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Advancing Modern Power Grid Planning Through Digital Twins: Standards Analysis and Implementation

Eduardo Gómez-Luna [1], Marlon Murillo-Becerra [1], David R. Garibello-Narváez [1] and Juan C. Vasquez [2,*]

[1] Grupo de Investigación en Alta Tensión—GRALTA, Escuela de Ingeniería Eléctrica y Electrónica, Universidad del Valle, Cali 760015, Colombia; eduardo.gomez@correounivalle.edu.co (E.G.-L.); murillo.marlon@correounivalle.edu.co (M.M.-B.); garibello.david@correounivalle.edu.co (D.R.G.-N.)
[2] Center for Research on Microgrids (CROM), AAU Energy, Aalborg University, 9220 Aalborg, Denmark
* Correspondence: juq@energy.aau.dk; Tel.: +45-20378261

Abstract

The increasing complexity of modern electrical networks poses significant challenges in terms of monitoring, maintenance, and operational efficiency. However, current planning approaches often lack a unified integration of real-time data and predictive modeling. In this context, Digital Twins (DTs) emerge as a promising solution, as they enable the creation of virtual replicas of physical assets. This research addresses the lack of standardized technical frameworks by proposing a novel mathematical optimization model for grid planning based on DTs. The proposed methodology integrates comprehensive architecture (frontend/backend), specific data standards (IEC 61850), and a linear optimization formulation to minimize operational costs and enhance reliability. Case studies such as DTEK Grids and American Electric Power are analyzed to validate the approach. The results demonstrate that the proposed framework can reduce planning errors by approximately 15% and improve fault prediction accuracy to 99%, validating the DTs as a key tool for the digital transformation of the energy sector towards Industry 5.0.

Keywords: Digital Twins; electrical network planning; optimization model; industry 5.0; regulations; implementation methodology

1. Introduction

Digital Twins (DTs) industrial implementation represents a fundamental advance in the era of Industry 4.0 and beyond, towards Industry 5.0 [1,2]. In essence, a DT is a real-time dynamic virtual replica of a physical asset, system, or process that connects to its real counterpart through sensors and data. Figure 1 illustrates the evolution of industries in the implementation of technologies until today with the implementation of DTs.

This is not just about having a virtual representation of a physical element (such as a computer-aided design—CAD), this replica must have a connection from the physical world that allows the surrounding data to be virtualized so that this data generates an understanding of the replica and that, in turn, solution services can be offered with this collected information.

In areas of Smart Grids of different topics, such as the generation of electricity from non-conventional energy sources such as photovoltaics, models based on the use of FPGAs are being used. Thus, achieving the immersion of Hardware in the Loop (HIL), enabling autonomous learning of systems, and exploring trends such as Power to X (P2X).

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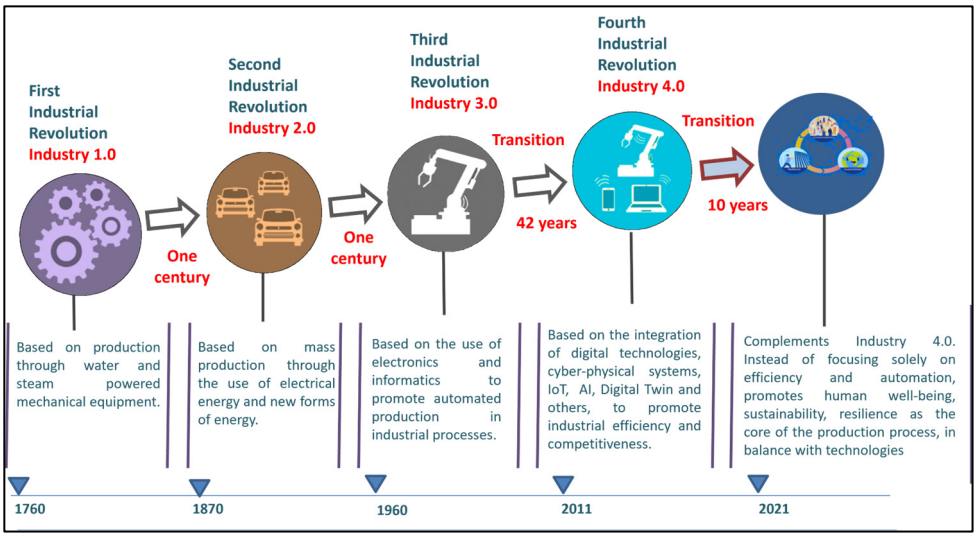


Figure 1. Industry evolution.

The complexity that a large-scale development of a DT could entail leads to the search for co-simulation protocols, allowing for individual development models that generate high fidelity and maintain the confidentiality of each development if required. This type of proposal allows for the use of DTs in a wide range of solutions, such as advice in control rooms, education and training, post-mortem failure analysis, asset management, field support with AR, and predictive operations.

In the context of the electrical industry, the implementation of DTs presents challenges due to the vast amount of data that must be analyzed and converted into relevant information. However, these DTs offer several benefits, such as improved monitoring and control, predictive maintenance, and optimized asset management. By exploring successful case studies, we seek to demonstrate how DTs can revolutionize the planning and management of modern electrical networks.

DTs face significant challenges in power grid planning, including the need to predict energy demand with machine learning models to optimize power distribution [3] through real-time simulations, and the identification of abnormal behavior in renewable energy systems to improve maintenance interventions and technical support [1].

The contribution of this work is the following:

1. A critical and comparative analysis of leading software platforms for electrical network Digital Twins. The analysis evaluates each platform based on key metrics, including computational efficiency, scalability for large-scale grids, real-time data integration capabilities, and modeling fidelity. We discuss the trade-offs between proprietary and open-source solutions, offering a practical guide for researchers and industry practitioners.
2. A structured, step-by-step methodology for the end-to-end implementation of Digital Twins in electrical grid planning. The proposed methodology, which we validate through a pilot case study, includes clear guidelines for data acquisition, model calibration, simulation and analysis, and decision-making feedback loops. This framework serves as a practical blueprint for utility companies and grid operators aiming to adopt DT technology effectively.

Unlike previous works that primarily review the conceptual benefits of Digital Twins, this research addresses the lack of quantitative planning frameworks by proposing a specific Mixed-Integer Linear Programming (MILP) model. While the existing literature focuses on the operational monitoring capabilities of DTs, this paper presents a novel mathematical formulation for Grid Expansion Planning. Specifically, we introduce a decision-support model that utilizes the time-series data ingest of the Digital Twin to

optimize binary investment decisions (x_{ij}) and minimize total expenditure (CAPEX and OPEX). This approach shifts the paradigm from static, worst-case planning to a dynamic, probabilistic methodology grounded in actual operational data profiles.

The remainder of this document is organized as follows: Section 2 discusses the use of DTs in the electrical sector. Section 3 introduces the proposed mathematical planning model. Section 4 presents the regulatory framework. Section 5 presents the proposed methodology, and Section 6 contains the conclusions.

2. DTs in the Electrical Sector

The evolution of electrical grids forces various grid operators to develop strategies that allow them to adapt to infrastructure changes. In the transition to Industry 5.0, the interaction between human operators and intelligent machines becomes critical. DTs provide the interface for this collaboration, allowing operators to visualize complex data streams intuitively [4].

The maintenance of overhead lines and underground cables is a difficult and costly operation for any transmission or distribution network operator. Overhead lines suffer several problems throughout their lifespan, such as damage from mechanical fatigue (wind oscillation), electrical fatigue (overloads, partial discharges), and damage from external causes (forestation, weather, animals, third-party damage). Pole-connected secondary transformers suffer similar problems. Underground cables are difficult to inspect and replace optimally. These problems increase in extreme geographies such as mountainous areas or proximity to the coast.

2.1. Implementation Cases

The implementation of DTs in the electrical industry is expected to test methodology and build a comprehensive application to support asset performance management and predictive maintenance, from problem detection and prediction of future failures to computer-assisted decision-making for asset investment and maintenance work.

DTEK Grids: cases such as that of the Ukrainian company DTEK Grids, which is dedicated to energy distribution and which is distinguished by incorporating digital technologies, is projected to invest around USD 355 million that will be used to modernize the network. This focus is mainly on the city of Kiev because it houses approximately 10% of the total population of the nation. This development considers the construction of four new substations, which in turn will require an approximate amount of 51 km of cables for medium- and high-voltage, including operating voltages between 35 and 110 kilovolts and another 2000 km of electrical wiring for low-voltage lines. For this reason, DG implementations are required to project changes in the network infrastructure, with which it is expected to have 80% of the precision of the inputs to be used for said expansions in a period of 3 years [4].

IGNITIS ESO: the company IGNITIS is working with the company ESO (*Energijos skirstymo operatorius*), from the Lietuvos group Enrgija of Lithuanian origin, to implement a DT for the deployment of 16,000 km of cables corresponding to overhead lines for both medium- and low-voltage, including with it the installation and start-up of different transformers within the existing networks. This is intended to reduce failures and to more accurately predict when they will occur, going from 88% to an expected prediction of 99%. This implementation is expected to be executed in a period of no more than 5 years [5]. Also to be implemented are pilot tests for the commissioning of micro islands from photovoltaic generation.

AMERICAN ELECTRIC POWER: The largest grid operator in the United States, AEP (American Electric Power), is implementing the use of DTs to provide real-time load flow

estimates for approximately 400,000 end-user customers. This is intended to improve its predictive maintenance and enable improved grid planning and real-time load dispatch. This seeks to ensure that distributed energy resources (DER) generate a secure, reliable, affordable, and sustainable supply.

For this reason, the electrical industry could view the DTs as a high-fidelity model that acquires and manages data from different parts of the energy chain, including generation, transmission, distribution, and end-use, enabling optimal management of physical assets. Despite these advances, the existing literature often lacks a formalized mathematical description of how these DTs are utilized for planning optimization. The following section addresses this gap.

2.2. DT in Modern Power Grid Planning

The implementation of DTs in power grid planning can be considered booming given the technological innovation it brings, as well as a great number and variety of benefits from various perspectives; however, it is recognized that one of the main reasons is to define the scope and level of detail for the development of virtual models [3]. Of course, this depends on the field where the DT is to be implemented, so it is necessary to recognize the levels of impact that these have had in the planning of electrical networks. Figure 2 illustrates in percentage terms the amounts of DT research there is for certain sectors of electricity grids.

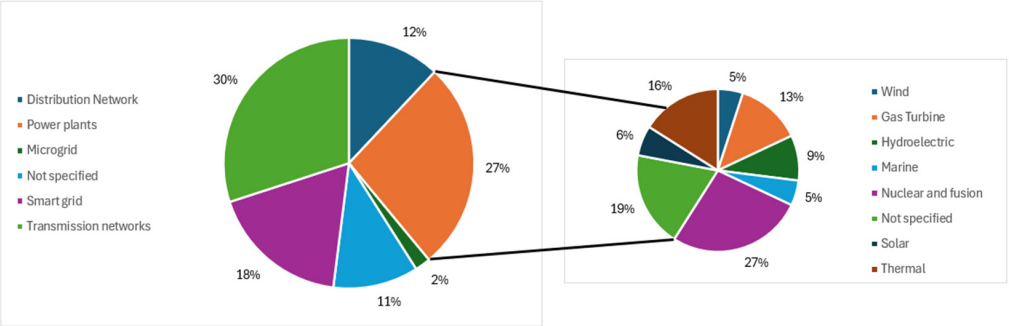


Figure 2. Impact on the development of DT for fields in electrical networks [3].

In this regard, to facilitate the integration of DTs into electrical network planning, it has been proposed to divide the networks into small units and create DTs for each of the divisions [3]. These actions facilitate the efficient generation and consumption of energy, minimizing losses and improving network reliability. They can also predict equipment failures before they occur, enabling preventive maintenance and avoiding interruptions. These systems are also capable of simulating cyber-attacks to identify vulnerabilities and, thus, implement effective strategies that mitigate security risks. On the other hand, they can also simulate consumption patterns, optimizing demand management and improving the response to variations in energy consumption [2].

Furthermore, with the assets being the most important resource in industry, referring from the power grid both to the infrastructure, the elements of measurement, and control and maneuvering, as well as inputs such as electrical wiring, the use of DTs brings benefits as well. These benefits include the ability to extend the life of assets and equipment as a support to implement preventive maintenance by reducing costs in addition to validating equipment prior to deployment and mass purchase resulting in time and material cost savings.

DTs drive operational improvements by integrating state-of-the-art assets with efficient practices, as having advanced technology without optimized processes limits operational productivity. Thus, DTs allow operational inefficiencies to be discovered, the response to downtime improved, and processes optimized, which reduces errors in operation and

maintenance, decreases production downtimes, and improves service quality. They also facilitate smarter network monitoring, data-driven strategic decision-making, diverse asset integration, and accident risk reduction.

Beyond operational optimization, DTs also allow you to simulate the impact of distributed generation (DG) on the grid, helping to manage variable energy from renewable sources such as solar and wind [2]. Companies like GE have applied this technology in wind turbine plants, improving production, predictive maintenance, and reliability through real-time data, while DNV GL has developed DT tools to optimize the performance of wind turbines. Similarly, DTs have been implemented in solar farms to maximize energy generation and to troubleshoot, in nuclear plants for on-line monitoring and resilience improvement, and in hydroelectric plants for early fault diagnosis [1].

In the field of smart cities, DTs have a long-term transformative potential, enabling more efficient microgrids planning, optimized energy management, and intelligent monitoring that improves stability, network reliability, and resilience through proactive fault detection [1].

In the digital age, data has become the most valuable asset for businesses, and the electrical industry is no exception. Having a robust database to analyze network behavior, user demand, and requirements is essential for continuous service improvement and future strategy planning. By properly processing and leveraging these data in the implementation of a DT, significant advantages are obtained, such as the unification of data taking from various functions, peak demand analysis to optimize distribution, and the ability to configure adaptive protections that increase system resilience. In addition, these data allow the development of simulation software tailored to operational and technical needs, as well as applying advanced analysis engineering to transform raw information into strategic decisions that drive power grid efficiency and reliability.

Knowing the behavior of assets together with optimization in operation and due analysis of data acquired from the network and its assets allows for constant improvement of the current and future design of the network.

DTs deployment transforms technical knowledge into concrete benefits for electrical systems, offering scalability to adapt to future growth and allowing interoperation between different network models. These tools facilitate real-time simulations that integrate various transmission and distribution models, optimizing both the costs of implementing new lines as well as repowering existing ones. In addition, they enable real-time communication and monitoring systems when required, improve efficiency in the design of future infrastructures through virtual prototyping prior to their physical implementation, and allow early verification of operability to ensure that systems are tailored exactly to specific needs. This combination of capabilities not only increases operational efficiency, but also reduces the risks and costs associated with expanding and modernizing power grids.

3. Proposed Mathematical Modeling for Grid Planning with DTs

To formalize the planning process described in the subsequent methodology, we define a mathematical optimization model that the DT kernel executes. The objective is to minimize the total cost of planning and operations (TC).

The incorporation of binary decision variables, denoted as x_{ij}, is fundamental to transforming the problem from a standard Optimal Power Flow (OPF) analysis into a Transmission Expansion Planning (TEP) problem using Mixed-Integer Linear Programming (MILP).

Unlike continuous variables, which represent energy flows, the binary variable acts as a logical switch representing the investment decision:

- If $x_{ij} = 1$, the Digital Twin activates the asset in the virtual model, incurring a fixed investment cost (C_{inv}) and enabling power flow capacity (P_{max}) on that branch.

- If $x_{ij} = 0$, the asset is not built, the investment cost is zero, and the capacity remains zero.

This discrete formulation allows the optimization solver to explore combinatorial trade-offs between capital expenditure (CAPEX) and operational efficiency (OPEX), directly addressing the need for 'planning decision variables' typically absent in purely operational models.

The objective function is defined as

$$\text{minTC} = \sum_{(i,j)\in\Omega_L} \left(C_{inv,ij} \cdot x_{ij}\right) + \sum_{t\in T} \sum_{i\in\Omega_G} \left(C_{op,i} \cdot P_{g,i,t}\right)$$

where

Symbol	Description	Unit
Ω_N	Set of all electrical nodes (buses) in the grid.	-
Ω_L	Set of candidate transmission lines/branches for expansion.	-
Ω_G	Set of generation units.	-
i, j	Indices representing network nodes (from node i to node j)	-
t	Index for time periods in the planning horizon (1 to T)	h
$C_{inv,ij}$	Capital cost (CAPEX) of constructing/reinforcing line ij.	$
$C_{op,i}$	Marginal operational cost (OPEX) of generation at node i.	$/MWh
$P_{d,i,t}$	Active power demand at node i during time t (from SCADA profiles).	MW
$P_{max\ i,j}$	Maximum thermal capacity of candidate line ij.	MW
M	Large positive constant (Big-M) for relaxation logic.	-
x_{ij}	Binary investment decision variable (1 if built, 0 otherwise).	0, 1
$P_{g,i,t}$	Active power generation dispatched at node i at time t.	MW
$P_{ij,t}$	Active power flow through branch ij at time t.	MW

Subject to the following physical and operational constraints:

1. Nodal Power Balance (Kirchhoff's Current Law):

$$P_{g,i,t} - P_{d,i,t} = \sum_{j\in\Omega_i} P_{ij,t}$$

This ensures that the digital replica adheres to Kirchhoff's laws for every node *i*.

2. Line Capacity Constraints (Planning logic):

$$-P_{max,ij} \cdot \left(x_{ij} + x_{ij}^{existing}\right) \le P_{ij,t} \le P_{max,ij} \cdot \left(x_{ij} + x_{ij}^{existing}\right)$$

3. Investment Budget (Optional but good):

$$\sum_{(i,j)} C_{inv,ij} \cdot x_{ij} \le Budget_{max}$$

Unlike traditional static planning, which relies on peak-load snapshots, the Digital Twin utilizes historical SCADA data to construct time-series profiles. This allows the planning model to identify thermal capacity violations that occur only under specific dynamic conditions (e.g., low wind generation with high demand) and apply Dynamic Line Rating (DLR) constraints. The SCADA data is not used for real-time dispatch in this context, but to calibrate the planning constraints (P_{max}) based on actual operational realities rather than theoretical nameplate ratings.

4. Regulatory Framework and Standards Applied to DT

The digitalization of the network and the interconnectivity of various devices when implementing a DT bring with them many requirements, which are reflected in the different

regulations that apply to various fields, from the conceptualization of a DT covered by a regulation to the cybersecurity requirements for the data obtained during its implementation.

The concept of a DT itself is approached differently depending on the perspective from which it is viewed and the topic itself. This is why the regulations to be applied can be segmented into various fields. Tables 1–6 provide a comprehensive mapping of these standards. While dense, these tables are critical for developers to identify the specific IEC or IEEE standard applicable to each layer of the DT (physical, communication, or cyber).

- **Table 1** covers physical systems (IEC 62832).
- **Table 2** focuses on communication protocols (IEC 61850, DNP3).
- **Table 3** details cybersecurity (ISO/IEC 27000), which is paramount for protecting the critical infrastructure data.

(Tables 1–6 are retained here but conceptually grouped by the explanation above to reduce information overload).

Table 1. DT's standards applied to physical systems.

Number	Title	Description	Reference
IEC TS 62832-1	Industrial-process measurement, control and automation-Digital factory framework-Part 1	General principles: generally, defines the principles of a digital factory, which is a set of elements from a model and the rules that must be followed for modeling a production system. This defines models of fixed assets and the relationship between these and the production system. It applies to three different production processes: continuous control, batch control, and discrete control	[6]
IEEE 1451	Standard for Smart Transducers	Defines a set of communication interfaces for connecting smart transducers to microprocessor-based systems, instruments, and networks, and provides a set of protocols for both wired and wireless systems	[7]
IEEE 2888.1	Specification of Sensor Interface for Cyber and Physical World	Defines the vocabulary, requirements, metrics, data formats, and application programming interfaces (API) for acquiring information from sensors, allowing the definition of interfaces between the cyber world and the physical world	[8]
IEEE 2888.2	Standard for Actuator Interface for Cyber and Physical World	Defines the vocabulary, requirements, metrics, data formats, and API to describe features, configure parameters, and control actuators that enable the definition of interfaces between the cyber world and the physical world. These actuators will be defined in either the cyber or physical world	[9]
ISO 23247-1	Automation systems and integration-DT framework for manufacturing-Part 1	Overview and general principles: describes a set of protocols for creating and communicating DT, describing their current state. This is further subdivided into four subsections covering different layers. ISO 23247-1 provides an overview of the DT framework, including terms, definitions, and requirements	[10]
ISO 23247-2	Automation systems and integration-DT framework for manufacturing-Part 2	Reference architecture: This standard specifies the architectural requirements for implementing the DT	[11]

Table 2. DT's standards applicable to virtual systems.

Number	Title	Description	Reference
IEC 63278-1	Asset Administration Shell for industrial applications-Part 1	Defines how to represent a real-world asset in the information world using the Asset Management Shell containing structures, properties, and services	[12]
IEC 62264	Enterprise-control system Integration	Describes the manufacturing operations management domain and its activities, and the content of the interface and associated transactions within manufacturing and between activities. This description enables integration between manufacturing operations and the control domain	[13]
IEC 62714	Engineering data exchange format for use in industrial automation systems Engineering-Automation Markup Language-Part 1	Presents the format for data exchange in AML (Automation Language)-format Markup Language is an XML schema-based data format and has been developed to support data exchange across a heterogeneous engineering tool landscape. The goal of AML is to interconnect engineering tools across their different disciplines, e.g., mechanical plant engineering, electrical design, process engineering, process control engineering, HMI development, PLC programming, robot programming, etc.	[14]
IEEE P2806-1	Standard for Connectivity Requirements of Digital Representation for Physical Objects in Factory Environments	Defines the connectivity requirements of the digital representations of the physical objects present in the factory environment considering the heterogeneity of the data, the connectivity requirements that contemplate high-speed protocols, data modeling, and access interfaces to comply with interoperability between physical and virtual environments	[15]
ISO 23247-3	Automation systems and integration-DT framework for manufacturing-Part 3	Digital representation of manufacturing elements details the characteristics and attributes of basic information that the digital representation of the manufacturing elements must have	[16]
ISO 10303	Industrial automation Systems and integration-Product data representation and exchange	Provides a representation of product information along with the mechanisms and definitions necessary to enable the exchange of product data. The exchange is between different computing systems and environments associated with the complete product lifecycle, including product design, manufacturing, use, maintenance, and disposal	[17]

Table 3. DT's standards applied to data.

Number	Title	Description	Reference
IEC 61987	Industrial process measurement and control-Data structures and elements in process equipment catalogs	Provides an operational list of properties for the description of operating parameters and the collection of requirements for measuring equipment	[18]
IEC 61360	Standard data elements types with associated classification scheme	Specifies the principles for defining properties and associated attributes and explains methods for representing verbally defined concepts with appropriate data constructs	[19]
ISO/IEC GUIDE 77	Guide for specification of product properties and classes	Provides recommendations for standards committees for the description of products and their properties for the creation of computer-processable product reference libraries, catalogs, and dictionaries	[20]
ISO 13584	Industrial automation systems and integration	Specifies the principles to be used to define part characterization classes and part properties that allow a part to be characterized independently of any supplier-defined identification	[21]
IEC 29002	Industrial automation systems and integration-Exchange of Characteristic data	Specifies a conceptual information model and an interchange file format for characteristic data. The conceptual model is in Unified Modeling Language (UML)	[22]

Table 4. DT's standards applied to connectivity.

Number	Title	Description	Reference
IEC 61158-1	Standards for Fieldbus and Real Time Ethernet	Specifies the standard fieldbus communication protocols that allow real-time reading and its applications, defining in turn eight different types of protocols	[23]
IEC 61784-2	Industrial communication networks-Profiles-Part 2	Additional fieldbus profiles for real-time networks based on ISO/IEC/IEEE 8802-3: specifies performance indicators that support classification schemes for real-time ethernet requirements	[24]
IEC 62657	Industrial communication networks-Wireless communication networks-Part 1	Wireless communication requirements and spectrum considerations provide the wireless communication requirements dictated by the applications of wireless communication systems in industrial automation and the related context requirements. The requirements are specified independently of the wireless technology employed	[25]
IEEE 2888-3	Standard on Orchestration of Digital Synchronization between Cyber and Physical Worlds	Defines the vocabulary, requirements, metrics, data formats, and API for configuring parameters and communicating with digital objects to provide synchronization sequences and interaction with physical objects	[26]
ISO 23247-4	Automation systems and integration-DT framework for manufacturing-Part 4	Information exchange: identifies the technical requirements for the exchange of information between entities within the reference architecture, information exchange is allowed between different networks such as user network, service network, access network, and proximity network	[27]

Table 5. DT's standards applied to services.

Number	Title	Description	Reference
IEEE 2888-4	Architecture for Virtual Reality Disaster Response Training System with Six degrees of Freedom (6 DoF)	Defines the reference architecture needed to implement a virtual-reality training system that can simulate responses to potential disasters in large physical spaces	[28]
IEEE 1671	Trial-Use Standard for Automatic Test Markup Language (ATML) for Exchanging Automatic Test Equipment and Test Information via XML	Specifies the framework for the ATML family of standards, where it defines a standard exchange medium for sharing information between components of an automated testing system (ATS), using the Extensible Markup Language (XML)	[29]
ISO 13372	Condition monitoring and diagnostics of machines-Vocabulary	Specifies the definitions of terms used in condition monitoring and diagnostics of machines. Its objective is to provide users and manufacturers of condition monitoring and diagnostic systems with a common vocabulary	[30]
ISO 17359	Condition monitoring and diagnostics of machines-General guidelines	Establishes guidelines for the general procedures to be considered when establishing a condition monitoring program for machines and includes references to the associated standards required in this process	[31]
ISO 20242-3	Industrial automation systems and integration-Service interface for testing applications-Part 3	Virtual device service interface: defines a service interface for communication with virtual devices comprising capabilities of software modules and physical devices, accessed through resource management services	[32]

Table 6. DT's standards applied to cybersecurity.

Number	Title	Description	Reference
ISO/IEC 27000	Information technology-Security techniques-Information security management systems-Overview and vocabulary	Provides an overview of information security management systems (ISMS). It also provides terms and definitions commonly used in the ISMS family of standards	[33]
IEC 62443	Security for industrial automation and control systems	Describes the basic requirements for component manufacturers and system integrators to avoid security risks	[34]

5. Software for the Development of a DT of Electrical Networks

In the industry, there are very diverse needs, and sometimes solutions are required to be conditioned to very specific needs that demand the problem be solved, which is why there are several software for the implementation of DTs. DT models can be created through modeling software which could be offline, online, or real-time. Table 7 presents the level of uncertainty offered by each type of simulation.

Table 7. Uncertainty level by each type of simulation.

Type of Simulation	Model	Uncertainty
Offline	Static	High
Online	Dynamic	Medium
Real-time	Dynamic	Low

Programs such as ePHASORSIM enable real-time simulations of robust systems with up to 100,000+ nodes in mixed T&D networks, allowing us to solve problems such as fasorial domain, transient stability phenomena, and integration of EMS/SCADA systems. It stands out for its processing speed (10,000 nodes in 10 ms), which makes it a very useful software for state estimation, control, and/or protection algorithms in very wide simulation areas [35].

On the other hand, HYPERSIM is recognized as a flexible software for the simulation of complex systems, and it is widely used because it has tools for the simulation of resistors, capacitors, inductors, transformers banks of capacitors, switches, circuit breakers, induction machines, synchronous machines, voltage sources, and other elements also passing through adaptive protections. It is characterized for being used in offline and real-time simulations, being faster in offline systems. It is widely used in studies of electromagnetic transients and power systems such as lightning-surge overvoltages, motor start transient stability, and the study of electric arcs, among others [36].

There is also eFPGASIM, which, from a power electronics-oriented solution perspective looking for PWM reading capture, mitigates the latency problems and processing speeds of algorithms (100 nanoseconds to 1 microsecond). It has a modular multilevel converter (MMC) which allows it to have different topologies of different submodules [37].

With eMEGASIM, real-time simulation in a closed loop for power and electronics systems (HIL-hardware in loop) is achieved and could create rapid control prototypes. It allows integration of RT-EVENTS, which makes it possible to simulate high-frequency modulated signals from discrete systems using converter trigger signals [38].

RSCAD allows the simulation of HIL and PHIL, creating a wide versatility, with the ability to configure microgrids in physical form already simulated allowing simulated energy exchange. Using RSCAD, the most complete real-time simulation modeling library, allows for diversity, flexibility, and accuracy [39].

The company Siemens, as a provider of elements and services, implements a DT with Siemens Electrical DT that allows the planning of the power grid from the management of models for the transmission network from the perspective of operation and analysis and management of data supplied by the network [40].

Finally, ETAP offers an integrated platform with intelligent solutions on a multidimensional basis, allowing for adaptability of the project as it grows and evolves. Large companies such as SCHNEIDER ELECTRIC work hand in hand with ETAP to offer digitization services for their single-line diagrams with EcoConsult [41].

Considering the main characteristics and protocols of the different software, Table 8 is compiled.

It is worth noting that before beginning the process of implementing DTs for electrical grid planning, it is essential to understand the network's size, capacity, potential mediation elements, and number of nodes. This is essential because every solution's needs are different. If existing elements are already in place, it is important to evaluate the protocols used in them to validate whether communication is possible or if some type of API is required.

Table 8. Software summary for DT implementation.

SOFTWARE	GRID SIZE	SIMULATION MODE			FEATURES	PROTOCOL	SOURCE
		ONLINE	OFFLINE	REALTIME			
ePHASORSIM	Up to 100,000 nodes		X	X	Support: Simulink, Excel, PSS/E, CYME, PoweFactory, Open Modelica, Dymola, EXataCPS	UDP/IP, TCP/IP, IEEE C37.118, DNP3, MODBUS, OPC, IEC60870.104, AURORA	[35]
HYPERSIM	Up to 100 nodes		X	X	Support: MATLAB, ASCII, PDF, POST-SCRIPT	IEEE C37.118, DNP3, OPC, IEC 60870.104, IEC61850—accelerated simulation	[36]
eFPGASIM	Up to 500 nodes		X	X	FPGA support Python, TestStand, labVIEW, C++ and Java	DNP3, IEC60870-5-104, IEC61850-8-1 GOOSE, IEC61850-9-2 Sampled Values, Modbus, C37.118	[37]
eMEGASIM	Up to 500 nodes		X	X	Support RT-LAB, eMEGASIM FX75, ScopeView, ARTEMIS SSN	IEEE C37.118, DNP3, IEC61850-8-1	[38]
RSCAD	Up to 500 nodes		X	X	RSCAD library and GUI applicability	UDP/TCP, DNP3, MODBUW, OPC, IEC 60870.104, IEC61850	[39]
Simens Electrical Digital Twin	Up to 100 nodes	X	X	X	Support MindConnect, PSS@ODMS, PSS@MOD, MindSphere	DNP3, IEC60870-5-104, IEC61850-8-1 GOOSE, IEC61850-9-2 Sampled Values, Modbus	[40]
ETAP Electrical Digital Twin	Up to 100,000 nodes	X	X	X	Support PSSE (RAW, SEQ & DYR) files	UDP/TCP, DNP3, MODBUW, OPC, IEC 60870.104, IEC61850—output format: .DXF, CAD, .xls, .doc, .PDF	[41]
Power Factory	Up to 100,000 nodes	X	X		Support DPL and Automation, HIL and PHIL, Connection to SCADA/EMS systems for quasi-real-time analysis, relays and controllers (RTU, IED's)	UDP/TCP, DNP3, OPC, IEC 60870.104, IEC61850—output format: .dgs, .csv .PDF	[42]
Neplan	Up to 100,000 nodes	X	X		Support SCADA/EMS systems for quasi-real-time analysis, Python, VBScript, MATLAB,	IEC61850, IEC60870-5-104, DNP3, OPC UA, Modbus, CIM, PSS/E, PSCAD, DXF.	[43]

With this research, it can also be deduced that, although not all DTs are capable of working in real-time, in the electrical industry the developments carried out so far are 100% under this mode of use. Aside from each supplier depending on its market niche, which orients the other attributes of its software, 42% of those investigated additionally have an offline mode of use and 29% an online mode, as shown in Figure 3.

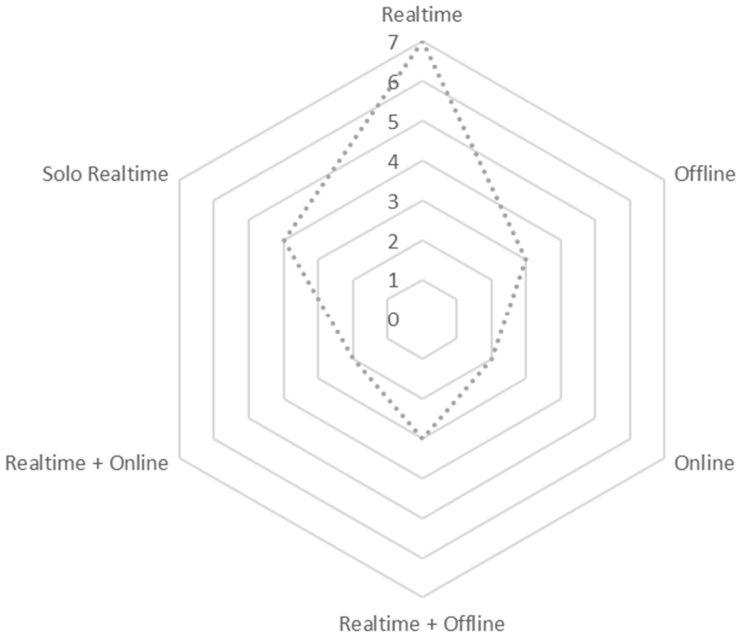


Figure 3. How to use DT software for network planning.

6. Guide for the Implementation of DT for Planning Modern Electrical Grids

Understanding that power grids are constantly evolving and becoming more data intensive as sensor and measurement technology evolves, it is not necessary to define an ideal environment, since the more data the grid obtains from the surrounding environment and its natural characteristics, the more accurate the DT created with this data will be.

It is not only necessary to know the electrical data of the network (voltage, current, resistance, capacitance, harmonics, impedances, etc.). Factors that affect even the measurement equipment will generate deviations in the measurements, such as temperature, humidity, atmospheric pressure, wind flow, and irradiance, among other factors that will also depend on the size and type of network. This is not the same as analyzing an interconnected network and one that is not in the interconnected system, due to the interaction with the network and the number of transducers that each can count on.

Having said this, it is of great importance to know the network before implementing a DT and to know the characteristics of its elements and the behavior towards different eventualities such as environmental and geographical areas. This also means having personnel who meet professional profile characteristics in accordance with the needs of the implementation. The different profiles must work together and be aimed at developing and implementing DTs according to the needs of each network, considering size, usage needs, connectivity, data management, scalability, and its own needs, for the sole purpose of ensuring a reliable, safe, and constantly adaptable and changing electricity grid.

It is very important to be clear that the creation of a DT is the result of a process in which a network project must be defined, and you must perform integration tests of the different elements and finally implement the project with DTs.

In this way, we must start to capture data by means of physical sensors such as current transformers, power transformers, multimeters, thermometers, hygrometers, and barometers, among others, that depend directly on the robust required development. When these data have already been taken from the environment, treatment must be performed, and in this way the relevant data for implementation is extracted, the algorithm corresponding to the need is applied, and after that the processed data are reported. When these data are ready to be used, they should be sent to the software for the implementation of the DT that will be used for the planning of the electrical grid, but, before such transmission, it must be known if the format of the data is compatible with the software. In the case of not being compatible, an API should be used to allow such data communication, taking into account the security protocols that the network must have for both data retention and cybersecurity.

Taking as a reference the need for the network (size, number of nodes, mode of use, etc.) we choose the software that best suits such an implementation, after this, and considering the response data, the information is sent back to the actual part and the system becomes cyclical, constantly being replenished and mutating with the needs.

Through systematic examination of the preceding analysis, this study establishes the following guidelines for DT implementation:

1. Define the objective and scope of the DT: the first objective is to define what you want to achieve with the DT and which elements of the power grid will be included. This will allow efforts to focus on the areas that matter most and avoid information overload. Determine the optimization variables (minimize cost vs. maximize reliability) based on the model in Section 3.
2. Collect and analyze grid data: this includes information on grid topology, network components (such as transformers, lines, substations, etc.), load and energy demand data, information on power sources and generators, and weather data, among others. Deploy sensors adhering to IEEE 2888.1 [8]. Ensure data is time-stamped and synchronized via PTP.
3. Develop the DT model: from the data collected, a mathematical model of the system will be developed to be used in the DT. This includes the definition of equations describing the dynamics of the electrical system, constraints, and model objectives. Considering the characteristics of each available software (number of nodes, frequency, etc.). Calibrate parameters (Y_{ij}, impedances) using historical fault data to minimize the error between $x_{measured}$ and x_{model}. Connect the data stream to the visualization engine using APIs (REST/MQTT).
4. Validate the model: it must be verified that the created model accurately reflects the reality of the electrical network. For this purpose, historical data and tests in the real system can be used to compare model results with actual data. Run the DT in "Shadow Mode" alongside the physical grid to verify prediction accuracy (target >95%).
5. Integrate the DT into the planning process: enable closed-loop control where the DT suggests set-points to the SCADA. The DT can be used to test different design scenarios and solutions, simulate failure situations, and evaluate the power grid's ability to handle different conditions.
6. Update and maintain the DT: the power grid is a constantly changing system. It is, therefore, important to update and maintain the DT to ensure that it accurately reflects the current state of the electricity grid and can remain useful for long-term planning.

It is important to note that the implementation of a DT for electrical grid planning is a complex project requiring knowledge in mathematics, programming, and electrical system theory. In addition, a large amount of data is required to build an accurate model. If the necessary experience or resources are not available, external expertise or collaboration with academic institutions may be considered. Figure 4 comprehensively summarizes the

proposed process for implementing Digital Twins in modern electrical network planning, representing the interaction between three fundamental components: the digital twin of the electrical network, connectivity, and the physical electrical network. This diagram reflects the architecture of a cyber–physical system that brings together Industry 4.0 technologies such as the Internet of Things (IoT), real-time simulation, data analysis, and machine learning.

The block corresponding to the Digital Twin describes the virtual environment responsible for reproducing the behavior of the electrical network. Its implementation is based on the definition of the size of the network (measured in number of nodes), which determines the choice of the most appropriate simulation software (at the time of the research). Among the most notable tools are eFPGASIM, eMEGASIM, ePHASORSIM, and HYPERSIM from OPAL-RT, RTDS, ETAP, and Siemens Electrical Digital Twin, selected for their modeling capabilities and compatibility with different modes of use (real-time, online, or offline). These platforms allow simulations to be performed with different levels of fidelity, facilitating behavior analysis, operational strategy validation, and predictive scenario evaluation.

Connectivity is the link between the physical and digital environments, ensuring the secure, continuous, and bidirectional exchange of information. In cases where platforms or devices use different protocols, the creation of application programming interfaces (APIs) is envisaged to ensure interoperability between systems. This flow of information is supported by standardized protocols such as IEC 61850, DNP3, MODBUS, OPC, and TCP/IP, which, together with the IEC 62443 and ISO/IEC 27000 cybersecurity standards, establish a robust and reliable communication framework. This ensures that the data obtained from the physical environment is correctly interpreted, transmitted, and used by the Digital Twin.

For its part, the electrical grid represents the actual physical system from which the data needed to feed the Digital Twin is captured. Sensors, controllers, and actuators installed in the field allow critical variables such as voltage, current, temperature, irradiance, and humidity to be measured, which are then processed and analyzed using machine learning algorithms. This data processing involves stages of acquisition, cleaning, processing, and reporting, generating useful information for fault prediction, operational optimization, and maintenance planning. The processed data is transformed into dynamic models that reflect the behavior of the system and continuously feed back into the Digital Twin, allowing it to be updated in real time.

The interaction between these three blocks shows a constant flow of data that integrates the physical world with the virtual world, consolidating an ecosystem of monitoring, analysis, and intelligent control. This approach enables more accurate and efficient planning of electrical networks, with the ability to simulate operating conditions, anticipate critical events, and optimize resources before their actual implementation. Consequently, the figure illustrates a comprehensive methodology of technological convergence, where digitization, advanced simulation, and data analysis combine to transform traditional electrical grid management into a dynamic, predictive, and sustainable process.

In summary, we can analyze the figure as three independent blocks that constantly interact with each other:

- 1st Block: Digital Twin of the Electricity Grid.
- 2nd Block: Connectivity.
- 3rd Block: Electricity Grid.

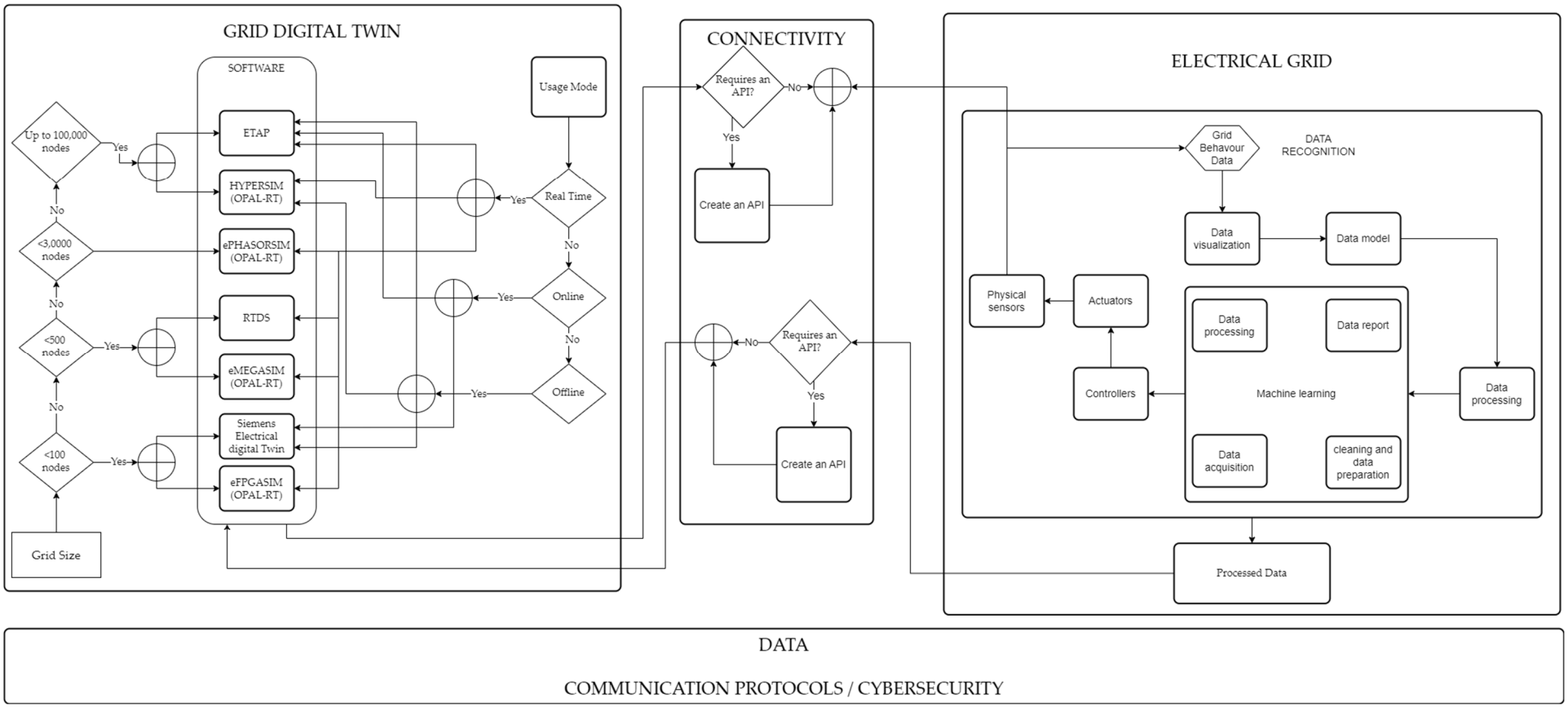


Figure 4. Flowchart for the implementation of DT in power grids.

7. Conclusions

This paper presented a technically robust framework for integrating Digital Twins into power grid planning. We addressed previous gaps by

1. Formulating a mathematical optimization model that allows for reproducible quantitative planning.
2. Defining a clear software architecture separating backend processing from frontend visualization.
3. Aligning with Industry 5.0 trends, emphasizing resilience and human–machine collaboration.

The results indicate that following this structured methodology allows operators to transition from reactive maintenance to predictive planning, reducing investment risks (C_{risk}) and operational costs.

Digital Twins (DT) represent a transformative tool for the planning and management of modern power grids. Beyond being a repository of processed data, they enable predictive maintenance, optimization of assets, and more resilient responses to operational challenges. The analysis carried out shows that their value lies not only in improving efficiency and service quality, but also in opening new paths for integration with emerging technologies and digital transformation strategies.

For Colombia, where implementation is still incipient, the challenge is twofold: to adapt international experiences to local needs and to establish regulatory and technical frameworks that ensure scalability, security, and interoperability. In this sense, DTs are not a distant possibility but an urgent opportunity to modernize the electricity sector.

Ultimately, the originality of DTs lies in their capacity to anticipate, simulate, and optimize—turning uncertainty into informed decision-making. Their adoption will define the competitiveness and sustainability of electrical networks in the years to come.

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Abbreviations

AEP	American Electric Power
API	Application program interfaces
AR	Augmented Reality
BIM	Building Information Modeling
CAD	Computer-aided design
DER	Distributed Energy Resources
DT	Digital Twin
GE	General Electric
HIL	Hardware in the Loop

IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IOT	Internet of Things
ISO	International Organization for Standardization
SEDIT	Semantic DT
VR	Virtual Reality

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