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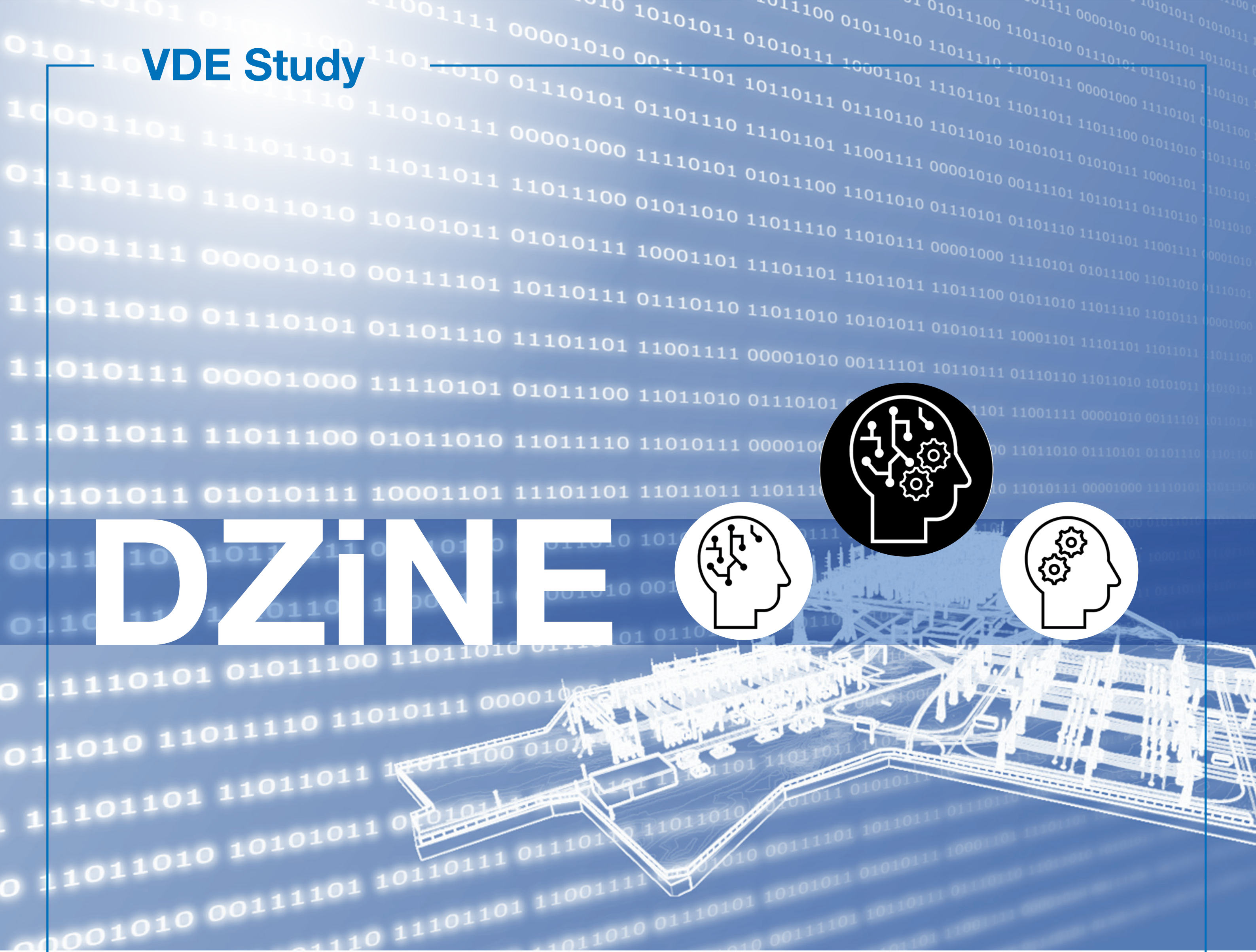

The Digital Twin in the Network and Electricity Industry

by VDE ETG

VDE

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Content

Management Summary

The network and electricity industry is facing gigantic challenges. A look at the planned investment projects of the grid operators reveals the massive efforts in network reconstruction and expansion to implement the energy transition and thus decarbonization. The ambitious goals of the federal government (6 million heat pumps and 15 million electric cars by 2030) clearly demonstrate how green electricity, especially (according to the Easter Package [1]), with an annual addition of 22 GW of photovoltaic and 10 GW of wind power expansion by 2030, replaces conventional energy sources in sectors such as households, industry, commerce, and transportation, driving further investments in the grids. These increasing investments encounter processes and structures that have grown in isolated silos over decades. Often, there was a lack of awareness that the introduction of digital technology and software, without sufficient coordination by management, leads to redundancies in data models. In overall operations, hidden productivity losses and difficult-to-manage projects are the result. Due to the numerous uncontrolled redundancies of these silos with their own data models, data is continuously manually validated and processed in many manual steps. Thus, there is neither trust in the data nor the ability to accelerate or automate processes to relieve skilled workers or achieve higher efficiency per worker. This is precisely what is necessary because the increased workload coincides with an already severe shortage of skilled professionals at all levels of the process chains. Moreover, it is foreseeable that this will be further exacerbated by the increasing retirement of many experts, competition from modern and digital industries, as well as ever-shortening employment relationships.

Within these framework conditions, our power grid must be completely rebuilt. From the Task Force's perspective, network reconstruction and expansion cannot be achieved solely through more funding and the opportunities arising from the third industrial revolution (introduction of digital technology). The increased and more flexible new requirements for the grids specifically require intelligent and interconnected solutions to uncover and safely utilize the existing reserves in the power grid. Working according to the methods of Industry 4.0 (I4.0), with solutions such as the Digital Twin in the network and electricity industry (DZiNE) presented here, addresses precisely this point. This interconnected simulation model, based on I4.0 methodology, forms the data foundation for continuous, data-driven processes from planning through operation to decommissioning. The implementation of weather-dependent overhead line operation (WAFB) is already a step in this direction, using interconnected simulation models to dynamically utilize the built-in reserves of the power grid. The classical planning methods of the past often included worst-case scenarios, which is why the resulting reserves can now be utilized through the introduction of DZiNE. The promised curative network management further builds on this approach. By means of DZiNE, controlled overloading of power circuits can be enabled through precise bottleneck analysis. Thus, while it cannot replace stalled network reconstruction and expansion, it can be reduced through intelligent and digital solutions.

The foundation of such intelligent and digital solutions lies in data models consisting of valid and interconnected data that can be evaluated by algorithms - so-called Digital Twins. As one of the core results of this task force, a definition of DZiNE is presented, which differentiates it from conventional digital data models based on a series of characteristics. The digital twin...

- is a virtual representation of an existing or to-be-created real object.
- has attributes and a functional description.
- covers at least two domains of the real object.
- reflects the real object with continuous control and high fidelity.
- is closely coupled to the real object via communication infrastructure (up to real-time synchronization).
- accompanies the real object throughout its life cycles.

In addition, interconnected digital twins consist of a (hierarchical) linkage of multiple digital twins and connect their components through communication connections.

When introducing digital twins, data inventory according to I4.0 is essential and can lead to short-term productivity improvements. As I4.0 methods have proven themselves in the industry for years, there are already models, data standards, and software that can be built upon. The task force has taken on the task of making the digital twin tangible in the network and electricity industry to provide impetus for implementation. The goal of this technical report is to summarize and translate the concepts of I4.0, including the introduction of digital twins, for the network and electricity industry and to build competence. By showcasing practical use cases and providing recommendations, it aims to enable the development of digital strategies that bring direct benefits.

The intensive interdisciplinary collaboration within the task force has elaborated, based on practical use cases, how value is created within the life cycle (planning, commissioning, operation) of systems. These values were then qualitatively assessed in terms of costs, quality, duration, risk, and challenges. In general, the added values resulting from the introduction of DZiNE can be summarized as follows:

1. Reduction of uncontrolled redundancies.
2. Expansion of the data basis.
3. Timeliness of the data basis.
4. Reduction of data or information gaps.
5. Easier and faster development of simulation models.
6. Cross-life-cycle data basis, simplified data governance, and more effective controlling.
7. Reduction of project duration, testing efforts, and costs through validated requirements.
8. Seamless system integration through simulations with DZiNE, even with software patches.
9. Reduction of errors through validated and consolidated data.
10. Minimization of data maintenance efforts through interconnected DZiNE.

Furthermore, the task force has formulated recommendations for action. Within the organization, this includes, for example, creating a migration path and initially starting with a limited use case while enabling employees through suitable training measures. Through the cross-functional collaboration of experts (modeling, standards, IT, etc.), further collected use cases can be prioritized and implemented. Digital system interfaces should be standardized and enable vendor-independent, modular system architectures that meet the needs of the use cases and align with the principles of the IEC 61850 and IEC 61970 standard families in terms of compatibility. Since there are currently no specific standardization initiatives beyond this scope in the IEC regarding Digital Twins, it is necessary to develop a standardization roadmap. In addition, recommendations for action were also addressed to policymakers and regulators. With advanced risk management through DZiNE, methods such as curative network operation can be introduced, allowing the network to be utilized beyond the (n-1) criterion. However, the corresponding framework conditions need to be adjusted.

The discussions within the task force clearly demonstrate one thing: In order to reap the benefits of digitalization, management must make the introduction of DZiNE an organizational goal and coordinate it due to its cross-functional integration. Only in this way can uncontrolled redundancies be resolved and the methods of Industry 4.0 be introduced.

1 Motivation

The term “Digitaler Zwilling” (Digital Twin) has been on everyone’s lips for some time now. From the perspective of the VDE ETG Task Force “Digitaler Zwilling in der Netz- und Elektrizitätswirtschaft” (Digital Twin in the Network and Electricity Industry), the significance of Digital Twins goes far beyond what the term is often used for today. However, what is crucial is the implementation of the concept in practice, which is still often inadequate. In particular, the energy industry is still in its early stages in this regard. The Task Force, as the creator of this working paper, aims to contribute to the energy industry recognizing the opportunities that arise from the use of Digital Twins in the network and electricity sector (hereinafter abbreviated as DZiNE, based on the German translation “Digitale Zwillinge in der Netz- und Elektrizitätswirtschaft”) and consistently leveraging them in the future.

1.1 Framework / Initial Situation

Connecting the real world with the virtual world efficiently is not only essential in the industry but also in the network and electricity sector, which is undergoing a massive structural transformation worldwide. This transformation is driven by the energy transition and the desire for decarbonization. Decarbonization leads to a shift in energy consumption from other sectors, such as industrial processes, heating, and transportation, to the electricity sector (cf. [2, 3]). Fossil resources are being replaced, for example, by green hydrogen or electric propulsion. Consequently, significantly more electric energy will be required in the future than today.

This results in diverse challenges. Notable among them are the increasing cost and expansion pressure in the network sector, the decentralization of the energy system based on renewable energies, and the ever-growing demands for reporting. One significant obstacle is the slow implementation of grid expansion, partly due to a shortage of skilled workers, bureaucratic hurdles, and more complex technical and regulatory requirements. Ultimately, these future challenges can only be overcome with new approaches and technologies. Therefore, the necessary digital transformation calls for the evolution of existing business models, process adaptation, and the introduction and utilization of new technologies. Current trends are giving rise to a new generation of energy supply companies and the development of digital ecosystems. This digital model will depict the real world with its objects, processes, and systems and constantly interact with it. Thus, Digital Twins play a central role in building these ecosystems and can be seen as enablers for these new ecosystems.

For decentralized and sustainable energy systems, the digitization of the network and electricity sector forms the foundation. The Digital Twin embodies the overarching trend of IT/OT convergence. This refers to the integration of data-centric information technology (IT) systems with operational technology (OT) systems, such as process monitoring [4]. The concept of the Digital Twin combines several mature technologies, although there is no standardized definition. The excessive use of the term as a buzzword poses the risk of potential users becoming skeptical about its benefits. As a result, the potential advantages enabled by the concept may not be fully realized.

The shortage of skilled workers also means that in the future, plant and system operations must be more efficient and, where possible, (partially) automated to maintain supply security. Employees need to be empowered through further training to efficiently and effectively utilize data and new technologies. This will enable the full potential to be harnessed and these new systems to be implemented and made usable for the company.

It is therefore evident that companies in the network and electricity sector need to approach digital transformation holistically and gradually develop systems such as the Digital Twin in conjunction with processes and employees. This is also in line with the current efforts of ENTSO-E and E.DSO, who recently agreed on a joint impulse on the topic of the Digital Twin [5].

The goal of this Task Force is to make the concept of the Digital Twin more tangible by presenting a reference architecture for the network and electricity sector, as well as various use cases. This will concretize the understanding of the Digital Twin in the energy industry and drive its implementation. In contrast, there are currently non-existent or outdated analog plant documentation, manual processes, data silos and redundant databases, insufficient data of poor quality, and a multitude of systems and interfaces that are not harmonized with each other.

1.2 Trends and New Technologies

The increased use of Digital Twins is favored by newly available technologies such as connected systems and, at the same time, is almost “demanded” by trends that the energy industry must face. The transition to a decentralized energy system, for example, requires a completely different level of detailed planning and, in particular, the interaction of various assets and processes (charging stations, rooftop PV systems, wind turbines, etc.). Digital Twins can support coordination, planning, and operation throughout the entire lifecycle, such as during network upgrades.

The diagram presented in Figure 1 represents a brainstorming session conducted by the task force regarding technologies and trends that act as enablers or drivers for Digital Twins. These technologies and trends facilitate and promote increased utilization or expanded use cases of Digital Twins. The sketch does not claim to be exhaustive but aims to illustrate the range of technologies and trends that have an impact on Digital Twins. It seeks to demonstrate how general trends influence components used in the energy industry (e.g., protective devices), the system landscape, the electricity market, or several selected categories.

Here are a few selected technologies and trends that promote the increased use of Digital Twins in general and Digital Twins in the energy industry (DZiNE) in particular:

- Cloud technologies [6]:

The emergence of cloud technology is a significant enabler for the use of Digital Twins because cloud services provide fast access to large computing power. Complex Digital Twins require substantial computing capabilities. Additionally, cloud technologies enable remote access to Digital Twins, collaborative work, and the integration of various systems, with data from different sources being incorporated into Digital Twins.

- Artificial Intelligence / Machine Learning algorithms [7]:

Self-learning algorithms and artificial intelligence, when combined with Digital Twins, offer new possibilities for realistically modeling the operational states of components, plants, and systems. This allows for virtual preplanning of operational and maintenance processes [8]. This approach goes beyond simulating states and extends to proactive improvement of real-life operations and processes.

- Single Source of Truth as a consistent and trusted data foundation [9]:

As the volume of available data continues to grow, it becomes increasingly important to link data and ensure that different systems use the same data foundation. Currently, it is common for different software systems to operate independently without the ability to link and utilize each other’s data. This leads to inefficiencies and a lack of comparability in analyses. A Single Source of Truth (SSoT) ensures a universally valid data repository, which is a fundamental requirement for the application of Digital Twins.

- Product Life Cycle Management [10]:

While the idea of Product Life Cycle Management (PLM) is decades old, recent technological innovations and resulting opportunities have given it a significant boost. PLM involves considering a component or system throughout its entire life cycle, from ideation and product development to operational use and recycling. Digital Twins serve as an enabler for implementing PLM. Additionally, PLM plays a substantial role in sustainability considerations.

- Sustainability [11]:

The increasing alignment of business and society with sustainability criteria is a key driver for the increased use of Digital Twins in general and as DZiNE in particular. Digital Twins enable engineering of components, plants, and systems in the virtual realm long before procurement processes or material sourcing needs to be initiated. This minimizes design flaws that could lead to wastage of time and resources.

- Visualization of complex relationships / Decision support [12]:

The need to visualize complex relationships is another trend that promotes the use of Digital Twins. Visualization helps manage the growing complexity of systems and technologies and serves as decision support by providing a clearer understanding of intricate relationships.

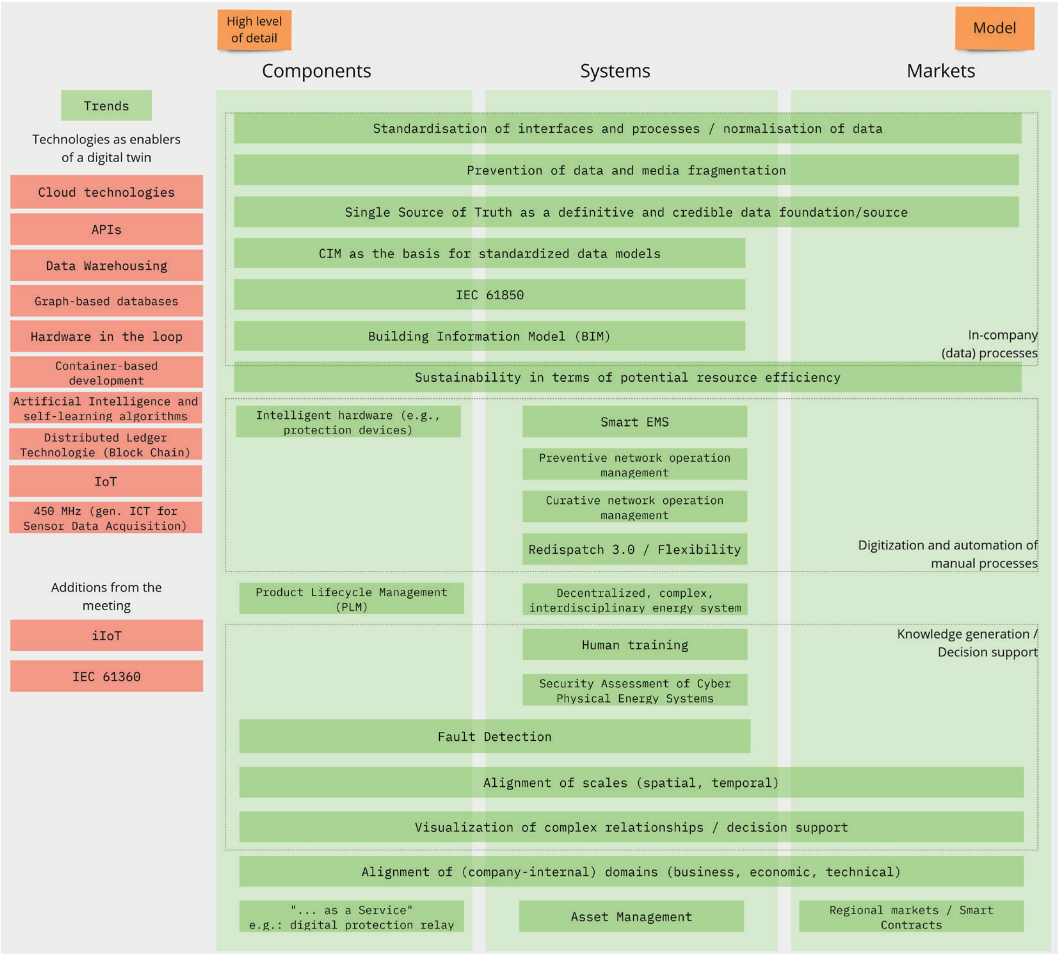

Figure 1: Hand sketch of the task force brainstorming on technologies and trends

DZiNE provide the transparency necessary to virtually design, test, operate, and optimize products, processes, and systems. The Internet of Things (IoT) technology can add a new dimension to monitoring and controlling the operational state of assets or processes. This is a complex topic and has a significant impact on both internal and external processes. The technical challenges are distributed across various areas, so a well-founded implementation strategy is necessary. This includes organic growth with customer benefits and consistent change management within energy companies.

1.3 Objective of the Task Force

In the face of the rapid transformation of the energy system, the energy industry is confronted with significant challenges. In addition to the immense shortage of skilled workers, the slow digitization of data and processes, as well as their lack of integration, pose obstacles to the future viability of today's network and electricity sector.

The goal of this task force is to raise awareness of the current challenges and foster a common understanding within the energy industry regarding the use of DZiNE. Through concrete use cases, the task force aims to demonstrate the added value of implementing DZiNE and contribute to overcoming these challenges.

2 Definition of the Digital Twin for the Electricity and Network Industry

The term "Digital Twins in the network and energy industry" (DZiNE) implies that a real object (device, system, process, etc.) is digitally represented. This creates a semantic proximity to "model" and "simulation." In the following section, the latter two concepts will be defined and distinguished from DZiNE.

2.1 Conceptual Classification (From Simulation to Digital Twin)

Modeling and simulation are used to investigate the behavior of a real object without conducting the experiments directly on it. For this purpose, the object is considered within an "experimental framework" that defines the specific properties and relationships relevant to the planned investigation [13, 14]. These properties and relationships are described in a model, which is a virtual representation of the real object [13, 15].

A model has several characteristics that distinguish it from a DZiNE: The experimental framework focuses only on the properties and relationships of a real object that are relevant to a specific research question. Therefore, the resulting model only approximates the real object [13, 15]. Additionally, different experimental frameworks can lead to different models of the same real object [14]. An example is an electrical or thermo-mechanical model of a power transformer. Furthermore, there are no specific requirements for the descriptive formalism of a model - even a thought experiment is a valid model [16]. In contrast, DZiNE imposes specific requirements on the technical feasibility of implementation.

The term "simulation" is not as precisely defined. We understand it as a means of conducting investigations using a model as a representative, without influencing the real object [13]. Simulations take place in a virtual reality, decoupled from the actual object. While the model describes the response of the real object to input variables or events (such as measurements, switching actions, short circuits, etc.), simulation is the process of stimulating the model with these (virtual) input variables [14]. The simulation answers the question of how the real object would behave under the same circumstances, assuming that the model and simulation are sufficiently verified, validated, and accredited for that situation.

While simulation deliberately establishes a decoupling between the actual and virtual reality (in terms of "what-if" analysis and post-fault analysis), it is the explicit goal of DZiNE to tightly connect the virtual representation to reality and the stimuli observed there. The connection between the virtual model and reality is established through the indispensable communication interfaces between the DZiNE and the real world.

2.2 State of Science and Technology

In the literature, there are several definitions of the Digital Twin, which are not always consistent, and their details often depend heavily on the specific industry in which the Digital Twin is used. For this reason, this section provides a brief overview of the available definitions and classifications.

In [17], a definition for the term Digital Twin was proposed by Michael Grieves. According to the proposed definition, a Digital Twin consists of three parts: the entity in the real world, the virtual model in the digital space, and the data and information interaction channels between the entity and the virtual model. The Digital Twin can serve as a bridge between reality and the digital space. Other scientific publications [18–23] support this definition and refer to the Digital Twin, in a broader sense, as a virtual or software-based representation of a real object that is connected to the real object through interfaces. In the aforementioned sources, the Digital Twin as a simulation model is only implicitly mentioned. However, Digital Twins are more than just data. They include algorithms that accurately describe their real-world counterparts. Often, these simulation models simulate functional or physical properties of the Digital Twin. When these simulation models are executed with real data, the Digital Twin ideally behaves just like its real counterpart [24].

In the electricity and network industry, the term is gradually gaining more attention, and the development of such concepts or systems is gaining momentum. So far, these scientific efforts have been documented only in a limited number of publications. [25] provides a compilation of publications that investigate DZiNE in the context of use cases in the power and electricity industry. Use cases include power generation and distribution, renewable energy, nuclear energy, electric vehicles, energy storage, and energy project planning. For example, in [26], a DZiNE was used to operate an energy generation plant flexibly. Another example is described in [27], where a DZiNE was used for proactive maintenance of wind turbines. A list of additional use cases and related publications can be found in [22].

At the current time, a specific definition of DZiNE cannot be found in the literature. Therefore, within the scope of the present task force, a definition has been developed, which will be presented in the following section.

2.3 Definition of the Digital Twin in the Electricity and Network Industry

> The DZiNE is a virtual representation of an existing or to-be-created real object, consisting of an identifying component, a description of its attributes, and its functional properties. It is linked to its real object and accompanies it from the initial idea to recycling (lifecycle capability). This coupling with the real object should be performed autonomously through digital communication infrastructure, although manual indirect coupling is also possible (Figure 2) [23].

The ideal DZiNE includes comprehensive data capture (e.g., 3D data, delivery times, prices, etc.), but in practice, simplified views can be used on the path to the ideal twin due to a lack of detailed data sources.

Compared to traditional models, DZiNEs represent a linkage of multiple digital models from typically at least two different domains [28]. For example, objects from the secondary technology of a switchgear communicate with objects from the primary technology through management shells to initiate a switch simulation in the primary technology model. A DZiNE can represent a combination of multiple DZiNEs. This means that DZiNEs can be integrated into other DZiNEs of different domains or can communicate with other DZiNEs of different objects. DZiNEs can be products from multiple manufacturers that must have compatible interfaces. Thus, the DZiNE offers a 360-degree view of the real object it represents, including all details collected by the operating company about the object, such as financial, maintenance, and operational data. Furthermore, with the help of simple or advanced data analysis, a DZiNE can gain insights from the available data.

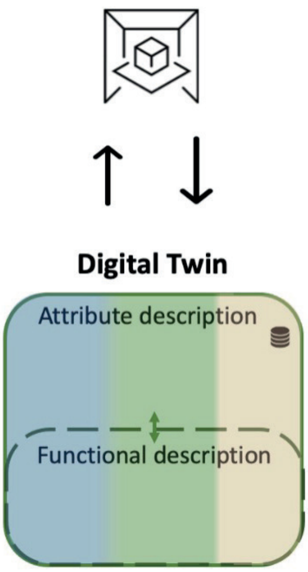

Figure 2: DZiNE connecting multiple domains (color-coded)

The DZiNE of an object or system essentially consists of two parts: an attribute description and a functional description, with the attribute description composed of a model description and specific attribute values. Access to the attributes, as well as the processing of the attributes, for example, within analysis and evaluation functions, is enabled through the functional description.

Model Description
The model on which the DZiNE is based should simulate the behavior of the real object with sufficient accuracy and plausibility, corresponding to the use case. The essential property of the DZiNE is to provide a description of object states that can be updated or adapted throughout the object's lifecycle. In general, a model for a DZiNE should possess the following properties [29]:

- Timeliness: The parameters within the model can be updated based on new information (e.g., from measurement data) and it is meaningful to do so.

- Mapping accuracy: The model must be sufficiently accurate for the updated parameter values to be of interest and usable for the respective application.

- Response time (within the functional description): Decisions can be made within the required timeframe for the use case.

Attribute Values
A fundamental component of the DZiNE is the description through attribute values, which are maintained as a Single Source of Truth (SSoT) or obtained from other DZiNEs. The data is object-oriented, continuously updated, and archived. They form the basis for describing various functions in particular. For this purpose, a unique identification of all used objects throughout their lifecycle with machine-readable, globally valid identifiers (UUID, Universally Unique Identifier) is necessary. It must be ensured that the values are sufficiently valid, structured, and machine-readable. By using the time dimension, synchronization of current or historical attribute values to a specific temporal state (snapshot) can be achieved.

Functional Description
Within the functional description, the data and models from the attribute description can be further processed to map downstream functions related to current or historical states of the real object. This can include analysis, monitoring, optimization, or control functions, for example. It is crucial that any functions solely rely on information from the attribute description of their own or other DZiNEs, thus implementing the concept of SSoT.

Snapshot Twin
For simulation purposes, a snapshot twin can be extracted, which freezes information from a specific point in time to perform analyses such as for planning purposes, "what-if" analyses, real-time simulations, virtual reality, training systems, etc. Following the paradigm of keeping all information about the real object within the DZiNE, the snapshot twin and its simulation results are also stored in the DZiNE's database.

The interaction between the real object and the DZiNE throughout the different lifecycle phases, as well as the model extraction of the snapshot twin, is illustrated in Figure 3.

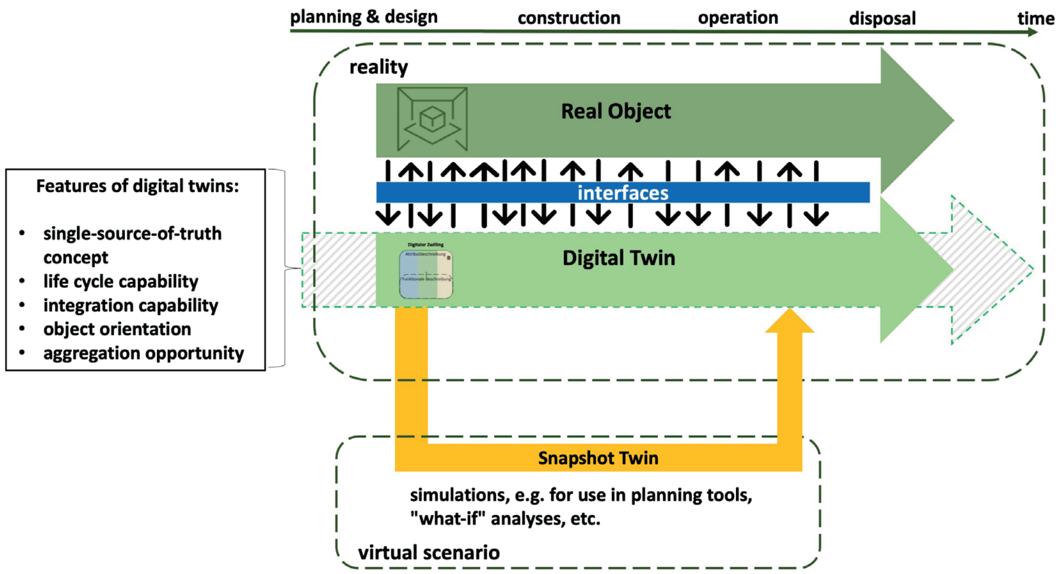

Figure 3: Interplay between real object and DZiNE across different lifecycle phases

In Figure 4, the various terms presented in this chapter are summarized. An example of the interaction between multiple DZiNEs follows.

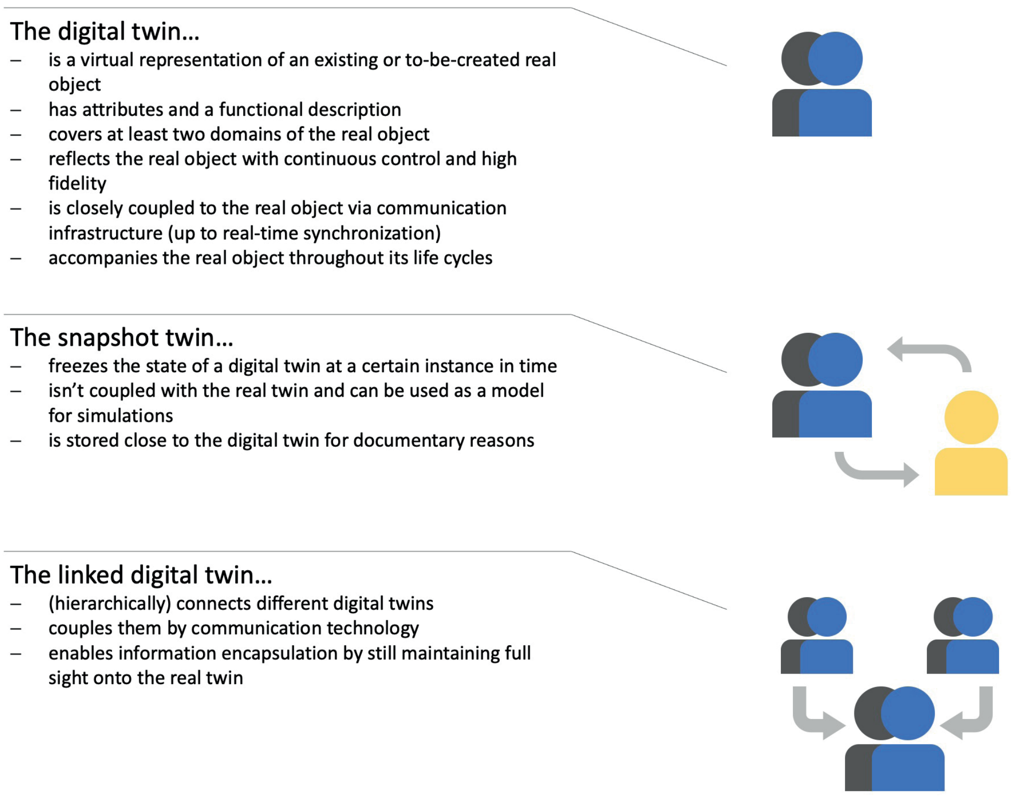

Figure 4: Overview of DZiNE definition

Example:
To illustrate the interaction between multiple DZiNEs, Figure 5 depicts a coordination process between network planning, a switchgear, and a protective device.

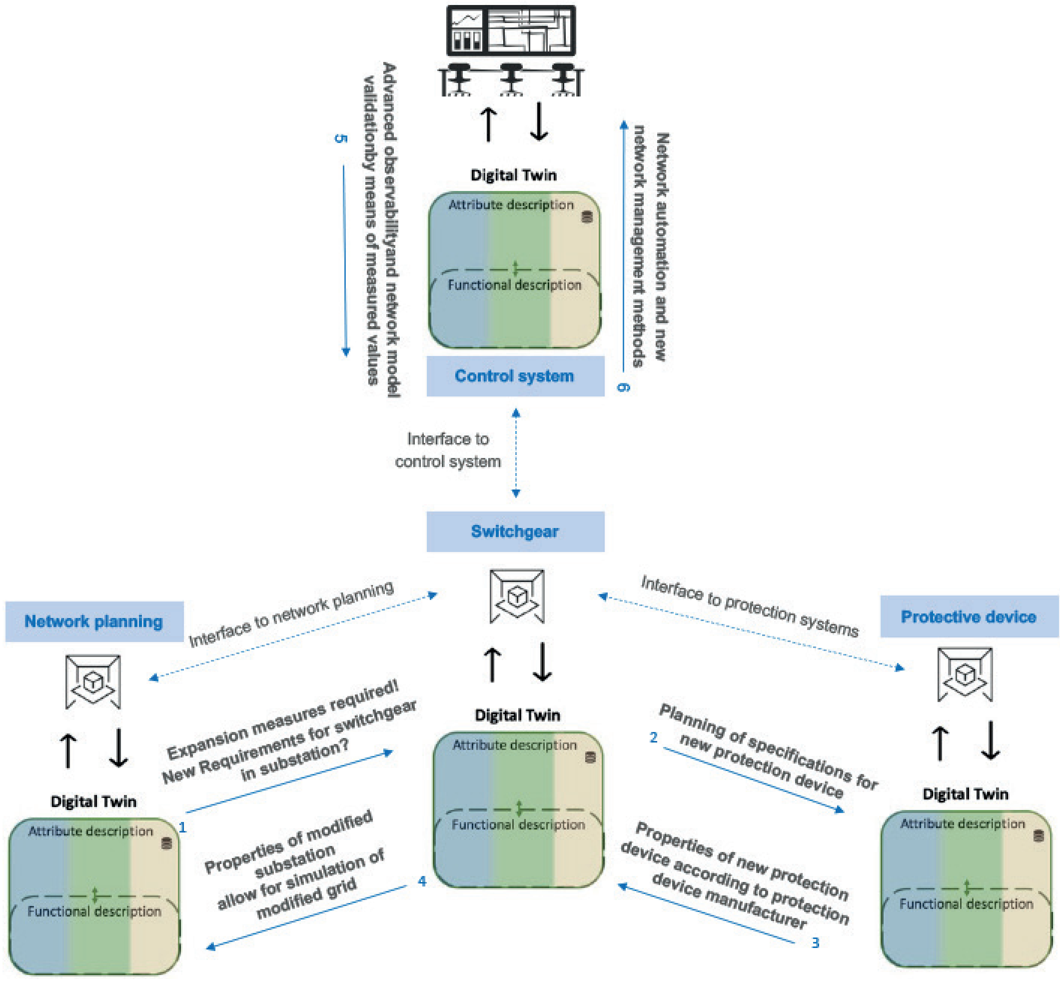

Figure 5: Example of interaction between multiple DZiNEs

In network planning, a network reinforcement needs to be carried out due to a new wind farm. In this context, the protection concept in a switchgear must be revised. The new requirements from network planning are transferred to the DZiNE of the switchgear (Step 1). This identifies the need for a new protective device, and a new protective device is designed in the DZiNE of the switchgear based on the switchgear's requirements (Step 2). The DZiNE of the protective device forwards the requirements to protective device manufacturers, who then create offers and communicate the associated properties of the protective device to the DZiNE of the protective device. These properties are passed on to the DZiNE of the switchgear (Step 3) to evaluate the entire protection concept of the switchgear. The properties of the modified switchgear are transferred to the DZiNE of network planning (Step 4), where the new protection concept is evaluated from the perspective of the entire network. Based on the evaluation results, further iterations with protective device manufacturers can take place until all requirements are met and a protective device is ordered. The subsequent implementation process involves similar interactions between the DZiNEs. For the transition of the project to regular operation (next lifecycle phase), additional interactions between DZiNEs are required, such as integration into the control system. Enhanced observability and network model validation (Step 5) can be achieved for network operation. This is done by comparing measured values to the model response in the simulation. The DZiNE of the entire network or overall system can be used for developing new network control methods and can be applied in further stages of high automation of network operation or system control (Step 6).

3 Architecture of the Digital Twin for the Energy and Electricity Industry

To implement the properties presented in the definition of the Digital Twin in the energy and electricity industry (DZiNE), an appropriate architectural model is required. In the following section, existing reference architecture models are discussed regarding their suitability for modeling DZiNE. Well-known representatives are the Smart Grid Architecture Model (SGAM) and the Reference Architecture Model Industry 4.0 (RAMI 4.0).

3.1 Classification of Existing Architecture Models

The SGAM framework is a technology-neutral architectural approach for representing interoperability aspects for current and future implementations of the smart grid. It includes a three-dimensional model that combines the dimensions of five interoperability levels (business, function, information, communication, and asset component). The hierarchical representation in the form of levels covers the entire chain from energy generation to end customers, with levels separated into process, field, station, operation, company, and market [30].

In the field of Industry 4.0, RAMI 4.0 represents the essential aspects in a three-dimensional structure. This structure encompasses the hierarchy levels of IEC 62264, with the classification of functionalities in the application context, as well as the dimension of the lifecycle of plants and products according to IEC 62890. RAMI 4.0 also allows for the representation of the initial planning phase as the first life phase.

For the consideration of DZiNE, the layer model of RAMI 4.0 consisting of six layers is relevant. It is revisited for the modeling of DZiNE in Chapter 3.2, as it has many overlaps with the reference architecture model for the electricity and network industry presented there.

Distinct from the aforementioned architecture models is the Building Information Modeling (BIM), as it represents more of a procedural model. BIM is widely used for power plants, switchgear, etc., during the planning phase (first life phase), thus allowing for the representation of the planning phase of the building components of DZiNE. Information exchange can be done, for example, through the open Industry Foundation Classes (IFC) standard. This standard provides a standardized, manufacturer-neutral digital description of buildings and is usable through a wide range of interfaces for various use cases. However, it is only defined for objects with a voltage of up to 1 kV. Necessary developments are referred to in Chapter 5. The data model authority lies with the owner, enabling consistent modeling. The challenge lies in generating multi-layered models from these modeling approaches to ensure cross-domain data availability and consistency.

3.2 Basic Elements and Structure of a Digital Twin

Figure 6 shows the basic structure of a DZiNE with the direct mapping from the Reference Architecture Model Industry 4.0. This demonstrates the immediate derivation of the structure and paves the way for a detailed representation thereof. The information and function levels from RAMI 4.0 are harmonized in the information architecture of the DZiNE levels to achieve seamless integration. This concept is illustrated in the generic architecture of a DZiNE in Figure 7.

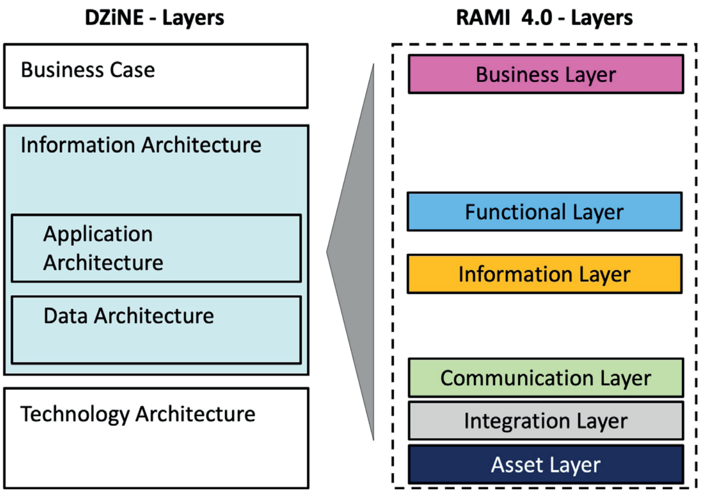

Figure 6: Basic structure of a DZiNE based on RAMI 4.0

The generic architecture of DZiNE in Figure 7 is structured in layers. The advantage of this representation is that it allows for a fundamental understanding of the function of each layer/element and the defined interfaces between the layers. The business model forms the top layer (business level) and indirectly influences the applications of the application layer. The applications and functions directly build upon the data model and can be flexibly configured through a model view.

The information layer contains all data and information, as well as functions for information provision, data validation, and data synchronization (e.g., calculating thermal mapping). This information model should exist as a Single Source of Truth (SSoT) to ensure an up-to-date, consistent, and validated database. The data stream management (middleware) corresponds to the administration shell in RAMI 4.0 and relates the information to each other. The administration shell serves as the interface for all available information about the asset and the DZiNE. Depending on the application, it can be multidirectionally organized.

The information and communication layer couples the process or physical object/system to the information layer, which is organized as an SSoT, through secure communication channels via the integration layer and the communication layer (see Figure 7). Data aggregation already takes place in the integration layer, where the data from condition monitoring sensors and controllable actuators (measurement, control, and reference variables) from the real system are passed to the communication layer. The asset, i.e., the operating equipment, is condition-monitored and controlled through sensors and actuators.

In the context of Industry 4.0, the term "administration shell" has also been established as a digital representation of devices or components. The administration shell includes the standardized description of asset properties regarding communication, information, and models related to the corresponding functions. The partial models contained within the administration shell enable the representation of the asset throughout its entire lifecycle. Each asset requires at least one administration shell to be integrated into the DZiNE [31]. It serves as the interface to ICT and communication with the physical object (see Figure 7).

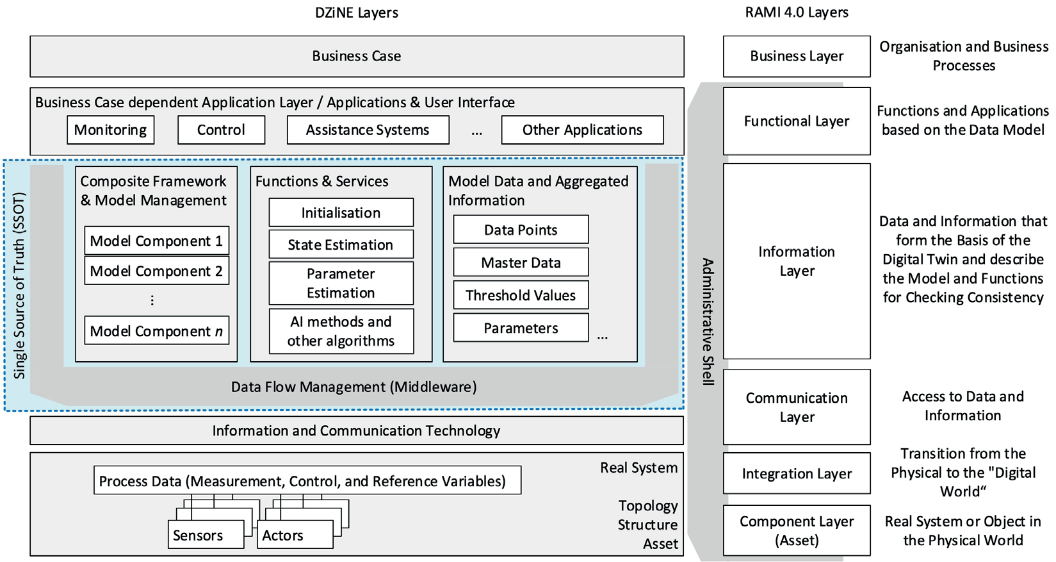

Figure 7: Illustration of the basic structure of a DZiNE in the energy supply sector (own figure)

As shown in Figure 7, the Information Layer must be divided and expanded according to RAMI 4.0 in order to enable the necessary granularity of a digital twin (DZiNE). The Functional Layer of the DZiNE derives new information from the information model, which consists of the model components and the model management, functions & services, and makes it available again to the information model. The information layer of RAMI 4.0 is completed and is not contradictory to the DZiNE concept. The information model, along with the corresponding databases and interfaces, is supplemented by algorithms that extend the information from process data and keep the model information up to date. The composite model also allows for flexible representation (model view) according to the application. Similar to the administration shell in RAMI 4.0, a suitable middleware establishes the relationship between the components of the information model. It also manages the data streams within the DZiNE, which include input and output (sensors/actuators) as well as changes in the topological connection or mapped phases of the lifecycle. Standardized communication protocols for electrical power supply (e.g., IEC 61850, IEC 60870-5-104, IEEE C37.118) can be used for managing the data streams (Chapter 3.3.1). To ensure the temporal consistency of the data models, meta-attributes such as validity and timestamps of the information must be maintained. Reproducibility is possible through methods such as snapshots and caching.

Attributes are obtained in the Digital Twin either directly or through controlled caches via interface objects from the responsible source (Single Source of Truth - SSoT). These interface objects contain attribute objects that, in addition to values and IDs, also contain meta attributes such as validity. In bilateral and multilateral interface definitions, objects are described using hierarchies (inheritance tree) of classes and references among the classes. An object instance is then formed from these descriptions and is responsible for the value transfer. Object identification should be done using a vector of UUIDs (Universally Unique Identifiers) for type, instance, and revision. To avoid redundancy, the defined technical attributes must be independent of each other. To implement this, it is recommended to involve relevant experts and rely on existing well-defined definitions (e.g., ECLASS, CIM, IFC) when developing interfaces.

An ideal DZiNE behaves like the real technical system it represents. This means that the resulting output data of the DZiNE should correspond to the measured variables of the physical system, or the functions of the DZiNE should ensure an approximation to these measured variables (e.g., a function

for parameter adaptation). The measured variables of the physical system can, for example, be the target variables for parameter optimization in the DZiNE. Additionally, information from measurements not captured in reality (virtual measurements) can be generated through corresponding virtual sensors or their measurement channels. Depending on the application scenario, various model depths (e.g., power flow or time domain models) can be represented. To increase the accuracy of the representation, a function for plausibility checking of the DZiNE is necessary. This function can address syntactic, semantic, or parametric errors and provide feedback to the DZiNE developer.

If the model and the process coupling are correctly implemented, the DZiNE can provide information that is not observable through measurement techniques (e.g., state estimation, Kalman filter, Fourier transformation, wavelet transformation, machine learning, etc.). At the same time, the DZiNE enables or improves the practical use of these methods. Together, the creation of a self-learning system with the highest quality of modeling is achievable with the help of DZiNE. In this context, the DZiNE can assist in fulfilling the specific requirements for observed states during the learning phase (e.g., creating a suitable database foundation).

In general, DZiNE is also necessary in the context of electricity and network economics. Non-technical models can also be represented in the form of DZiNE, such as a sociological model that can be used to make generic statements about behavior to optimize customer acquisition or other market-oriented processes. Although these models also fall within the scope of electricity and network economics, they are clearly distinct from technically oriented processes and are not part of this document.

3.3 Requirements for creating Digital Twins in the network and electricity industry

3.3.1 Information exchange for energy system management

Interoperability standards for information exchange within, from, and with energy systems already exist and are clearly presented in IEC TR 62357-1 [32]. These standards should be maintained as a basis for structuring DZiNE and expanded as needed. This includes communication interfaces, information security, and data model specifications for the automation of power supply systems, market communication, as well as information exchange between the power grid and home, building, and industrial automation. IEC TR 62357-1:2016 includes IEC 61970 [33], i.e., the Common Information Model (CIM), as well as its extension with IEC 61968 [34] to represent distribution networks or IEC 62325 [35] for energy markets. Furthermore, the IEC 61850 [36] standard series is included for energy supply.

3.3.2 Cybersecurity requirements

Due to the extensive use of advanced technologies and applications involving central and decentralized controls, sensors, physical devices, and various processes, the future intelligent power grid expands its functionality into a cyber-physical system. These technologies enable flexible energy and information flow. Modern energy systems heavily rely on ICT infrastructures for their real-time operation, particularly for control and protection functions. A disruption, failure, or cyber-attack on one or more intelligent assets can jeopardize the operation of the physical power grid.

DZiNE, which serve the representation and simulation of energy and data flows, enable the investigation of dependencies in the interaction within the cyber-physical system. Moreover, DZiNE is an important component in the representation of cyber-physical systems, i.e., the combination of IT/software components with mechanical and electronic components that communicate via a data infrastructure such as bus systems and the internet. Due to the use of various communication channels, cyber-physical systems need to be secured.

The requirements for algorithms, individual components, and systems and applications composed of these components are summarized in the BDEW white paper “Requirements for secure control and communication systems 2.0” [37], which are also relevant for DZiNE.

The basis for this is primarily provided by the IEC 62351 [38] series of standards, which define the supported cryptographic procedures. In addition, security requirements for maintenance processes, project organization, and development processes, anchored in the IEC 2700X series of standards for information and IT security, are also addressed. Therefore, a DZiNE enables an integrated multi-physical and probabilistic real-time simulation of a system for precise decision preparation of complex security algorithms, including the identification of vulnerabilities in the transmission path.

3.3.3 Communication structure

A communication infrastructure must be provided for the communication between the physical object and the DZiNE, enabling real-time data acquisition, transmission, and evaluation. For reliable data exchange, the infrastructure must provide sufficient bandwidth or suitable buffers to allow data to be exchanged by a large number of decentralized sensors with low latency. The required bandwidth depends on the desired use case, technical implementation, and protection mechanisms. It should also be noted that a large number of decentralized sensors can transmit data in parallel over a common communication channel. In principle, Virtual Private Networks (VPN) using the internet's communication infrastructure provide a suitable basis to meet the requirements. However, in the context of critical infrastructure, it is assumed that unencrypted communication over public routes without intelligent routing is critically evaluated for a variety of possible use cases in the electricity and network industry. Closed, encrypted communication networks with intelligent routing will therefore play a greater role in establishing DZiNE in the future. With increasing decentralization and parallel application of sensors, a wireless communication infrastructure, which can offer economic advantages over wired communication paths, should be considered in the future. In this regard, various technological implementation options and frequencies are possible.

3.3.4 Technological and standardization development needs

Existing gaps in technical standards need to be gradually closed to guarantee the necessary interoperability regarding the previously described multi-layered reference architecture and to realize usable DZiNE. A platform-independent, service-oriented software architecture based on an object-oriented and abstract data model facilitates a fast and flexible implementation of DZiNE. To leverage the value of DZiNE, i.e., correlating multiple data to extract new information, an appropriate IT infrastructure needs to be established.

The use of suitable communication protocols is a prerequisite for the compatibility of data interfaces and data models. DZiNE includes application-specific data types, i.e., model-based data and instance data, enabling the representation of asset information throughout its entire lifecycle.

The Asset Administration Shell from the context of RAMI 4.0 can be used as a template for a DZiNE.

The (real-time) processes of the electricity and network industry require an expansion of the Asset Administration Shell regarding the communication interface. Middleware approaches such as transaction managers or Data Streaming Platforms (DSP-Clusters) can be used for this purpose. These approaches promote data clustering, information aggregation as a Single Source of Truth (SSoT), and resilience regarding data availability, consistency, and plausibility.

The use of CIM/CGMES to describe asset models and their interconnections allows flexible modeling and model exchange. The CIM/CGMES model classes are continuously evolving to represent a wide range of conventional and novel asset types. For the implementation of a DZiNE, it is also necessary for it to communicate with established standards such as IFC, ECLASS, and CIM.

The model composed of model components (CIM/CGMES), ideally organized as an SSoT, must be gradually developed towards DZiNE. This involves expanding model classes and flexibility regarding model depth and category (e.g., thermal, electrical).

Traditional SCADA protocols are only partially suitable for realizing DZiNE. The IEC 60870-5 series of standards, such as the widely used IEC 60870-5-104 in Germany, provide an inadequate basis for modeling DZiNE due to the numerical addressing model. The lack of metadata prevents the protocol-level provision of model-related data, which is necessary for realizing DZiNE. In contrast, IEC 61850 already incorporates standardized metadata within an object-oriented structure that can be utilized for DZiNE. The explicit standardization of data points in IEC 61850-7-4 can serve as a basis for a DZiNE. Extensions are possible but should be standardized or at least cross-manufacturer profiled. The structure of IEC 61850 provides guidelines for model formation but is designed as a universal communication standard and thus needs to be harmonized with CIM/CGMES. To represent a multi-layer information model analogous to RAMI 4.0, it is necessary to describe logical nodes in a generic structure according to IEC 61850.

4 Practical Use Cases & Examples

This section describes use cases and examples from the field of network and electricity industry to illustrate the benefits and challenges of using DZiNE. A evaluation table is used with the following basic assumptions:

Evaluation Table for Digital Twin in the Network and Electricity Industry

In the following evaluations, we assume the hypothetical existence of an "ideal" DZiNE, which is formed by various interacting DZiNEs. Furthermore, we assume the existence of DZiNE for every physically or virtually (e.g., software) relevant component of the DZiNE.

In this model, each DZiNE offers services (functions and interfaces) to other DZiNEs. Each DZiNE can communicate with all other DZiNEs and can thus utilize data and services (algorithms) of other DZiNEs without redundancy (Single Source of Truth - SSoT). The internal logic of each DZiNE is encapsulated in a way that ensures reliable provision of the promised services and interfaces despite internal development.

In the evaluation table, we assess the expected benefits and challenges in the dimensions of cost (K), quality (Q), duration (D), and risk (R). The following three life cycle phases are considered:

- Planning & Design/Engineering
- Construction/Commissioning
- Operation

4.1 Network Planning

Network planning utilizes digital models of the systems being planned. At the same time, network planning involves coordination with various stakeholders. These circumstances make network planning an application area suitable for the introduction and use of DZiNE.

The technical complexity, ownership structures, and regulatory requirements necessitate that the digital models used in network planning, which represent the underlying system, are accessed by a multitude of users. When these models are interconnected through a DZiNE, one of the central characteristics of the model becomes that of a universally valid data repository (SSoT). This SSoT ensures that all users work with identical data, allowing for mutual traceability and reliability of results, assuming validated simulation tools are used. By designing the model underlying the network planning task as a DZiNE, it can be utilized for multiple consecutive or parallel planning tasks. This guarantees the consistency of network planning decisions while avoiding the significant effort involved in preparing digital models for individual planning tasks. The integrity of the DZiNE enables simplified usability for service providers through the definition of interfaces and standardized result formats, thus enhancing the comprehensibility of the results for third parties.

The work steps of network planning can be classified into life cycle phases for evaluating a DZiNE as follows: The "Planning & Design/Engineering" phase can be interpreted in the context as the internal network planning of the network operator. The "Construction/Commissioning" phase can be seen as the exchange of internally prepared network expansion plans with the regulator. The "Operation" phase is understood as the application of DZiNE in the preparation and support of the physical implementation of network expansion.

Phase	Value Added/Challenges
Planning & Design/Engineering ➔ Internal Network Planning	**K:** In the medium term, a DZiNE brings cost reduction through its comprehensive modeling and highly qualitative database, as the model can be continuously reused. The introduction of DZiNE leads to harmonization of models, standardization of data formats, and improvement in the quality of underlying master data, resulting in a sustainable concept. However, the initialization phase requires high initial effort, as building the necessary data foundation for a comprehensive and up-to-date network model involves significant personnel and systemic resources, especially due to the involvement of multiple stakeholders. Considering the existing hidden costs associated with data research and validation, a return on investment can be expected in the short term through the initial data collection. **Q:** The quality of network planning improves over time based on the necessary harmonization and standardization. It leads to increased planning reliability through a unified and consistent data foundation of essential asset data. Moreover, the planning accuracy is enhanced by the ability to perform more extensive analyses of planning-relevant parameters and incorporate operational factors through interconnected DZiNE. Challenges to quality arise particularly in the areas of data accuracy, result quality, and data availability. The quality of internal network planning is significantly influenced by the quality of the available master and basic data in the DZiNE. Incomplete or inaccurately provided data can have a negative impact on the quality of planning results. At the same time, ensuring the provision of complete data sets can be challenging, requiring the generation of sufficiently accurate and valid substitute data. **D:** Defined interfaces and a solid data foundation can reduce the duration of network planning, especially by minimizing the number of coordination iterations among stakeholders and streamlining the validation process. However, the challenge lies in designing the DZiNE in a way that does not restrict the usability of simulation tools and avoids increased computation time due to greater model complexity. **R:** -
Construction/Commissioning ➔ Exchange with the regulator	**K**: Once the initial hurdle of establishing a common definition of standardized interfaces, as well as standardized interfaces for visualization if necessary, is overcome, costs can be greatly reduced in the exchange with the regulator. At the same time, there is a risk that the regulator's demands may necessitate a necessary change in the definition of the models, resulting in additional efforts. **Q:** Improvement through defined interfaces and integrity **D:** A DZiNE offers the opportunity to make the exchange with the regulator more efficient through defined interfaces and unified data pathways, thereby accelerating the approval processes and the expansion of real networks in a long-term manner. **R:** -
Operation ➔ Implementation of construction	**K:** By continuously utilizing a stable database in internal network planning, exchanging information with network operations, and implementing construction, costs can also be reduced through utilization by third parties. **Q:** This results in a potential increase in quality through the use of a unified data set/model in construction (e.g., BIM; see Chapter 3.1). Additionally, the network model can be enriched with real-world data, thereby sustainably improving it. This is especially possible when the idea of improving the model is incorporated early in the construction process. **D:** Reduction through defined interfaces. **R:** The complexity of the model is increased by additional requirements from a construction perspective. The identification of uniform requirements and mapping the necessary data into a DZiNE (possibly a system or platform) represents a significant additional effort, which is generally compensated for after the introduction of DZiNE by avoiding uncontrolled redundancies. At the same time, a reduction in the risk of faulty construction implementation can be achieved since all relevant data is already available and can be considered in all phases of network planning in DZiNE.

Table 1: Benefits and challenges of a DZiNE from the perspective of network planning

4.2 Application of a Digital Twin for Network Operations

The integration of decentralized generation and load structures, as well as the opportunities associated with automation and digitalization for centralized monitoring and control, significantly influence network operations in the distribution network as well as the operational management models. Intelligent distribution grids offer the possibility to master the challenges of the energy transition and mitigate the costs of grid expansion. Noteworthy examples include the convergence of protection and control technology at the functional level and power flow calculation. In combination with consistent further development, this results in new automation solutions such as fault localization and (partial) restoration.

Efficient implementation of these developments relies on interoperability, utilization, and generation of information and data. This is where the concept of the Digital Twin in the Energy Sector (DZiNE) comes into play, as it integrates multiple technologies and offers a new quality of data modeling, transferring it into a consistent data basis (Single Source of Truth - SSoT).

An example of a “next generation” SCADA architecture with embedded DZiNE is shown in Figure 8. The relevant aspects of the physical energy system can be represented in this architecture through various models and levels of detail, which are assigned to respective areas such as network planning, network operations and provisioning, protection technology, and fault clearance. The utilization of existing information, synchronization, and consistent data management are crucial in data modeling. The modeling of the network configuration mainly incorporates continuously measured conditions such as load flow situation, switch status, and static master data. The OT/IT communication, using online remote control protocols, and the integration of “non-real-time data” from enhanced sensors such as MQTT or narrowband IoT shape the structural design of the software architecture for broad application of DZiNE. The focus will be on the curative network operations for explanation purposes.

The entire communication between protection and control technology based on IP also means more frequent functional and security patches. For the network control system, market-ready products already exist, but the comprehensive integration of protection and control devices is still under development. Potential errors can thus be identified and resolved before commissioning.

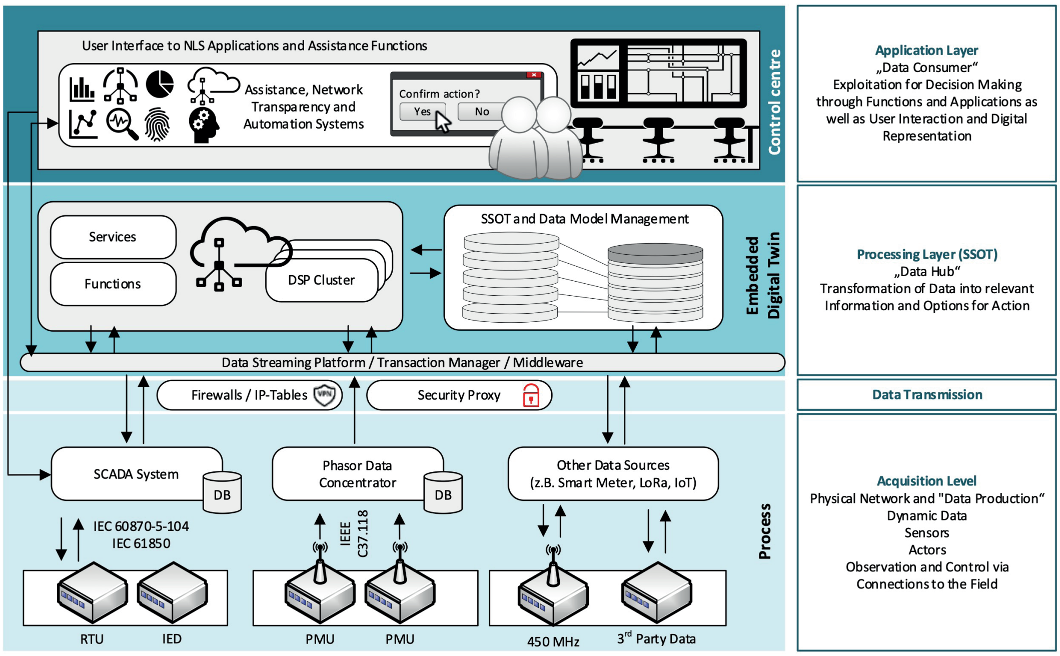

Figure 8: Next Generation SCADA architecture with embedded DZiNE (adapted from [39, 40])

Application Level

Curative network operations define operational measures that are automated after the occurrence of a network event. The system is brought back to a state without limit violations. In addition to operational switching actions, significant use cases include adjusting operating points for active power exchange with the distribution system operator (DSO) or determining setpoints for power management of customer installations based on the network condition. The strength of the DZiNE concept is particularly evident in its simulation capabilities. By functionally utilizing current and reliable data, precise determination of network and operational states is achieved. Furthermore, the training of network operators is supported with scenarios such as unknown network configurations, emergency operations, and equipment failures.

Processing Level

This includes data exchange, synchronization with source systems, as well as preprocessing and preparation of data for the respective DZiNE applications.

Phase	Value Added/Challenges
Planning & Design/Engineering	**K:** Reduced design/engineering costs. **Q:** Minimization of errors through redundancy reduction, integration of additional source data (e.g., weather), expanded testing capabilities, support for system evolution/migration towards an "evergreen" control system. **D:** Automation of processes. Coupling of different source data/systems is necessary. **R:** Reduced error risk in design. Migration of existing and new data models to establish a Single Source of Truth (SSoT) and creation of standardized interfaces between DZ (Digital Twin) and online systems.
Construction/Commissioning	**K:** Automation of processes in testing/inspection during SAT (Site Acceptance Test) and FAT (Factory Acceptance Test). Establishment of scalable and real-time capable DZ models and infrastructure. **Q:** Expanded testing capabilities through integration of protection and control devices. Training of employees and building trust in the system. **D:** Automation of processes in testing/inspection during SAT, FAT, support for system evolution/migration towards an "evergreen" control system. **R:** Data quality in planning, simulation, and project engineering.
Operation	**K:** Employee focus on complex tasks, possibility of (partial) automated network operation, efficiency improvement in patch management, enhanced update and maintainability. Continued maintenance and updates of the system. **Q:** Simulations of switching actions, forecast calculations, increased supply reliability, process efficiency improvement. **D:** Reduced response time in network operation, shortened fault clearance duration, optimized maintenance processes. **R:** Monitoring/surveillance can enhance personnel safety and prevent critical failures.

Table 2: Benefits and challenges of a DZiNE from the perspective of network operations

4.3 Digital Twin of a Switchgear

In the following subsection, the maintenance of a switchgear is considered as a use case, with the goal of optimizing maintenance downtime. This is done based on existing data of the various components installed. Of course, the digital twin of a switchgear can also be used for other use cases, such as engineering or the construction of the switchgear. However, since maintenance and servicing are of paramount importance for the safe operation of the power grid, we focus on the aforementioned use case as an example application.

In this example, the digital twin holds data and information of a switchgear that needs maintenance (e.g., components, circuit diagrams, 3D models, and related information, cable plans, etc.). These data include information about the hardware and software used. With the help of the digital twin of the switchgear, comprehensive planning and simulation of maintenance downtime becomes possible, ensuring that no information is missing or problems occur during the actual maintenance process. Information for maintenance downtime is also obtained through interfaces with other digital twins (e.g., protection devices, as discussed in section 4.4). Figure 9 depicts an exemplary 3D visualization of a switchgear based on the underlying data and information.

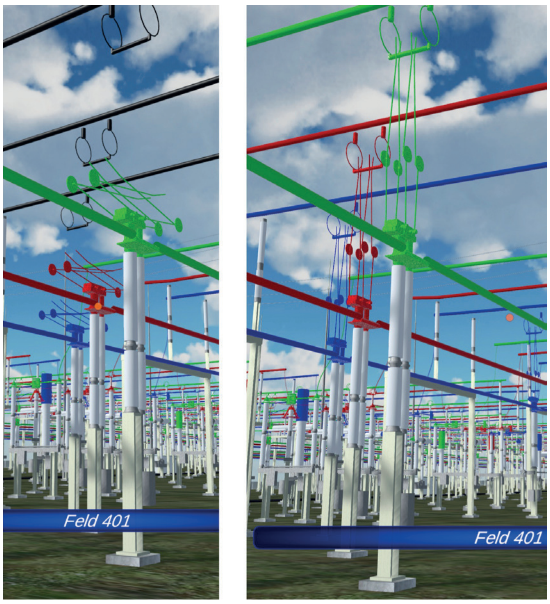

Figure 9: Switching simulation within a switchgear (Source: entegra eyrich + appel gmbh)

The following table examines the life cycle phases of the digital twin of a switchgear in terms of their impact on the use case “maintenance downtime” (time-based maintenance) and evaluates them according to the defined criteria. The construction/commissioning phase is not considered in this particular example.

To address the challenge of interfaces mentioned in the table below, data is required according to the requirements of the previous chapter. Already in the planning of the station (in the context of BIM), there is a potential data basis from the planning and construction phase. In order to ensure a low-loss reuse of data already collected at the phase transitions of a project, especially if they are already part of a cross-phase SSoT (Single Source of Truth), it is essential that the data model can also describe the corresponding operating equipment. Currently, in the IFC (Industry Foundation Classes) interface standardized for the construction industry (ISO 16739), operating equipment above 1 kV is not yet implemented normatively. Please refer to the recommendations of the standardization study in Chapter 5 for more information.

Phase	Value Added/Challenges
Planning & Design/Engineering (of the switchgear itself)	**K:** Initial additional effort/investment to collect and integrate the additional information required for the use case “maintenance downtime” into DZiNE (Single Source of Truth), which typically leads to subsequent return on investment. However, strong reduction or cost advantages through later reusability of such information and modern, software-supported processes. **Q:** Visualization of maintenance operations and optimized component arrangement to avoid downstream costs (e.g., plant failure planning). **D:** Simultaneous processing possible for all domains. **R:** Reduction of the risk of impossibility of maintenance work.
Operation (of the switchgear)	**K:** Optimized maintenance downtime reduces operating costs. **Q:** More reliable operation increases the quality of switchgear operation. **D:** Reduced maintenance downtime duration leads to longer operating periods. **R:** -
Preparation/Planning of maintenance downtime (outage)	**K:** Investment for automated interfaces/processes to implement all approaches (K/Q/D/R) in terms of personnel and cost. Optimized procurement management through automated exchange regarding availability (discontinuation) of spare parts. Created database for the use of robots/drones. **Q:** Availability of current plant information (overview of installed components including maintenance intervals, from manuals to virtual reality replication) ==> increased and targeted qualification of maintenance personnel. **D:** Reduced duration due to digital availability of current information. **R:** Risk management BEFORE maintenance downtime through feedback from DZiNE (comparison of sensor values, component condition, network condition).
Execution of maintenance downtime (outage)	**K:** Minimization of unplanned and avoidable costs. **Q:** Dynamic feedback from DZiNE, e.g., through augmented reality, and optimal preparation ==> high quality maintenance. **D:** Low deviation from planned duration, perspective of shorter duration through remote maintenance at DZiNE and active feedback from DZiNE (elimination/reduction of certain maintenance steps). **R:** Minimization of unplanned activities.
Post-processing	**K:** Investment for automated interfaces/processes to implement all approaches (K/Q/D/R) in terms of personnel and cost-effectiveness. Significant reduction in manual data collection and verification. **Q:** Currency of data due to SSoT, updated DZiNE is available for further use cases (asset management, feedback to manufacturer). **D:** greatly reduced with fully digital interfaces. **R:** No loss of information.

Table 3: Benefits and challenges of a DZiNE of a substation

4.4 Digital Twin of a Protection and Control Device

Modern digital network protection and control devices can be virtually replicated in a digital twin. Except for the physical analog data acquisition module for current and voltage conversion of the measurement point to be modelled, the firmware and configuration already exist in digital form (Figure 10). Such twins are typically used in product development by the manufacturer. There are also advantages for users in terms of device selection, training, and testing purposes.

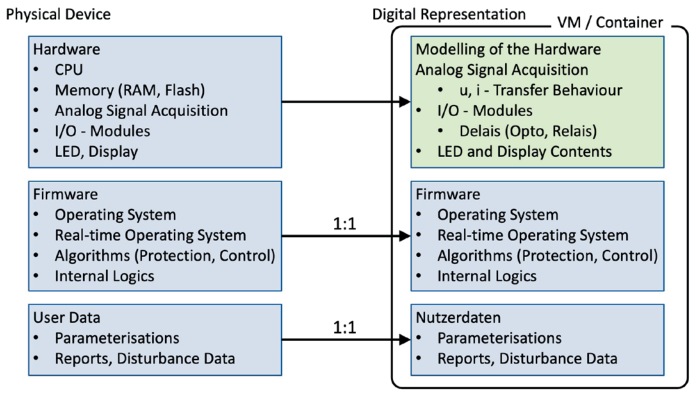

Figure 10: DZiNE of a protection and control device

Digitale Twins of network protection devices are particularly suitable for investigating and simulating critical network events (simulation of short circuits, ground faults, dynamic network effects). Especially in the context of collaborative work, a clear data foundation (SSoT) of the digital twins is essential, which is guaranteed by the use of DZiNE. Necessary interfaces (i.e., the administration shell) are available today through the IEC 61850 series of standards (GOOSE, Sampled Values) and also IEC 60255-24 (COMTRADE exchange format).

By coupling multiple digital twins of components from different manufacturers into a DZiNE of the protection system, complex network studies will be efficiently enabled on office PCs in the future (see Chapter 4.6).

Cross-dimensional and phase-crossing prerequisites:

- Complete modelling (e.g., sufficient consideration of remanence in current transformers)
- Complete data availability
- Trained employees
- Validity of data

Phase	Value Added
Planning & Design/Engineering	**K:** Reduced design costs or engineering costs (fewer prototypes required, fewer returns due to error minimization), resource conservation. **Q:** Error minimization, more extensive testing possibilities (not limited by hardware), use of standardized interfaces, consideration of operational experience (engineering loopback). **D:** Parallel work possible, time savings in automated tests through standardized interfaces. **R:** Error risk minimized through simulations (e.g., design errors), ensuring data security towards customers already in the planning stage (preventing readability of algorithms by customers in prototypes).
Installation/Commissioning	**K:** Reduced setup and commissioning costs through pre-simulation of the process, allowing optimization of setup and commissioning time, duplication of functionalities enables cost reduction through increased scalability, prerequisite is the use of standardized interfaces and processes. **Q:** Improvement of commissioning quality through simulation of deployment effects, prerequisite is the use of standardized interfaces and processes. **D:** Reduction of commissioning tests (SAT), replication of missing hardware through DT during factory acceptance tests (FAT) of station control technology in particular, prerequisite is the use of standardized interfaces and processes. **R:** Simulation of necessary technical commissioning steps reduces error risk, prerequisite is the use of standardized interfaces and processes.
Operation	**K:** Optimized maintenance planning, OT security, costs of data storage and maintenance of the DZiNE throughout the entire lifecycle of the physical device, development costs of methods and algorithms for targeted evaluation for maintenance planning, OT security, fault clearance time, verification and validation of accuracy, e.g., of optimized maintenance planning, to achieve secure maintenance cycles. **Q:** Higher quality of maintenance (through simulation and potentially manufacturer-specific instructions directly available to maintenance personnel, such as augmented reality, patches/bug fixes), trained personnel through DT, for simulation, measurement data must be available with necessary accuracy, e.g., for modeling effects. **D:** Optimized maintenance processes, reduced fault clearance time. **R:** Reduced risk for employees, reduced risk in case of disruptions as investigation of critical failures is possible, reduced failure frequency through improved data foundation (all devices in the field can be analyzed and the results used).

Table 4: Benefits and challenges of a DZiNE of a protection and control device

4.5 Digital Twin of a Transformer

A power transformer is inherently a complex technical system. Therefore, the concept of a digital twin of a transformer is based on its generic model, which describes the transformer as a functional model of its subsystems.

This means that a transformer can be described by the interaction of its main construction assemblies with their individual functions and their fault modes [41]. The question of how far the transformer can be divided into further sub-assemblies can be answered by weighing effectiveness and efficiency because although breaking down the transformer below the main construction assemblies refines the granularity, further division becomes inefficient due to the multitude of individual functionalities. The relevant main construction assemblies for representation in a digital twin are:

- **Bushings**
- **Active part** with magnetic core, windings, lead-outs, insulating fluid, potential control shields, and press construction
- **Transformer tank** with expansion tanks for insulating fluid
- **Cooling system** including circulation pumps
- **Tap changer**

Thus, a functional transformer model consists of several subsystems, each of which is described by its own models and fault modes.

However, for the use of the digital twin in operational management, it is neither possible nor necessary to fully describe each main construction assembly with a detailed model since the majority of assemblies can be monitored and described through condition monitoring. Additional parameter datasets for describing the operational state can be generated during cyclic condition monitoring or during maintenance and used to enhance the description of the digital twin.

However, when the digital twin of a transformer is directly involved in operational network management, the focus is on the main construction assemblies that are associated with the smallest time constants and a change in operational state or, in this case, load variation. In the case of a transformer, this is typically the active part and the tap changer. Therefore, thermal models play a crucial role in a day-ahead prognosis for preventive assessment in network operation, actual curative network operation, or even in planning-oriented simulation of curative measures in the transmission network (Figure 11).

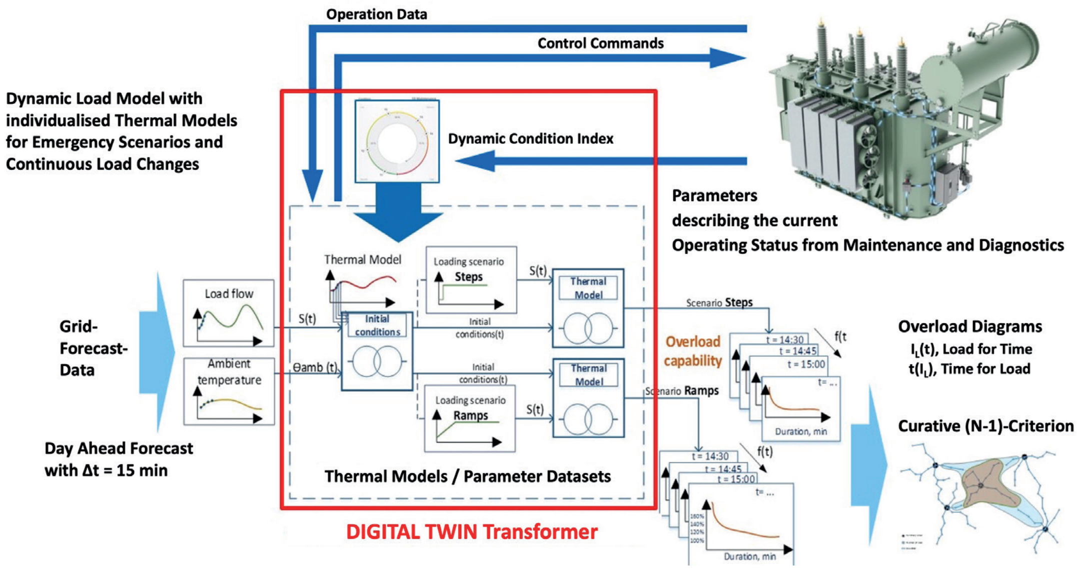

Figure 11: DZiNE of a transformer in grid operation (based on [42])

To provide the control system with concrete values for "Load for time" (the load that a transformer can sustain for a specified time without exceeding thermal limits) or "Time for Load" (the time a transformer can operate with a specific load without exceeding thermal limits), bidirectional data transfer between the transformer and the control system is essential.

In any case, this increases the requirements for the communication infrastructure of the process and station buses in terms of data volume and cybersecurity. Converting the multitude of data into a state information and thereby reducing the data volume is possible when the digital twin with its models is directly available in the transformer control, as this is where the sensor data from transducers and all necessary temperature sensors converge.

Phase	Value Added/Challenges
Planning & Design/Engineering	**K:** Reduced engineering costs. **Q:** Extensive testing possibilities for winding design using empirical values and testing of design parameters with knowledge of material parameters. **D:** Parallel testing of multiple designs. **R:** Risk reduction in thermal design while approaching design limits.
Construction/Commissioning	**K:** Utilization of material limits; qualification of the information exchange interface. **Q:** Ensuring cybersecurity for secure data transfer. **D:** Reduction of testing time in Factory Acceptance Tests (FAT). **R:** Failure to incorporate manufacturing tolerances in the model increases the risk.
Operation	**K:** Cost comparison between redispatch and lifetime consumption. **Q:** Knowledge of lifetime consumption under overload conditions and increased safety in curative network operations. **D:** Improved planning certainty for maintenance. **R:** Overloading can lead to exceeding thermal limits.

Table 5: Benefits and challenges of a DZiNE of a tranformer

4.6 Value Added through the Networking of Digital Twins

In addition to the value-added described in the individual examples, further value can be generated through the networking of DZiNEs. The following is an exemplary business case, without claiming to be exhaustive, motivated by the energy transition and the provision of essential services.

Due to a newly planned wind farm, grid reinforcements are required in the transmission grid of TSO A. In collaboration with neighboring TSOs, a definition of measures is carried out by collecting and jointly analyzing planned changes in the load and feed-in situation of the network operators. This results in the need for a new substation called "Volt City" at TSO A, which requires the installation of a new transformer A.

Figure 12 illustrates the DZiNE of Transformer A over multiple life cycle phases on a timeline. The horizontal arrows represent the general connection of the transformer's DZiNE to the DZiNE of the "Volt City" substation and the network twin of TSO A. The life cycle of the substation and the network can be significantly longer than the life cycle of the transformer being planned. The lower part of the image shows the interfaces to other DZiNEs outside of TSO A. In this example, the interfaces are used to create and utilize common simulation models for different purposes.

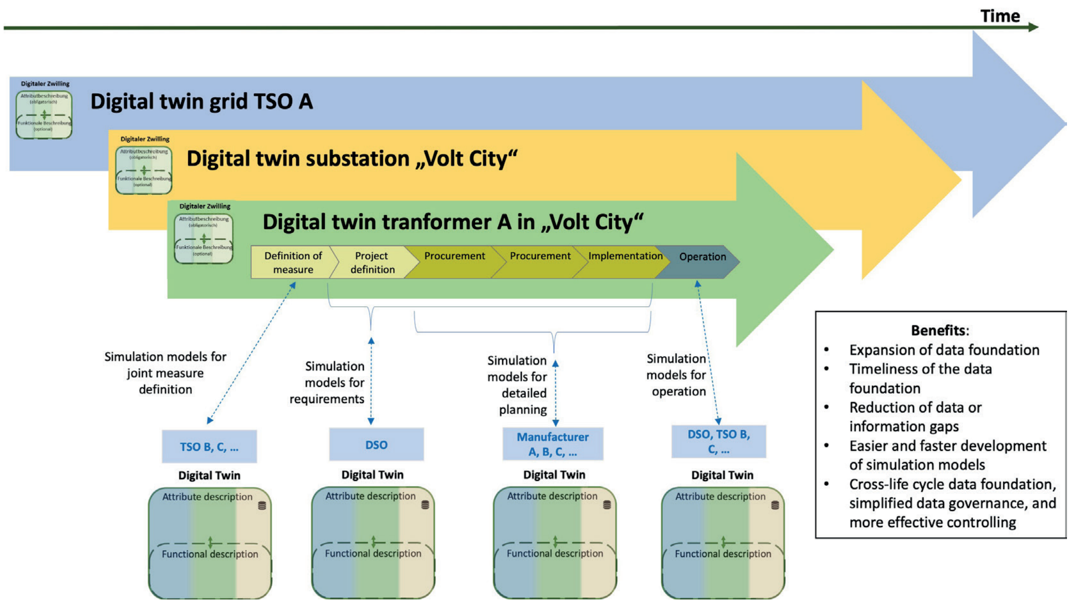

Figure 12: Exemplary interaction of multiple digital twins in the context of establishing a new transformer in a substation

Through the interaction of DZiNEs, the following value-added benefits can be achieved:

1. Reduction of uncontrolled redundancies.
2. Expansion of the data foundation.
3. Timeliness of the data foundation.
4. Reduction of data or information gaps.
5. Easier and faster development of simulation models.
6. Cross-life cycle data foundation, simplified data governance, and more effective controlling.
7. Reduction of project duration, testing efforts, and costs through validated requirements.
8. Seamless system integration through simulations with DZiNE, even with software patches.
9. Reduction of errors through validated and consolidated data.
10. Minimization of data maintenance efforts through interconnected DZiNEs.

The table below presents potential benefits from the linking of individual DZiNEs from Sections 4.1 to 4.5. The table primarily addresses the user perspective, describing the advantages for the DZiNE in the corresponding cell when combining the two DZiNEs from the respective row and column.

DZ – DZ	4.1 Grid (Planning perspective)	4.2 Grid (Grid control perspective)	4.3 Switchgear	4.4 Protection and control device	4.5 Transformer
4.1 Grid (Planning perspective)	Improving the quality and duration of the grid planning process for cross- grid operator planning tasks	Better and more precise consideration of new approaches from grid operation management (e.g. curative grid operation) in grid planning	Consideration of more precise data of the real switchgear in the status quo of the planning calculations	Perspective use of the real protection and control devices in grid planning	Simplification of the interplay between grid operator and manufacturer in the bidding and deployment process
4.2 Grid (Grid control perspective)	Optimization of future grid management through interaction of DZiNE of grid management and planning	SSoT e.g. for error prevention when exchanging data between grid operators	Current, validated and verified data for HEO - calculations.	Higher grid utilization through adaptive protection settings Contingency analysis with actual protection settings System-wide, cross-grid protection concepts	Time overload capability for curative grid management
4.3 Switchgear	Better planning of the operating equipment (including individualization in the development process, if necessary)	Better consideration of the current network condition e.g. switching operations as well as temporary overload capacity during service life	Standardized DZiNE incl. a common SSoT for e.g. improved asset management and mutual learning among DZiNE.	Increased level of detail of the DZiNE makes sense, since the model can also be used for protection and control technology.	Physical alignment through often spatial proximity Synergy through the use of similar tools/procedures
4.4 Protection and control device	Better data quality (e.g. for parameter settings) in the interaction between real protection and control devices and the grid planning data sets	Actual grid structure is transferred to the protection device (➔ protection setting, grading plan). Fault identification possible before commissioning.	Actual protection settings and breaker positions available Data on the switchgear including secondary technology (e.g. remanence models for current transformers or short-circuit power and max. operating currents)	Investigation of protection concepts or systems by coupling DZiNE from several manufacturers.	More detailed behavior of the transformer incl. aging for improved protection and control concepts (e.g. transformer regulator)
4.5 Transformer	Design of the transmission power considering volatile energy flows	Comparison of lifetime consumption through targeted overloading versus redispatch	Reduction of overvoltage loads during switching operations, e.g. in zero crossing (point on wave)	Tuning of setting parameters, limit values and protection ranges	Design optimization through experiences of the DZiNE

Table 6: Added value from linking the individual DZiNEs

5 Recommendations for Action

Background

The implementation of the agreed climate targets requires a significant transformation of the energy system to integrate new decentralized facilities. This requires significant additional network capacities, some of which can be achieved through higher utilization of existing networks. At the same time, the network and electricity industry is experiencing a significant shortage of skilled workers, which is expected to worsen in the coming years. Efficient management of these challenges requires a high degree of digital transformation and automation of the energy system, with DZiNE as an essential part of it.

Collaboration of Digital Systems

Currently, there are already numerous mostly standalone digitization solutions in the energy system. We recommend achieving a networking of digital systems, especially their data models, through the introduction of digital twins in our industry. This would improve the efficiency of these systems by reducing uncontrolled redundancy and unlock further potentials by creating additional value. Interfaces of digital systems should be standardized and enable manufacturer-independent, modular system architectures that meet the requirements of use cases and follow the principles of the IEC 61850 and IEC 61970 standard families in terms of compatibility. Due to the strong interconnection of IT systems, special security needs must be considered, and applicable IT security guidelines should be applied (see Chapter 3.2.2).

Broader Networking and Consolidation of Data

DZiNE requires valid, normalized, and structured data. The current data inventory usually does not meet these conditions. Over the years, independent data silos have developed, each representing partial aspects of the network. The data is now scattered across various data sources within the silos and can only be manually synchronized, making it potentially outdated. The data silos need to be broken down, and the data needs to be validated against each other and then consolidated. With today's technology, the validity of shared data from multiple independent and insufficiently valid data sources in the silos can be improved to almost 100%. The inconsistencies found can be eliminated by incorporating one or more additional data sources. However, on-site data collection may be necessary to obtain a truly independent data source. The Single Source of Truth (SSoT) principle ensures that there are no uncontrolled redundancies in the data for digital twins, and the responsible party for each data is defined. For algorithms to consume data, besides sufficient validity, the data must be standardized (or at least normalized) and structured. Structured and normalized data can generally be used to automatically generate data views in standard formats such as IFC, CIM, Eclass, etc. The normalization and structuring of larger data sets can be efficiently achieved today using weak AI methods within a data validation project (see below).

Normalizing Data Models

Uncontrolled redundancy is the ailment of digitalization. With every new software, every new file, and every new attribute, the redundancy of information unknowingly increases. After a certain period, updating the copies becomes impossible, and the data becomes outdated. Users increasingly encounter incorrect values, lose trust in the data, and consequently need to manually validate the values repeatedly. Automation is generally only possible with highly valid data. With increasing digitalization, the damage caused by outdated data can quickly outweigh the benefits of digitalization. Normalizing the data helps reduce uncontrolled redundancy. When normalizing, logically related attributes are grouped and assigned to a new table or class, which is then referenced.

Example of normalized data: Instead of directly assigning all material properties of a material to each object redundantly, the objects contain references to a material object from which they derive their specific properties. Updating the material properties immediately benefits all consumers. This is usually achieved through a parameter (material identifier) that contains a key value. The definition of the key attribute includes a set of values that only includes available materials. This normalization reduces data redundancy to a minimum.

In this context, it should be noted that in addition to avoiding uncontrolled redundancy, there is also controlled redundancy. In many cases, software architects allocate additional storage to optimize systems through controlled redundancy (e.g., cache memory).

In the Industry 4.0 system, the principle of normalization is also applied between software products and organizations. "Connecting the World" means obtaining data directly from the single source of truth (SSoT) as much as possible. Simulation results can only be as good as the input data used. In particular, DZiNE, as a simulation model, relies on valid, normalized, and structured data.

Precise analysis and prioritization of use cases

To achieve initial success quickly, it is advisable to proceed gradually when introducing digital twins by first analyzing and prioritizing potential use cases. Based on the use cases, requirements for data availability and data governance can be derived. This requires expertise from all relevant areas (modeling, standards, IT, UX, etc.).

Trying to do everything at once is not feasible - define a migration path

Introducing a digital twin is usually associated with a significant effort. For this reason, creating a migration path is of crucial importance. This includes preparing the data foundation by validating the data. Additionally, data needs to be normalized (as mentioned above) to prepare for the integration of interfaces with other digital twins. Furthermore, it is necessary to connect the internal and external processes of a company to the digital twin and provide appropriate training to the staff, as these are essential components of the migration path.

Migration Path

Since there is no definitive complete DZiNE of the entire network, it is necessary to start with a limited use case. Despite the limited use case, it is important to ensure that the DZiNE is future-proof (see Chapter 4.6).

After selecting a limited use case, the first step is to take stock of the available data for that use case. In some cases, such as CAD plant documentation, the data formats are so heterogeneous and partially outdated that a new acquisition is necessary. Using currently available data acquisition methods, highly valid, structured data models can be efficiently generated using artificial intelligence techniques. These data, independent of the remaining existing data, are suitable for gradually validating additional data sources. This allows a large portion of inconsistencies between data from different silos to be eliminated and provides the basis for the DZiNE.

In the next step, the DZiNE needs to be implemented for the defined use case by mapping the process of the use case in an overarching DZiNE and integrating the data from the underlying DZiNEs (e.g., assets) with the previously captured and validated data. The network operator assumes the role of the system integrator, although this role can also be delegated to suitable service providers. The underlying DZiNEs with corresponding models of real objects must be provided by the manufacturer.

Creating Acceptance

In particular, when introducing a digital twin within a company, a transparent information campaign should be conducted to create a clear understanding among the workforce of the expected benefits after the migration is completed. This helps to achieve a high level of acceptance and participation within the workforce for the migration process.

For the Scientific Community

The development and implementation of new DZiNEs present various research questions for the scientific community. The elevated and validated data treasure provided by DZiNE offers significant potential for exploring new functions and applications in the electricity and network industry based on the data model of DZiNE. This includes, for example, new possibilities in the area of cross-network operator functionalities.

Furthermore, the concept of the Snapshot Twin (see Chapter 2), which is used for conducting "what-if" analyses through simulations, offers further research potential. To harness the diverse potential of DZiNE, methods need to be developed to automatically make the usually manually initiated simulation models executable after importing a simulation scenario from DZiNE. In this context, suitable interfaces between DZiNE and research infrastructures (e.g., real-time laboratories, simulation platforms) need to be developed, taking into account existing or future standards (see the Standardization section).

There is also a need for research in the area of validating and plausibilizing the data treasure of DZiNE, considering technical and physical relationships. Building upon previous applications in the field of state estimation, which need to be extended to significant additional application areas or data sets, can be useful in this regard.

Moreover, the implementation of pilot implementations for specific use cases should be encouraged.

For Standardization

In the automation systems of power supply facilities, the following communication standards are typically applied during new construction and complete renewal projects: IEC 60870-5-104 is mainly used for the remote control interface, IEC 61850 for the station bus in station control systems, and parallel wiring with terminal blocks for the process connection. In selected projects, the process bus according to IEC 61850 is used for the process connection.

IEC 60870-5-104 and the terminal block interface are less suitable for modeling digital twins, as they require significant effort to connect digital twins with online systems.

The basic structure of IEC 61850 provides an excellent foundation for communication and data modeling within and between subsystems, utilizing its standardized metadata within an object-oriented model, which can also be used for DZiNE. The explicit modeling of data points in IEC 61850-7-4 and further in TR IEC 61850-90-3 can serve as a basis for DZiNE. Extensions are possible but should be standardized or at least cross-manufacturer profiled. Additionally, the CIM standard used in the context of network control systems can easily build upon the structure of the IEC 61850 standard.

At the network operator level, there are technical communication solutions geared towards system operation needs, which are required to meet network codes. Examples include CGMES and RAIDA, specifically for the connect+ platform for Redispatch 2.0. These approaches are not based on IEC 61850 and should be gradually developed towards DZiNE according to the task force. The previous communication and data standards of RAIDA have been developed and published by BNetzA/BSI and BDEW.

Currently, there are no specific standardization projects beyond IEC regarding DZiNE. It is necessary to develop a standardization roadmap for this purpose.

In the field of BIM, better support for high-voltage system construction is required. In the current IFC interface, objects related to electrical infrastructure > 1000 V are explicitly excluded. DZiNE encompasses the engineering, design, and construction phases of high-voltage systems throughout their lifecycle. To exchange information between the involved disciplines using the BIM methodology (Open BIM), an extension of the IFC interface with classes and definitions for high-voltage technology (> 1 kV AC; 1.5 k

V DC) is highly recommended. An working group at BuildingSmart Germany is currently working on developing the required IFC classes.

The extension of the IFC definition for the high-voltage domain should be based on the IEC 61850 standards, especially IEC 61970-301 (CIM). These definitions should then be included in a high-voltage technology domain in the object catalog of the federal BIM platform.

For Politics and Regulation

The Easter Package for the expansion of renewable energies in 2022 presents unprecedented challenges, especially for electricity network operators. In the current situation, network reinforcement is largely achieved through new construction projects using conventional technology. A digital twin enables advanced risk management. With this technology, it is now possible, for example, to operate network couplings, transformers, and lines at higher utilization levels than permitted by the (n-1) criterion (50% to 70%) and ensure curative network operation. However, the corresponding framework conditions need to be adjusted for this.

Furthermore, given the increasing shortage of skilled workers (as baby boomers retire) and the lack of production resources, it is already foreseeable that network expansion projects will be challenging to implement without intelligent digitalization. To address this issue, it is imperative for lawmakers to link the expansion of renewable energies with digital transformation. The concept of DZiNE, based on available technology, has been developed as a comprehensive approach that can serve as a basis for this. Incentives and support through appropriate funding measures are necessary to promote the implementation and research of DZiNE.

In addition to utilizing existing standardization and resources, the process of creating new standards needs to be expedited. The use of existing standards in the field of IEC 61850 and their significance for the design and use of DZiNE should be incorporated into ongoing and upcoming discussions with policymakers regarding the roadmap for system stability and the volatility of generation.

6 Critical Evaluation

This initial position statement in Germany has been compiled to the best of our knowledge and abilities. Not all stakeholders were necessarily involved in the circle of authors. The participation primarily consisted of transmission system operators (ÜNBs) and larger distribution network operators (VNBs) from the network operator side. The topic of DZiNE is already being heavily discussed among these network operators, and initial applications are being tested [5]. It would also be beneficial for medium-sized and smaller VNBs as well as municipal utilities to engage with the topic. This document can serve as an entry-level basis for them.

Within this task force, the position statement was developed with a focus on the German target audience. Currently, there is no comparable international position statement, and there are only preliminary attempts at standardization for DZiNE. Our German position should be presented at the international level and ideally developed into a shared position.

The successful implementation of DZiNE requires a high level of trust in the models used and the algorithms employed to update the model based on available data. By linking DZiNE to a Single Source of Truth (SSoT), a cross-domain and trustworthy, consistent, up-to-date, and continuous data and knowledge source is established. The establishment of interfaces between DZiNE instances and the connected real objects becomes a core concept. The SSoT is a crucial foundation for inspections and tests during commissioning, operational adjustments, and IT security patches.

The design and operation of DZiNE require cybersecurity, fraud prevention, and data integrity as one of the primary goals. However, the consolidation of all relevant information within an SSoT also makes it a central attack vector in case of corruption attempts. The architecture of DZiNE inherently supports the goals of an Information Security Management System (ISMS): ensuring the confidentiality, availability, and integrity of information, thus offering the potential to enhance system security.

The presented architecture is based on RAMI 4.0, as this model anticipates DZiNE in terms of standardization approaches and currently aligns closely with the presented concept of DZiNE. However, the DZiNE concept is technology-agnostic, and therefore, it is important to identify and further develop "best practices" in standardized form for all conceivable use cases.

Naturally, the transformation from individual digitizations to a DZiNE involves some effort. The extent of the effort primarily depends on the current state of data management and process structure. Since the individual aspects are usually well understood in terms of content, the transformation typically requires additional knowledge in change management, data technology, and computer science.
The processes under consideration must be mapped as comprehensively as possible. The depth of modeling processes and data needs to be determined and sufficiently accurate. When implementing DZiNE, it is recommended to ensure that the overall operating effort does not increase but rather decreases.

In addition to the added value generated by the use of DZiNE in internal processes, the provision of consistent, up-to-date, and continuous knowledge to third parties, such as external service providers, becomes more efficient. However, aspects of data and IT security need to be separately addressed.

7 Glossary

7.1 Used Abbreviations

BIM	Building Information Modeling
CGMES	Common Grid Model Exchange Standard
CIM	Common Information Model
DZiNE	Digitale Zwillinge in der Netz- und Energiewirtschaft (Digital Twin in the Network and Electricity Industry)
ETG	Energietechnische Gesellschaft (Power Engineering Society)
HEO	Höhere Entscheidungs- und Optimierungsfunktionen (Advanced decision and optimization functions)
I4.0	Industry 4.0
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IFC	Industry Foundation Classes
ICT	Information and Communication Technology
IoT	Internet of Things
ISO	International Organization for Standardization
ISMS	Information Security Management System
IT	Information Technology
MQTT	Message Queuing Telemetry Transport
OT	Operation Technology
RAMI	Reference Architecture Model Industry
SCADA	Supervisory Control and Data Acquisition
SGAM	Smart Grid Architecture Model
SSoT	Single Source of Truth
VDE	VDE Verband der Elektrotechnik Elektronik Informationstechnik e.V. (VDE Association for Electrical, Electronic & Information Technologies)

7.2 Definition of Terms

Term	Explanation
Application layer	Regulates the communication and interaction of various application programs depending on the use case.
Caching	A cache is a data storage that stores a subset of data to ensure fast access times. Caching refers to the associated process to enable this.
Instantiation	Refers to the creation of an information object along with all attributes and state variables of the object.
Meta attribute	Provides metadata to uniquely assign the object to the information structure of the SSoT.
Middleware	Middleware is software that helps bridge the gaps between other applications, tools, and databases, allowing users to benefit from seamless services.
Snapshot	A snapshot is the state of a system at a specific point in time.
SSoT (Single Source of Truth)	An approach to designing information systems in which information models are applied in such a way that a single source of truth structures data elements through referencing and associating, thus avoiding data redundancy.
Inheritance tree	The inheritance tree is used to establish a permanent relationship between classes built on existing classes.

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9 List of Figures

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