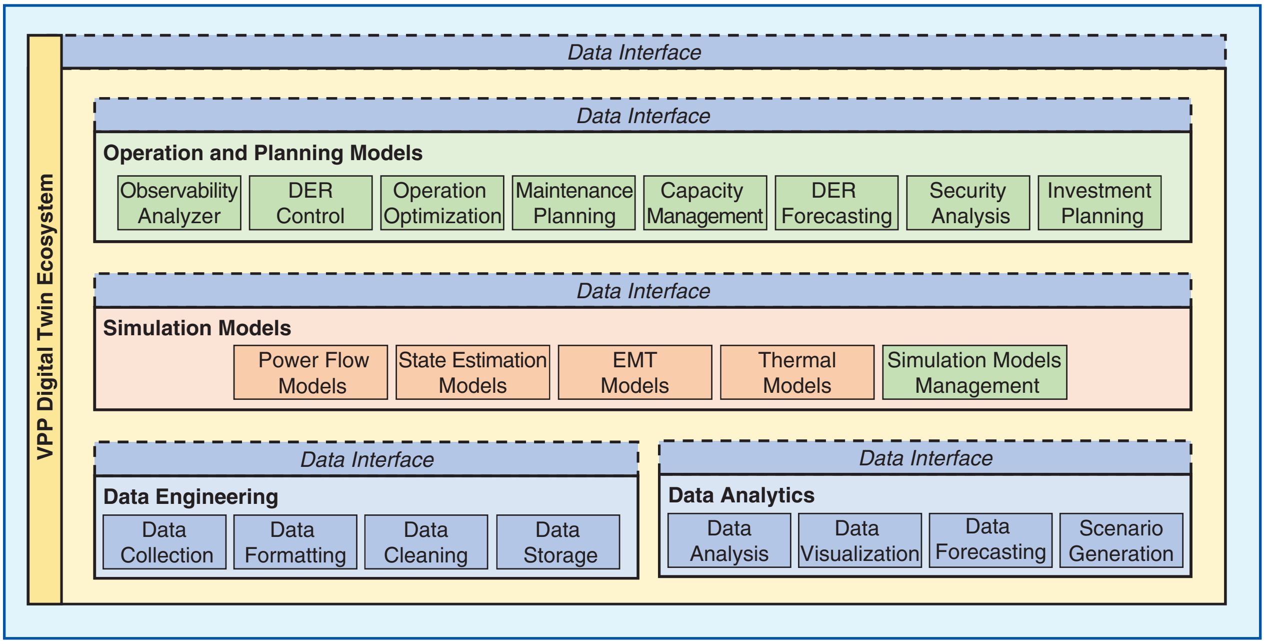

Figure 2. A proposal of a standard DT architecture for power systems applications. In the context of VPPs, this architecture can be deployed for DERs up to the VPP itself following a multi-DT approach.

documentation can also be executed by this simulation model management module with the support of the data engineering component.

- ✔ *Operation and planning*: Traditional VPP operation and planning applications, including those that perform DER control and dispatch and those that analyze the system's observability and stability, as well as those used for long-term maintenance and investment planning, etc., can all be contained in the operation and planning model components. In this case, a clear separation exists between the multiphysics models that such applications require as these are contained in the simulation model component. This separation enables the multiphysics models to be updated without interfering with the algorithms deployed to perform operation and planning applications. However, to achieve proper model synchronization, a standardization of the multiphysics model data interface is required, which can be done via functional mockup units. Functional mockup units enable the encapsulation of the model's physics equations and its corresponding solver into a single software-based component, facilitating its integration with multiple applications.
- ✔ *Data engineering and analytics*: Digital infrastructure is the foundation for the physical-to-digital connection. A DT is fed with data collected from field sensors; Internet of Things devices; and measurement units located at different assets (e.g., lines, switchers, and transformers), DERs, and customers (e.g., via smart meters and customers' apps). Other relevant data, including weather, energy market prices, and states of adjacent interconnected systems, can be included to compose a set of contextual information that is relevant, perhaps to planning tasks that require scenario-based analysis. Due to the large amount of data and the variety of sources with different spatial-temporal resolutions, formats, and quantities, proper data management functionalities must be implemented. These functionalities are deployed within the data engineering and analytics component, ensuring that all data are well prepared, accessible, and of high quality for all available modules within the other components. Data accessibility and compatibility can be guaranteed with the proper use of data formatting. For instance, network data containing power system equipment data, topology information, state variables, etc., can be stored and seamlessly transferred using the Common Grid Model Exchange Specification (CGMES) [based on the well-known Common Information Model (CIM)] standard developed by ENTSO-E. As historical data are expected to be stored for long periods, they can be leveraged to perform predictive and descriptive analytics, facilitating the discovery of trends, forecasting, and risk assessment. This new knowledge drawn from historical data can be used to feed the operation and planning models, empowering operators to manage the electricity infrastructure proactively, perform predictive maintenance, and properly handle uncertainty via risk management.

Figure 3 presents an example of an ensemble of multiple DTs representing DERs within a VPP. In this case, each DT coordinates the operation of its DERs that share the same operational objectives (e.g., market revenue) at the VPP level. The success in coordinating such DTs is achieved via proper data exchange standardization, which will ultimately depend on the final DT application. Data standardization can also help to resolve and minimize the impact of compatibility concerning multiple DT interfaces, as well as data formats, sampling time, etc. For instance, in a market setting, there is a need for VPPs to exchange market bids and offers using a standardized format. This is needed to enable an accurate exchange of imbalance and settlement data among DER participants and facilitate regulatory reporting and market transparency. VPP DTs can allow this data exchange, facilitating market deployment and implementation while guaranteeing flexibility to accommodate new DERs. Although a VPP multi-DT approach seems interesting, many technical and scientific challenges remain unresolved. For instance, it is not clear how to synchronize states from the multiple DTs in real time. State synchronization plays an important role during operation, considering that physical models are used to assess the impact on the multi-DT of any operational decision made. Another main challenge is the increased complexity regarding coordination among all DTs with respect to decision making. Nevertheless, as data are stored and processed locally, a local DT deployment per DER may facilitate decentralized control, enhancing scalability features and increasing robustness.

VPP DT Workflow

Although the proposed DT architecture represents an effort to standardize DT deployment in VPPs following a software development approach, it disregards the temporal dimension and its integration into the VPP's operation and planning lifecycle. To consider the temporal dimension, Figure 4 displays a VPP DT workflow. The relevant cycle of a VPP DT comprises continuous cycles of (dispatch and) control, operation, and short- and long-term planning processes performed by the VPP operators. In the initial stage, the physical infrastructure must be mapped into a digital model via advanced multiphysics models. The type of deployed model (e.g., dynamic and steady-state used for thermal and electrical simulations) depends on the final functionalities executed by the VPP DT. Nevertheless, as physical infrastructure changes (e.g., DERs switching off and network reconfiguration) affect the accuracy of the deployed digital model, an event-driven update process must be implemented, in addition to the continuous monitoring approach ensured by the advanced measurement infrastructure. This continuous update process represents the VPP DT "heartbeat" and ensures that the simulation models follow the physical infrastructure's evolution. As a result, a version control approach ensures that records are kept available (via the simulation models management; see Figure 2). This version control can be

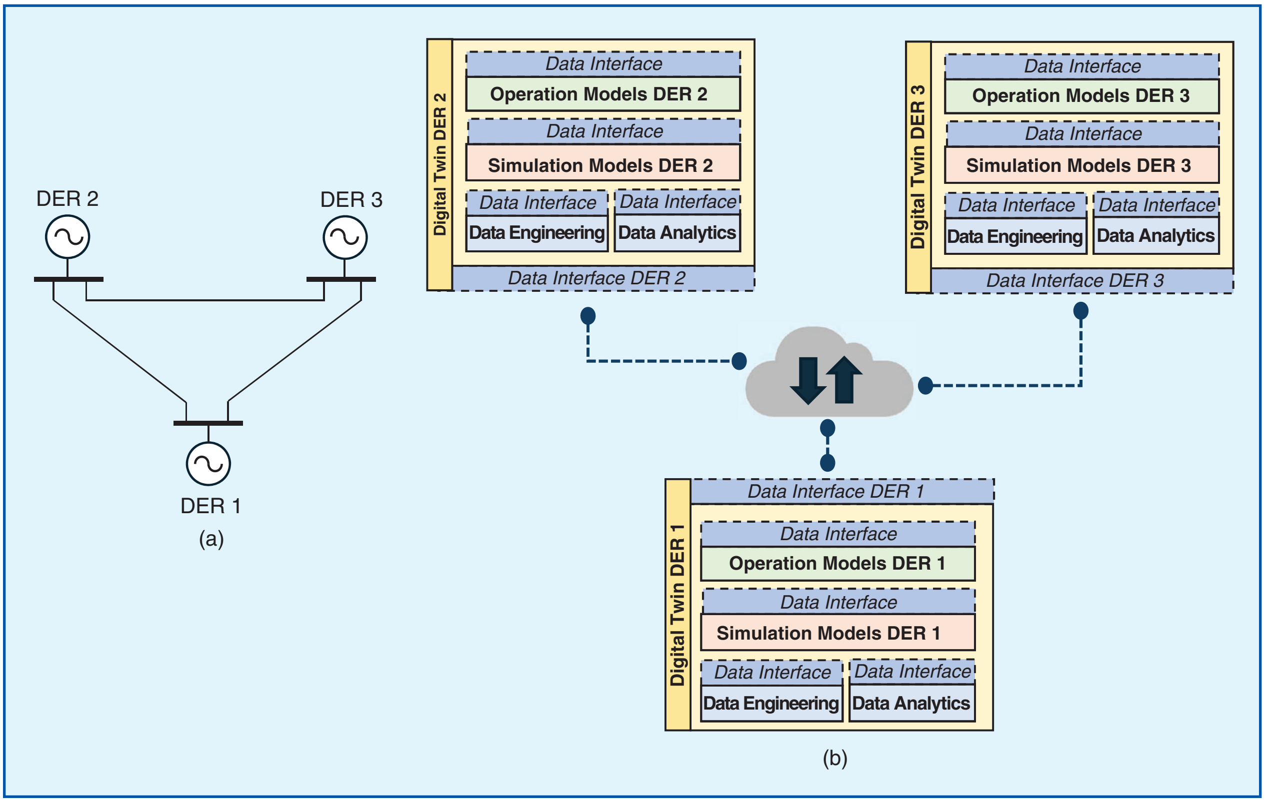

Figure 3. A representation of an ensemble of DTs for (a) a three-DER VPP using (b) the standard DT architecture. Notice that the same standard architecture can be used to develop DTs for assets such as lines and transformers.

deployed via the CGMES standard, ensuring that a centralized and unique modeling source is available. We define this approach as an SSI. Moreover, the availability of real-time measured data can be used to correct the model's assumptions, enhancing any multiphysics model's accuracy. From the scientific perspective, an open challenge relates to the VPP state and model synchronization due to the multiple types of multiphysics models that can be deployed within the VPP DTs (e.g., dynamic, steady-state, electrical, thermal, and chemical models) that rely on various data sources with different sampling rates (e.g., milliseconds for phasor measurement unit or 15 min for smart meter), as well as modeling phenomena that occur in other time scales (e.g., seconds, minutes, or hours).

From the VPP operation and planning perspective, an advanced digital representation of the physical infrastructure enables the VPP operators to consider uncertainty via a scenario-based approach. Control, operation, and planning functionalities can now run hundreds of such feasible scenarios making use of high-fidelity digital copies of the deployed physical infrastructure. This enables testing changes in the system's parameters, operation rules, infrastructure failures, etc., all with minimal effort and facilitated by the SSI concept. As a result, VPP operators can now assess the robustness of any decision-making process put in place before it reaches the physical infrastructure. Moreover, the availability of digital copies of the physical infrastructure and large historical data will enable fast deployment, validation, and operation of new devices, components, and infrastructure. This can be seen as an indirect process of knowledge transfer, perhaps facilitated by the introduction of intelligence via AI algorithms.

Role of AI in VPP DT Development

In the context of AI, ML models have been proven to learn from large datasets and even find new knowledge successfully. AI and ML are revolutionizing several sectors, including the financial and health sectors. A similar revolution is expected for the energy sector, with the potential for AI and ML

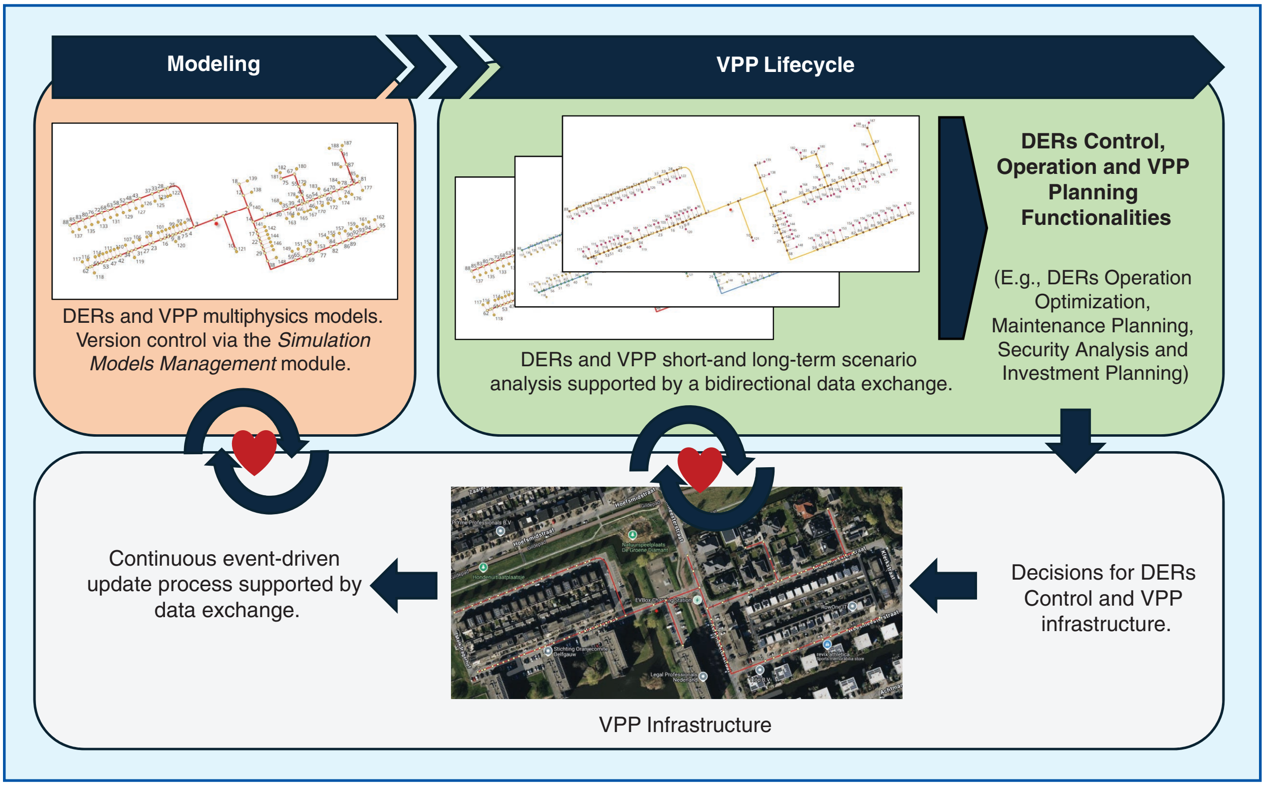

Figure 4. A DT workflow representation of a low-voltage distribution network VPP. As the VPP infrastructure dynamically changes (e.g., DERs switch on or off, topology reconfiguration), a continuous event-driven update process must be implemented to keep track of changes in the simulation models.

models to introduce intelligence to VPPs, enhancing the performance of backbone modules of VPP DTs. Some of the expected enhancements that AI and ML models can bring to the development of DTs are as follows:

- ✔ DTs are expected to store and process large amounts of data. ML models can facilitate this by analyzing large volumes of data in short periods and discovering hidden patterns that can be later used for predictive maintenance. Clustering algorithms can be deployed to group VPP resources to provide specific support services depending on the network conditions (e.g., voltage support or energy flexibility). The integration of automated clustering algorithms with decision-making algorithms would enable the self-organization of the VPP resources. As data collected and stored will certainly contain errors or be incomplete, ML models can automatically identify such data using anomaly detection algorithms, while incomplete data can be filled in using data imputation ML algorithms. The deployment of these algorithms will ensure that the stored DT data are of the highest quality, guaranteeing their availability for all the required DT modules and applications.
- ✔ Multiphysics models are complex: on one side, they are usually described by high-order models that uses many parameters for which direct data are unavailable, and on the other side, they require large amounts of computational resources to be solved. This results in such physics-based models turning unfeasible for tasks such as real-time control. ML algorithms can solve this issue by developing proxy models of DERs and VPPs. ML models have been proven to be capable of accurately representing physical systems. For instance, deep neural networks can be used to solve power flow problems for large networks in a short period of time. This performance enhancement is possible due to the ML algorithms' capabilities of leveraging the graph structure of the power network and accelerating calculations. Expectations are for ML-based physical solvers to solve scalability challenges still seen with classical solvers, ensuring large-scale coordination of the large number of DERs expected to be connected within VPPs. Nevertheless, an open challenge with the use of ML-based models is their lack of interpretability. Interpretability is essential to understanding the reasoning behind any decision-making tool.
- ✔ Manually executed processes, such as events or incident reporting (e.g., faults), can be easily automated by using large language models (LLMs). LLMs can be trained and instructed to generate such reports, reading from the VPP operators' database and freeing time for engineers and technicians. LLMs can also be trained to interact with engineers and technicians using a text-based interface, facilitating documentation preparation and review. The application of LLMs can go even further, automating VPP model standardization. This can be done by properly training such LLMs using large databases of files describing network components and topologies described using the CGMES (formerly known as CIM) standard. As a result, such LLMs can automatically generate CGMES files and extend the standard definitions, keeping DERs and network topology models updated.
- ✔ Control and optimization processes, including the dispatch of the VPP resources, can be accelerated with the use of reinforcement learning (RL). RL algorithms are proven capable of solving complex problems, learning from the large database of historical operational decisions and via direct interaction with the power network. As RL algorithms are developed via deep neural networks, they can make decisions quickly, enabling VPP operators to react fast to changes in operational conditions. Although the use of

RL algorithms is in its early stages, with the Learning to Run a Power Network Challenge as a research and collaboration initiative, transmission system operators and distribution system operators (DSOs) are already testing RL algorithm capabilities for large and complex control problems in the context of multiple DERs. Nevertheless, several challenges remain open, including RL algorithms' capabilities to ensure safety and feasibility by properly enforcing operational constraints. These safety capabilities are a must before they can be widely adopted in power system applications.

- ✔ VPP planning requires operators to run hundreds of possible operational scenarios. Different DER penetration and consumption levels characterize these scenarios. Generative AI algorithms, including generative adversarial networks and variational autoencoders, can be used for this purpose. For instance, generative AI algorithms can infer rarely seen operational states (e.g., states close to faults). These representative states can be used to plan and validate contingency steps, enhancing VPPs' resiliency. Similarly, generative AI algorithms can be used to generate DER generation and consumption scenarios via synthetic data generation. The Linux Foundation Energy Open Synth Project is an example of the use of such generative AI algorithms by DSOs to refine future planning investments and identify needs in infrastructure upgrades.

VPP DT Cybersecurity

Despite the benefits of the increasing level of digitalization in driving the development of advanced VPP DTs, a challenge that surfaces immediately is information security. Information security goes beyond topics such as data security and integration complexity. Increasing digitalization of DERs raises vulnerabilities to cyberthreats. Potential risks include data breaches, malicious control commands, or denial-of-service attacks, affecting the VPP reliability. Typically, one has to consider the following aspects:

- ✔ *Confidentiality*: Exchanged information can scale from unimportant, to market-relevant, to security-relevant. DERs operated via a multi-DT approach require secure data exchange with the central VPP DT. However, it is advised not to compromise in this respect and to treat all communication as being worth protecting from eavesdroppers. True end-to-end encryption is desirable but not always possible, coming with drawbacks such as poor latency, scalability, and resilience for real-time control or forecasting.
- ✔ *Authenticity*: This is linked to the VPP digital identity. In a multi-DER VPP, one question remains unsolved: how can we guarantee that DER agents are who they claim to be? Human identity is usually provided via side channels such as video-ident or PIN codes sent via classical mail. Machines, however, require SIM cards or other trusted platforms plus a sophisticated cryptographic key distribution and identity management workflow.
- ✔ *Integrity*: Integrity, frequently of greater importance than confidentiality, is commonly ensured through cryptographic techniques. In this context, the critical considerations involve key distribution and the management of the key lifecycle, specifically, the processes by which keys are updated or revoked, as well as the protocols governing their storage and usage. Integrity also relates to cyberresilience. From the VPP DT operation perspective, cyberresilience can also be ensured via mechanisms such as anomaly detection, intrusion detection systems, and encryption protocols. AI will play a role in deploying such protection mechanisms. For instance, AI systems can continuously monitor the VPP DT network traffic and detect anomalies that may indicate a cyberattack. ML algorithms can learn patterns behind the VPP DT regular traffic, potentially catching attacks before they cause damage. As

a prevention measure, AI algorithms can predict potential failures or vulnerabilities of the VPP infrastructure by analyzing the large amounts of data collected by the VPP DT. This will allow preventive actions to strengthen the VPP DT security measures before they can be exploited.

- ✔ *Nonrepudiation*: An entity must not be able to deny actions that it has undertaken. This principle is particularly crucial in transactional VPPs, where each action carries significant value and thus necessitates notarization, logging, and confirmation by a reliable authority. Trusted hardware modules can be instrumental in this process. Additionally, maintaining an audit trail of actions may even necessitate the use of digital watermarking or, at minimum, digital signatures for actions that are communicated.
- ✔ *Availability*: While this may appear to be the most straightforward feature, it is often the most challenging to ensure. Guaranteeing the continuous availability of a specific service, such as an energy market platform or an aggregator registry, presents significant difficulties. These services are vulnerable to hacking or denial-of-service attacks, which can result in financial losses or compromise system stability. The typical solution involves fortifying both hardware and software, complemented by implementing redundant and diversified IT infrastructure.

In summary, while securing a VPP that utilizes DTs for decision making and planning is feasible, achieving this security comes with significant considerations. The hardware and software required for a secure system are more costly and demand continuous attention, updates, auditing, and maintenance throughout their lifecycle. Additionally, implementing such security measures may impact system latencies and scalability. Nevertheless, integrating DT principles into security mechanisms offers substantial benefits, including advanced anomaly detection and AI-supported forecasting of potential attack impacts. This represents cutting-edge technology and illustrates how digital transformation can serve not only as a source of potential challenges but also as a solution.

VPP DT Experiences in The Netherlands

In this section, we introduce several pilots and projects in The Netherlands that explore the proposed VPP DT concept for applications related to planning and operation.

Bijlmer–Noord District in Amsterdam

The Local Inclusive Future Energy (LIFE) City Platform, or LIFE Project for short, was a Dutch national effort that gathered academic partners, large commercial and industrial consumers, residential associations, Amsterdam municipality, and grid operators, to jointly develop a district-scale digital platform aimed to resolve grid congestion problems, while integrating local stakeholders as the main actors to plan and provide solutions by leveraging their energy flexibility capabilities via a VPP concept. The objective of the LIFE Project Digital Twin is threefold: first, to enable consumers located in the Bijlmer–Noord District in Amsterdam to coordinate their DER operation aiming to avoid creating congestion; second, to enable a coordinated planning for their future energy investments, reducing the technical impact due to their integration in an already congested distribution network infrastructure; and third, to facilitate energy and/or flexibility trading via a VPP multimarket platform.

From the technical perspective, some of the main features of the LIFE DT platform are related to the following:

- ✔ A GIS-based digital model of the medium voltage infrastructure was developed using the operator's grid information. This deployment leveraged the SSI approach by using a single modeling source of the district's network topology.
- ✔ Medium-voltage transformer measurements are automatically read from the operator system. These measurements are used to show in real time (i.e., in a 15-min resolution) the current operational state of the medium-voltage

infrastructure. Simultaneously, these data are stored and later used to develop scenario-based assessments.

- ✔ A forecasting algorithm was deployed to forecast the demand for all medium-voltage transformers in the Bijlmer–Noord District area. This forecasting algorithm is used to predict the transformer's operation in a period of 24 hours.
- ✔ All stakeholders (industrial, commercial, and residential consumers) have access to the same digital platform (SSI) implemented via a web interface, as shown in Figure 5. Nevertheless, they only have access to data from their connection point with the medium-voltage network. This ensures that sensitive information from other consumers that can be inferred from the measurement data is not leaked.
- ✔ A power flow solver was executed in the background, enabling the DT to provide estimates of the severity of the expected congestion events in a 15-minute resolution. For instance, information related to the remaining available capacity, the severity of the congestion events, undervoltage and overvoltage anticipated issues, etc., is provided.
- ✔ Stakeholders could upload their own energy consumption profiles for a specific simulation period, generating operational scenarios validated in a centralized fashion considering other stakeholders' future energy plans. This is done to support the VPP DT applications for infrastructure planning.
- ✔ A multimarket platform was also deployed in which several stakeholders that owns multiple resources can leverage a VPP approach and provide flexibility by seamlessly trading considering the distribution networks technical constraints.

As an example of the LIFE DT Platform's applications, Figure 6 shows three different energy scenarios studied in the context of the district's future energy plans. These scenarios relate to the technical feasibility of supplying part of the Bijlmer–Noord District (specifically, the Venserpolder neighborhood) heating needs with electricity as the primary source. In this case, three scenarios were developed: scenario A assesses the case for individual electric heat pumps at each apartment; scenario B assesses larger heat pumps, one per building block; and scenario C assesses a heat pump per building block coupled with an aquifer thermal storage

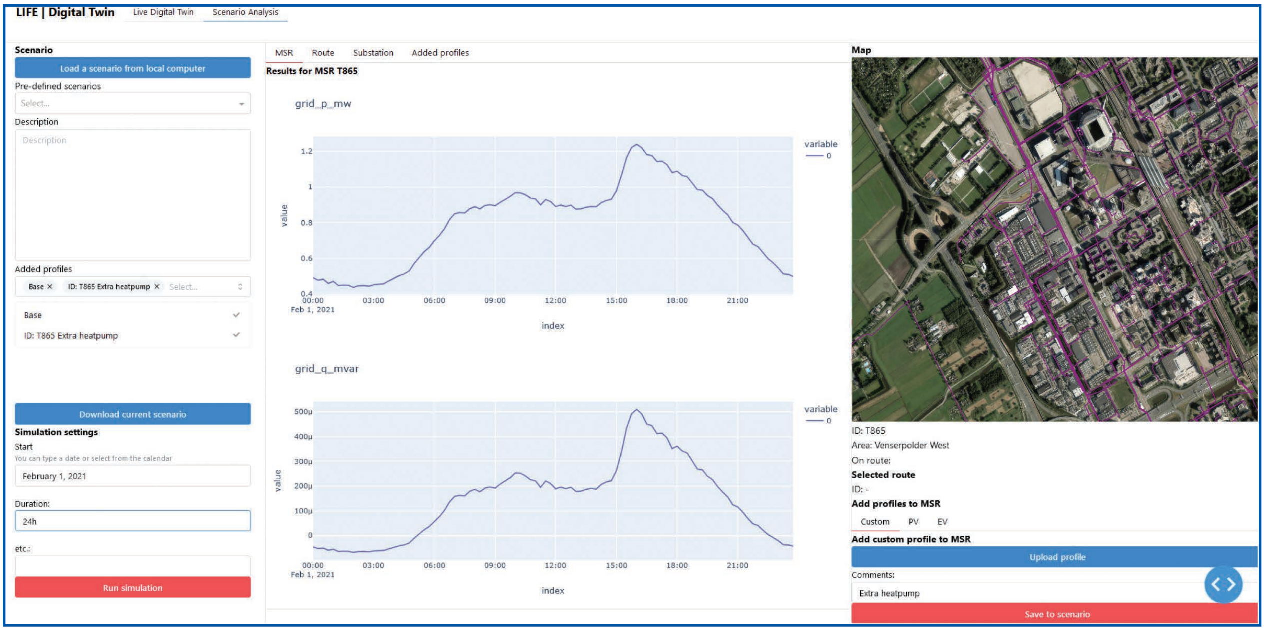

Figure 5. The front end of the LIFE Project DT for the Bijlmer–Noord District in Amsterdam. The front end displays information for the medium-voltage transformers (MSR) connecting residential and commercial customers in a 15-min resolution using data from the measurement units located in the district's network.

system. After assessing the scenario-based simulation results making use of the LIFE DT Platform, it was identified that scenario A will result in a total load exceeding the capacity in approximately 11.4 MWh, creating congestion events lasting approximately 20 h. The severity of the congestion events is reduced in scenario B, lasting approximately two hours, while in the case of scenario C, no congestion was reported. The expectation is that the government and local authorities (Amsterdam municipality) can use these results to coordinate investments with all the local stakeholders.

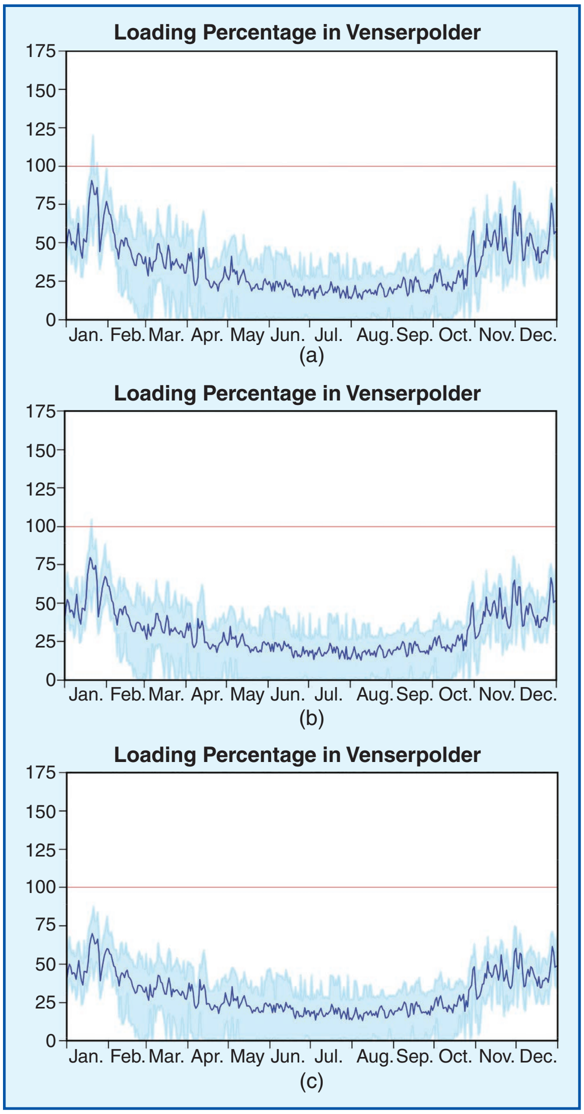

Figure 6. The total medium-voltage loading/capacity (in percentage) for the Venserpolder neighborhood for three different heating scenarios: (a) scenario A, heat pump per apartment; (b) scenario B, heat pump per building block; and (c) scenario C, heat pump per building block + an aquifer thermal storage system.

The Energie–Buurtscan Tool

The Energie–Buurtscan tool (Energy Neighborhood Scan tool), or EBS for its acronym in Dutch, is an online platform aimed at increasing large customers' participation in resolving the current congestion that is seen at the medium-voltage level in most of the larger cities in The Netherlands. The EBS tool, developed by the Dutch DSO Alliander (and partly under the LIFE Project), enables large customers to see the customer's connected region in detail (see Figure 7). The EBS tool provides insight into the current network conditions by leveraging a VPP DT framework in which the network topology, network demands as function of time, and available capacities are made available following an SSI concept. With the information provided by the EBS, customers can analyze the energy consumption profile at the substation level, aiming to perhaps identify possible synergies (e.g., periods of low consumption or high renewable generation) and or enhance their coordination with other DERs or (large) customers located in the same area. As a result, the EBS tool supports large customers with the necessary insights for setting up VPPs. This can be done by using the EBS platform as a tool to validate the technical feasibility of any DER dispatch plan, reducing in the long term the burden on DSOs in case such DERs increase the number of congestion events registered. Moreover, the EBS tool also facilitates coordination with the city planners as their energy teams now have access to the real network conditions, helping them identify suitable areas in which larger residential projects can be developed while avoiding areas with restricted network capacity. To ensure customers' privacy, information in the EBS tool at the medium-voltage substation level is only made available at an aggregate level, with restrictions in case fewer than five customers are connected to a specific medium-voltage substation.

From the VPP DT perspective, the main success of the EBS tool is to facilitate the access and use of DSOs' collected measurements and models to large customers and VPP operators while ensuring that critical infrastructure information (e.g., locations of substations) is secured. Moreover, as DSO models

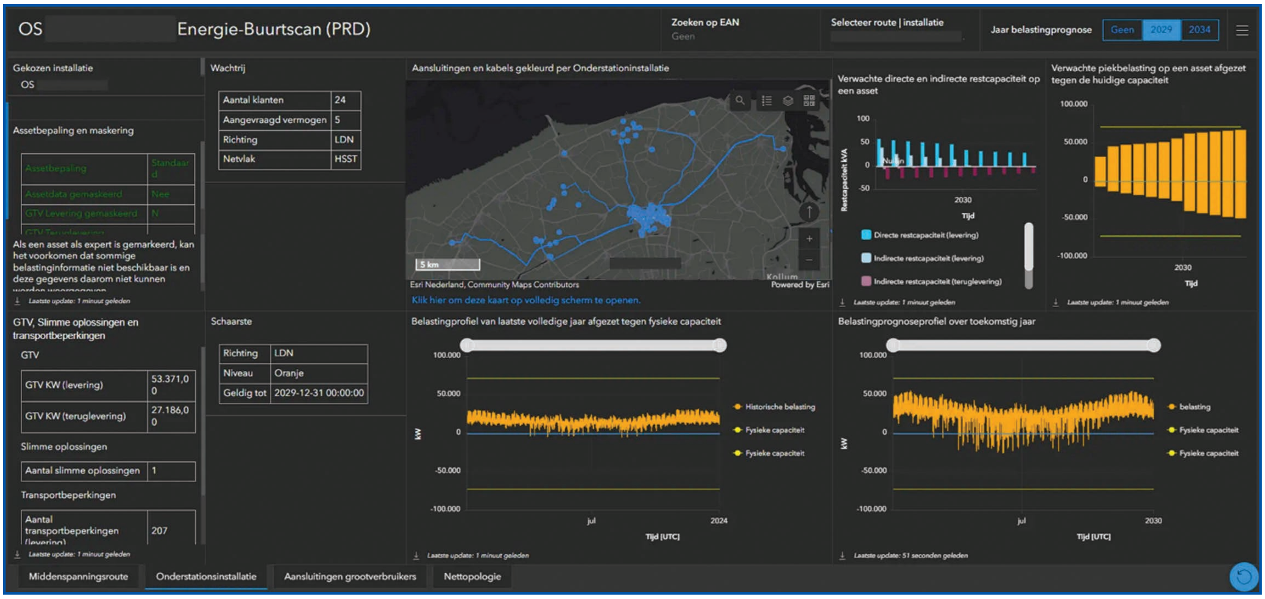

Figure 7. An example of the EBS tool for an area in the city of Amsterdam, The Netherlands. The EBS tool displays measurements at the medium-voltage level, including the remaining available capacity. (Source: https://www.liander.nl/grootzakelijk/energietransitie/innovaties-voor-marktpartijen/energie-buurtscan.)

are executed in the background in an automated fashion, the EBS tool enables nontechnical users (e.g., consultancy companies on behalf of municipalities) to develop preliminary solutions while ensuring that any conclusion drawn is aligned with the DSOs' operational requirements. This process aims to facilitate future final agreements between large consumers and the DSOs.

Summary

The implementation of VPP DTs, from devices up to the VPP level, depends on successfully deploying standard architectures that allow seamless operation and coordination. Data interfaces must also be standardized to enable easy data transfer between a centralized VPP DT and perhaps local DTs deployed at the DER level. In this regard, the CGMES standard will play an important role if it is widely adopted. Nevertheless, it is not yet clear if the CGMES standard can support multiphysics parameters in the description of assets and components. As VPP DTs will feature several multiphysics models, further research and development are needed to properly define the functionalities of a simulation model management module capable of keeping model version control. We foresee this to be deployed via the SSI concept. In this sense, a question that remains open is, from a software development perspective, how to design a module with enough intelligence capable of orchestrating all DT models, modules, and functionalities. AI and ML will play a role in answering this question, not only by automatizing and enhancing functionalities already part of the DT's architecture but also by introducing intelligence. Nevertheless, increasing reliance in AI and ML will naturally increase the DT's vulnerability to communication and data risks. In this sense, cybersecurity will play an important role in ensuring a reliable and safe VPP operation.

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For Further Reading

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