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A comprehensive review of the dynamic applications of the digital twin technology across diverse energy sectors

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A B S T R A C T

The energy supply sector, encompassing vital components such as generation, transmission, and distribution, holds a pivotal role in satisfying the energy demands of modern society. Its intricate web of technologies and infrastructure ensures the reliable provision of electricity from diverse fuel sources, bolstering economic advancement and enhancing overall living standards worldwide. In the context of ongoing global energy transitions, the energy sector assumes a critical role in addressing the escalating demand for alternative energy sources and adapting resource allocation strategies to align with evolving societal energy requirements. Nonetheless, the energy supply sector confronts formidable challenges, including infrastructure degradation and grid instability. Not only that, but the demand of energy supply is also expected to rise by 50% by 2050. To counter these issues and enable predictive maintenance and grid optimization, digital twin solutions have emerged as a necessity. This is particularly significant as industry integrates renewable and non-renewable energy sources while managing risks in a dynamic energy landscape that undergoes constant transformation. This paper presents a comprehensive analysis of the myriad applications, benefits, and impediments associated with digital twin technology within the energy supply sector. Employing a methodological framework grounded in systematic reviews, detailed case studies, and extensive data analysis, this review article utilizes illustrative diagrams and visual aids to enhance clarity and comprehension. These pedagogical tools elucidate essential concepts for the deployment of digital twin technology in the energy supply industry. The analysis reveals that 4.81% (35 out of 727) of the reviewed papers explored the application of digital twins in various energy sectors. The review paper yields several significant findings, including a meticulous synthesis of existing literature, an in-depth examination of case studies, an exploration of emerging trends, and the provision of informative visual aids. These collective insights offer a comprehensive grasp of the application and impact of digital twin technology in the energy supply sector.

1. Introduction

The Energy Information Administration (EIA) forecasts a 50% increase in global energy consumption by 2050 [1]. The Centre for Climate and Energy Solutions found that non-renewable energy generation technologies increase global greenhouse gas emissions by more than 70% [2]. This forces the global energy sector to actively seek more effective operating methods to reduce the negative impacts of unpredictable fuel costs, weather changes, power plant cycling, unplanned outages, etc. Existing solutions to these problems are only incremental, and the power generation industry needs to change to significantly increase energy efficiency in industry, buildings, services, and transport. See Fig. 1 for global energy consumption by region.

The growing need for energy is exerting significant strain on power generators, compelling them to augment their capacity and enhance electricity production [3]. This phenomenon has resulted in the emergence of novel power plants, alongside the enhancement of pre-existing facilities. Furthermore, there is an emerging inclination towards the utilization of sustainable energy sources, such as solar and wind power, due to the increasing affordability of these technologies. The rising need for power is concurrently exerting pressure on the transmission and distribution networks responsible for supplying electricity to residential and commercial establishments. There is a pressing requirement to enhance and expand the existing networks in order to effectively accommodate the escalating magnitude of power. Furthermore, there

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Nomenclature

DT	Digital Twin
EIA	Energy Information Administration
CIRP	College International pour la Recherche en Productique
PV	Photovoltaic
AI	Artificial Intelligence
FFT	Fast Fourier Transform
DFT	Discrete Fourier Transform
MQTT	Message Queuing Telemetry Transport
MMS	Manufacturing Message Specification
GOOSE	Generic Object-Oriented Substation Event
OPC	Open Platform Communications
CAD	Computer-Aided Design
DCS	Distributed Control System

exists a necessity for the implementation of intelligent grid systems that can effectively regulate the transmission and distribution of electrical power with enhanced efficiency.

Digital Twins (DT) for power plants is one such technology that enables rapid transformation of power systems and improves operational flexibility. DT is an important enabling technology for R&D with potential applications in cyber-physical systems to reduce development time and costs, as illustrated in Fig. 2, which shows how the digital transformation of power plants is accelerating and recognizes the main challenges in achieving it. The main difficulties faced by the power sector, the strategies to improve flexible operation and the benefits of applying DTs are summarized in Fig. 2 [3]. These difficulties can be reduced by improving the operation of flexible power plants through digitalization and networked plant technology, which is possible with power plant DT.

The CIRP Encyclopaedia of Production Engineering [4] defines a digital twin as a virtual model of a physical object, system or process that can be used to track and analyse its real counterpart's characteristics, properties, conditions, and behaviours. It is often used to improve understanding and predict the performance of complex systems by combining models, information, and data. Further comprehensive definitions and discussions of digital twins from various works in the literature can be found in Ref. [5]. The authors in Ref. [6] summarise the most important terms and associated processes related to digital twins. It is worth noting that a digital twin does not need to accurately represent all possible actions of a physical system, and there are no constraints on the computational power or speed required. How detailed and accurate the model needs to be depends largely on its intended use [7]. Not only can a digital twin be visualised as a 3-D model, but it could also be represented as a simple 2D visual of the model [8]. Visualisation significantly reduces the time required to comprehend a dynamic system compared to examining tables and graphs containing data.

Energy sectors can enhance the performance of their systems through the utilization of digital twins, which facilitate the prediction and enhancement of these systems [9]. Water firms can employ digital twins to monitor water usage and pertinent data, hence facilitating timely identification of issues and enabling well-informed decision-making on water resource management. Digital twins are subject to ongoing data updates, ensuring dependable and up-to-date information about the functioning of diverse systems. The provided data may be utilized to address inquiries on the probable ramifications of making the proposed improvement, as well as to identify the most productive approaches for enhancing our system. In general, using digital twins can improve utility firms' operational effectiveness, dependability, and ecological sustainability while mitigating expenses and environmental repercussions.

The concept of digital twin, which is a component of Industry 4.0, enables the digitalization of many energy sectors. This digitalization facilitates the optimization of asset management and performance through the integration of intelligent sensors and the analysis of raw data using Artificial Intelligence and machine learning algorithms. This would allow shareholders to effectively monitor the maintenance

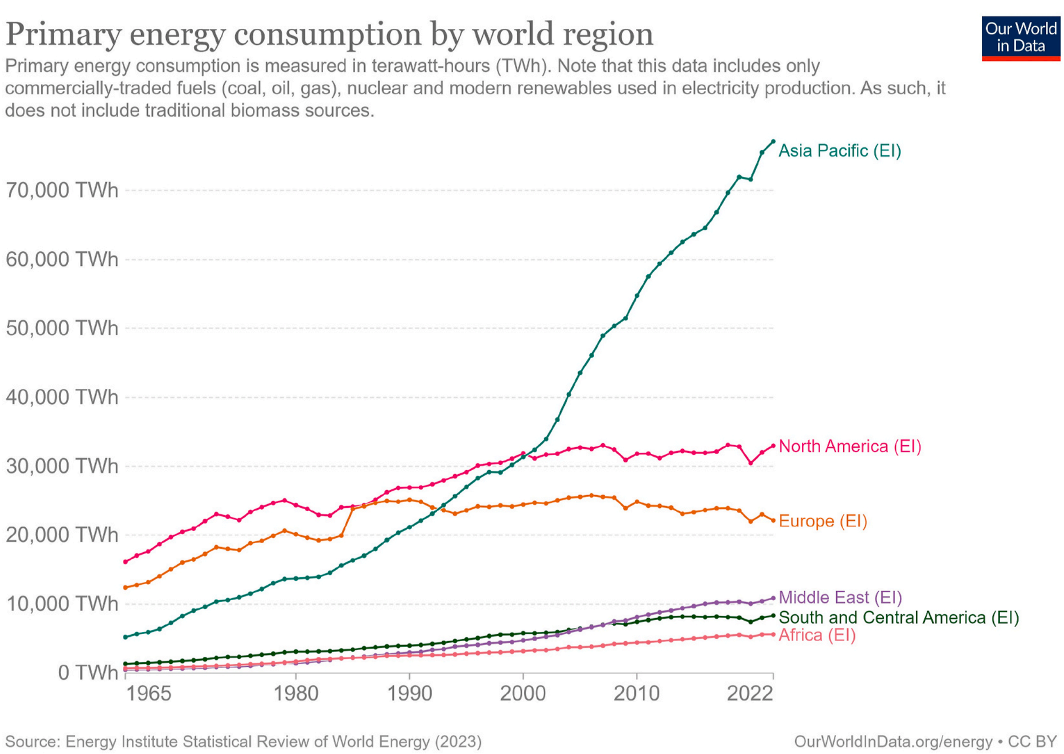

Fig. 1. *Global primary energy consumption by region (1965–2022)* [1].

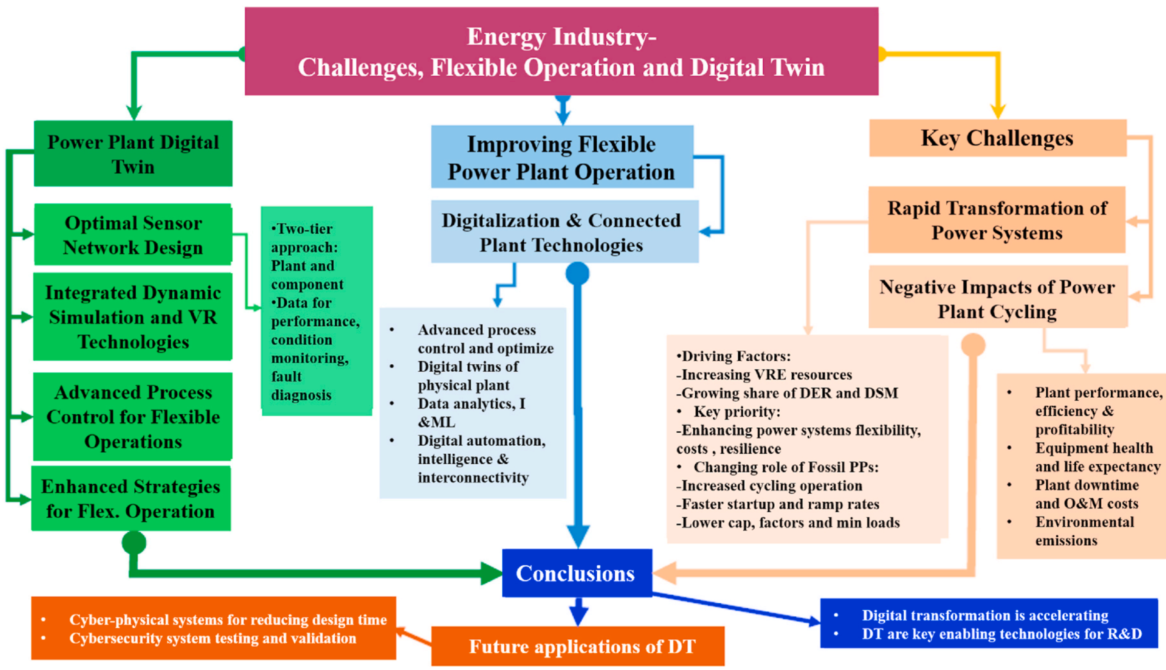

Fig. 2. *Digital transformation in the energy industry* [4].

process of their assets, resulting in a significant reduction in maintenance costs, as mentioned in Ref. [10].

Fig. 3 shows the twinning process and the relationship between the terms within the overall concept of the Digital Twin based on [6]. The figure illustrates the interaction between physical and virtual processes and the corresponding physical and virtual entities, the latter undergoing state changes by manipulating their parameters. These state changes are captured by metrological methods and transmitted through physical-virtual and virtual-physical connections so that they manifest themselves in the other domain by synchronising all parameters. The physical and virtual domains have tools for assessing and implementing these state changes, called twinning processes. The rate at which the virtual and physical twins are synchronised is called the twinning rate.

What differs from other survey papers is that this systematic review offers a comprehensive investigation of the wide-ranging uses of digital twins in the energy industry, spanning several areas. Moreover, this scholarly article provides readers with a profound perspective on the present-day software solutions propelling the advancement of digital twins presently employed in many domains.

Moreover, this study attempts to answer the following questions:

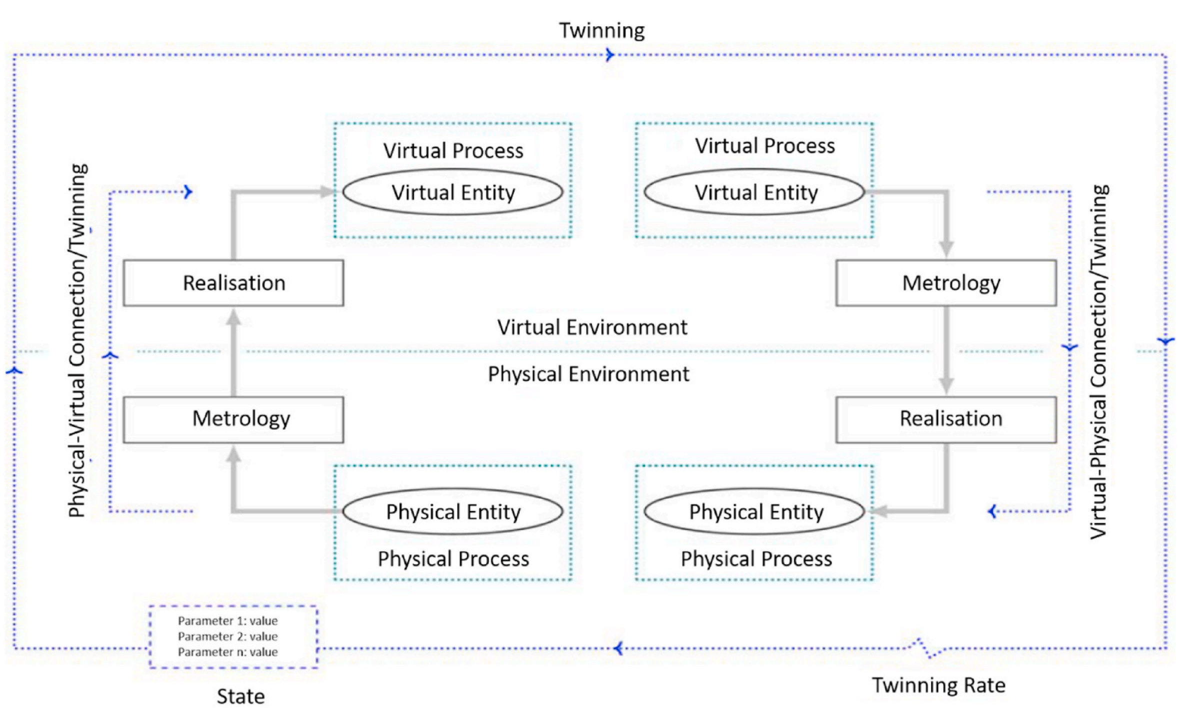

Fig. 3. *The DT twinning process* [6].

1. What resources are available for researchers or companies to use in developing their digital twin applications in their respective energy sectors?
2. How are unexplored domains of possible research and development prospects in sectors yet to fully harness the benefits of digital twin applications within the energy business?
3. What are the significant challenges of implementing digital twins in energy sectors?

Please ensure that you are prepared for an academic exploration of the concept of digital twins, where the convergence of invention and reality presents many possibilities constrained by our collective imagination. It also provides a wide platform for other researchers to understand the status of digital twins and their application in the energy sector.

The contribution of this systematic review paper are summarized as follows:

- It assists academia researchers and industries in identifying appropriate tools and software for developing digital twin systems tailored to their specific purposes.
- It offers academia researchers a comprehensive understanding of digital twin system implementation across diverse energy sectors, highlighting potential areas for further research and development.
- It equips practitioners in the energy industry with practical suggestions and guidance on addressing critical challenges that need to be considered before embarking on digital twin system development or implementation.

The remainder of the paper is organized as follows. Section 2 presents the methodology of the systematic review paper. Section 3 discusses the leading enterprise in digital twins. Section 4 presents the known software for developing a digital twin for various energy industry sectors. Section 5 presents an introduction to digital twin implementations for different sectors in the energy industry. Sections 6-10 discuss the implementations of digital twins for various sectors in the energy industry. Section 11 presents the challenges and limitations of implementing digital twin technology. Section 12 offers further research insights. Section 13 concludes the paper.

2. Methodology

The methodology employed for this systematic review, as elucidated within the schematic representation delineated in Fig. 4, has been meticulously structured to comprehensively analyse the progression of digital twin applications across diverse sectors within the energy power supply industry.

The work starts by listing down the relevant keywords, which are shown in Fig. 4. The journal articles will be downloaded from 3 notable research platforms: Science Direct, Scopus and Google Scholar. The accumulated downloads based on the query are 727 downloaded journal articles. The articles are then filtered based on ten years of publication from 2022. All the non-related and duplicates are removed before proceeding with the first scanning. For relevancy of the work, the paper would be scanned for the first time based on the title and abstract. The last scan will go deeper by reviewing the introduction and conclusion to ensure it is related to our work. Lastly, after a thorough filtering process, 35 related papers were found.

3. Leading Enterprise in Digital Twin

As digital twin technology gains traction in various sectors, numerous companies have emerged as major players in the industry. These companies have invested heavily in research and development and significantly enhanced their digital twin technology capabilities. Their cutting-edge technologies have paved the way for the widespread adoption of digital twins and offer practical benefits to their customers. This section introduces some prominent digital twin enterprises, including their software and use cases.

The use of DTs in industrial applications has the potential to offer numerous strategic advantages. DTs can be used for monitoring [11], diagnostics and forecasting [12], optimization [13], and to support operational decision-making by analysing historical data and predicting future trends. DTs can train operators, maintenance staff and service providers in conjunction with digital representations of assets, environments and people [14]. DTs are widely used in various industries, including construction, healthcare, agriculture, shipping, manufacturing, energy, automotive and aerospace. Much time, expertise and effort have been spent developing this software to meet clients'

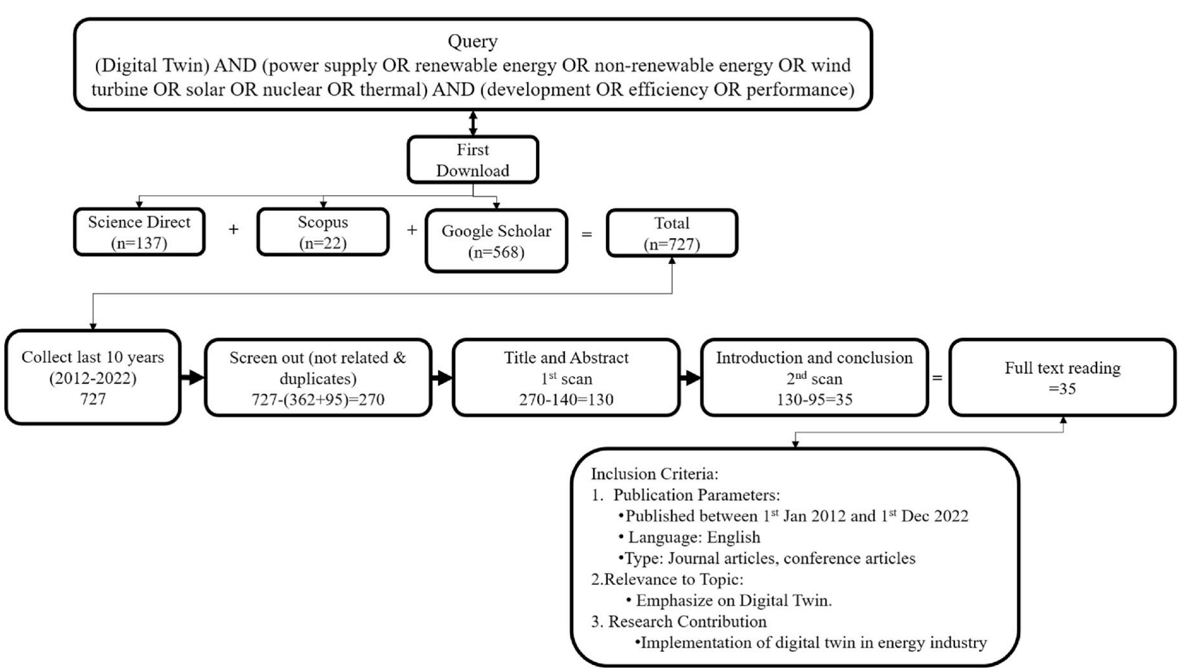

Fig. 4. Review methodology for the digital twin applications across diverse sectors within the energy power supply industry.

objectives. Fig. 5 shows some examples of leading and well-known companies and their software.

Table 1 presents a curated selection of prominent enterprises actively integrating DT technology into their operational frameworks. It is essential to note that this list reflects the most up-to-date information available at publication, considering that these companies introduce new software solutions annually. However, it is necessary to recognize that this compilation, while comprehensive, may not encompass every organization that has adopted DT technology across various industrial sectors, thus representing a cross-sectional representation of noteworthy industry players.

In summary, these companies have significantly contributed to many sectors by providing new solutions that help their customers implement digital twins for different use cases and applications. These companies have enabled their customers to create virtual duplicates of their actual assets, systems and processes using digital twin technologies. They have been able to test scenarios, model results and make informed decisions in a risk-free environment.

4. Software used to develop digital Twin

To date, companies and researchers can create and develop their digital twin using the latest digital twin-enabled software. This section will learn about the available software used to create digital twins. Table 2 shows the available software used for different areas of energy supply and related research.

From Table 2, we can conclude that the development of digital twins is becoming an increasingly common method for modelling and studying complex systems, goods, and processes. The use of software in creating digital twins has the potential to revolutionise the design, operation, and optimization of complicated systems across a wide range of industries. Software tools are essential for developing digital twins, providing the necessary modelling, simulation, visualisation and analysis capabilities. Several software alternatives exist for creating digital twins, each with advantages and disadvantages. The application and the desired outcome will determine the appropriate software tool. It is expected that as technology advances, more complex software tools will be developed that will expand the possibilities for digital twin applications.

3. Digital twin implementations for different electrical power supply system sectors

The digital twin architecture can model and simulate the performance and behaviour of power plants, transmission and distribution systems and other related assets accurately, which has been proven by Refs. [38,41,42]. The digital twin can accurately represent the physical system in real-time by collecting data from sensors and other sources. In addition, the digital twin can optimise operations, detect, and predict failures, and perform virtual commissioning and testing.

Anomaly detection algorithms typically create a baseline of normal behavior by using historical data and then comparing current data to this baseline to detect anomalies. The algorithms can use various statistical and machine learning techniques such as clustering, time series analysis and pattern recognition. Once an anomaly is detected, it can be investigated to determine its origin and potential impact on the physical system. This information can be used to take preventative measures to prevent or correct system malfunctions to ensure the effectiveness and reliability of the system. In this way, potential maintenance problems in a physical system can be detected before they occur, enabling proactive and preventive maintenance.

Predictive maintenance is a critical component of Industry 4.0 as it enables companies to optimise the maintenance of their physical systems, resulting in higher efficiency, less downtime and lower maintenance costs. Predictive maintenance algorithms often examine data from the digital twin and identify potential maintenance issues using machine learning techniques such as regression analysis, decision trees and neural networks. The algorithms can develop predictive models that use multiple data types, such as sensor data, performance data, and past maintenance data, to estimate future performance and identify potential maintenance issues.

In the following, we will discuss the implementations of the digital twin for different areas of power generation, as shown in Fig. 6. Monitoring is considered the basic application of the digital twin, where sensor data is collected and visualised in specific system parts, either in 2D or 3D. Anomaly detection in a digital twin is used to detect and monitor potential problems or deviations from expected behaviour that could indicate a problem with the physical system. Let us say a digital twin is used to monitor the operation of a wind turbine. In this case, an anomaly detection algorithm can find anomalies in the turbine's performance that could indicate a problem, such as a loss of efficiency or an increase in vibration levels.

6. Digital Twin in Photovoltaic Power Plant (PPP)

In a photovoltaic (PV) power plant, a digital twin can be used to model and simulate the performance of a PV power plant by collecting

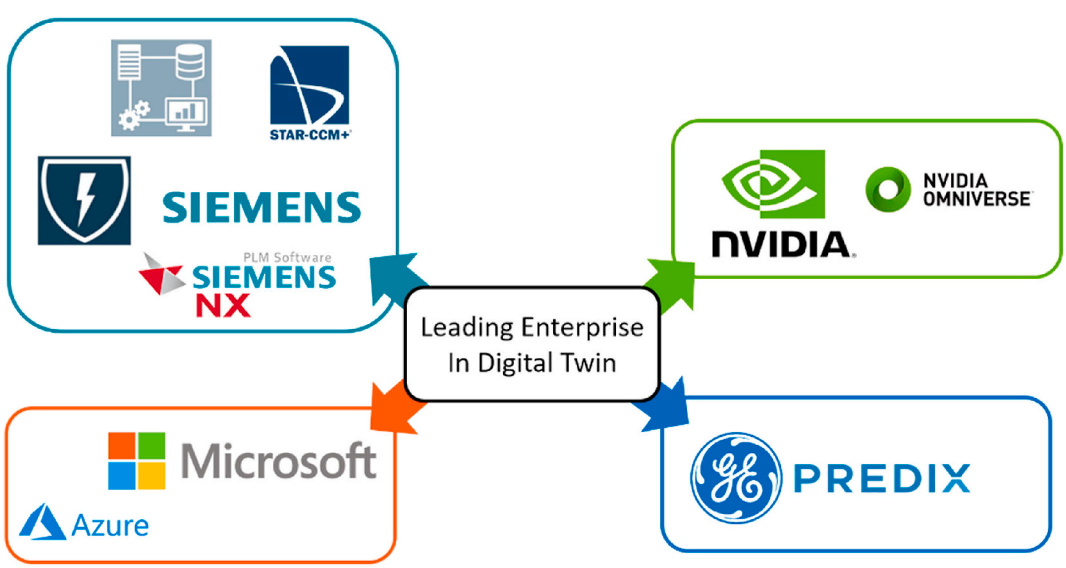

Fig. 5. Leading enterprise in digital twin and its software.

Table 1
List of Leading Enterprises in Digital Twin and its use case.

Leading Enterprise	Used Software	Software Entries (Inputs)	Software Description	Industry	Use Cases	References
Siemens	PSS®CAPE [15]	[12]-Modelling parameters of the transmission network	A software application for doing power system analysis. This technology guarantees precise depiction, facilitates the execution of simulations and studies, and enables real-time data synchronisation. The PSS®CAPE software platform improves the management and comprehension of power systems over their entire lifespan.	Energy	American Electric Power (AEP) creates a unified digital model of its entire transmission network, called T-Nexus.	[16]
Siemens	Siemens PSS ODMS [17]	[14]- Modelling parameters of the grid network and asset management.	The program augments power system analysis within the context of Digital Twins. This technology guarantees precise depiction, facilitates the execution of simulated scenarios, and allows instantaneous data synchronisation, enhancing the management and comprehension of power systems at any stage.	Energy	Fingrid, a Finnish company, developed a digital twin grid network by partnering with Siemens to model the transmission network and asset management. Data collection and verification now make up no more than 20 per cent of the time, while 80 per cent remains for the crucial analysis task.	[18]
Siemens	Small Hydro Sipocon-H Optimizer	[19]-Modelling parameters of the hydropower plant	It utilizes a software application that enhances the efficiency of small-scale hydroelectric power plants within the context of Digital Twins. This technology guarantees accurate depiction, facilitates the execution of simulations, and allows for the synchronization of real-time data, hence augmenting control and efficiency over the whole lifespan of the system.	Energy	Siemens Energy uses an optimization tool called Small Hydro Sipocon-H Optimizer, which uses the digital twin and creates operational set points for specific conditions.	[19]
Siemens	Simcenter STAR-CCM+	[20]- Modelling parameters of the energy reactor	A software that augments Digital Twins by offering sophisticated computational fluid dynamics (CFD) simulations. This technology guarantees precise depiction, facilitates intricate simulations, and allows instantaneous data synchronisation, enhancing comprehension and prognostication of the operational capabilities of tangible resources.	Energy	The flagship water-water energetic reactor was created and constructed by OKB Gidropress, who utilized Siemens software to enhance the safety features of their reactors.	[20]
Nvidia	NVIDIA Omniverse	[21]- water inlet temperature, pressure, pH, gas turbine power and temperature	Software that enhances the capabilities of Digital Twins by including sophisticated 3D simulations and facilitating collaborative efforts. This technology allows for accurate depiction of assets, permits the execution of intricate simulations, and helps synchronize real-time data. These capabilities enhance the collaborative design process and aid in making informed decisions inside digital twin settings.	Energy	Siemens Energy, a market leader in the trillion-dollar global energy sector for power plant technology, uses the NVIDIA Omniverse platform to build digital twins to support predictive power plant maintenance.	[21]
Microsoft	Microsoft Azure [22]	[23]- carbon intensity and energy efficiency	Microsoft Azure provides a comprehensive range of cloud-based infrastructure and services specifically designed to facilitate the implementation and management of Digital Twins. The platform offers features enabling scalability, storage, and analytics functionalities, supporting developing, administering, and examining digital twins in many sectors and applications.	Energy	BP uses a digital twin to calculate real-time carbon intensity and the energy efficiency of the facility's processes.	[23]
General Electric	GE Predix [24]	[25]-carbon intensity and energy efficiency	The GE Predix platform is the underlying infrastructure for implementing Digital Twins inside industrial environments. The technology provides capabilities in data analytics, connection, and real-time insights, facilitating the development and administration of digital twins to optimise performance and maintenance across diverse sectors.	Energy	Marubeni uses GE's Predix to enhance its operational efficiency for Japan's thermal gas power plants.	[25]

data from sensors and other sources, such as weather data and power measurements. The digital twin can then be used to optimise the operation of the PV power plant by analysing the data and making recommendations for things like panel alignment and cleaning schedules. A digital twin of a PV plant can also be used to detect and predict potential failures, such as degradation of modules or problems with inverters, allowing for proactive maintenance and repair. In addition, the digital twin can be used for virtual commissioning and testing, reducing the need for physical site visits, and improving the efficiency of the commissioning process. Using a digital twin in PV power generation can help companies increase their PV power plants' efficiency, reliability, and sustainability.

Fig. 7 shows a digital twin architecture developed by researchers for fault diagnosis in a photovoltaic system [40]. The PVECU control and monitoring stage contains fault diagnostics and control on a single computing platform and operating elements that perform fault

Table 2
Available software used for different power supply system sectors.

Power Supply System Sectors	Software used	Software Entries (inputs)	Software Source	Description	Related References Using the Software
Power Generation-Photovoltaic	Ptolemy II [26]	[27]-Heat generation assets, Combined generation assets, electrical generation assets [28]-Electrical supply models, Heat supply models, environmental variables, thermal storage models [29]-Electrical supply models, Heat supply models, environmental variables, thermal storage models	https://ptolemy.berkeley.edu/ptolemyII/index.htm	Ptolemy II is an open-source software framework that allows for actor-oriented design experimentation. Actors are software components that run in parallel and communicate via messages sent through linked ports. A model is a hierarchical network of actors. The semantics of a model in Ptolemy II are determined by a software component called a director, which implements a model of computation.	[27–29]
Power Generation-Photovoltaic	EnergyPlus [30]	[31]-heat demand data	https://energyplus.net/	EnergyPlus™ is a comprehensive energy simulation software employed by engineers, architects, and researchers to model energy consumption across multiple aspects of building design, including heating, cooling, ventilation, lighting, and plug and process loads, as well as water use within buildings	[31]
Power Generation-Thermal	ThermoFlowTM [32]	[33]-models of boiler island, steam-turbine island and emission control equipment	https://www.thermoflow.com/	ThermoFlowTM is a software that can compute thermodynamic performance accurately. Capable of creating detailed physical designs of the vital components and pipings. Compute economic results, such as ROI and NPV, based on energy prices and annual operating profile;	[33]
Power Transmission and Distribution	ANSYS [34]	[35]-Magnetic field model, thermal airflow model [36]-Electromagnetic, temperature, fluid, stress, motion, insulation strength	https://www.ansys.com/	ANSYS is a general-purpose finite-element modelling tool used to solve various mechanical problems numerically. These challenges include static/dynamic, structural analysis, heat transport, fluid difficulties, and acoustic and electromagnetic problems.	[35,36]
Power Transmission and Distribution	Matlab [37]	[38]-Voltage, current, resistance and inductance [39]-Power transformer electrical protection relay parameters [40]- PV energy conversion unit parameters	https://www.mathworks.com/products/matlab.html	A programming and numeric computing platform to analyse data, design algorithms, and build models.	[38–40]

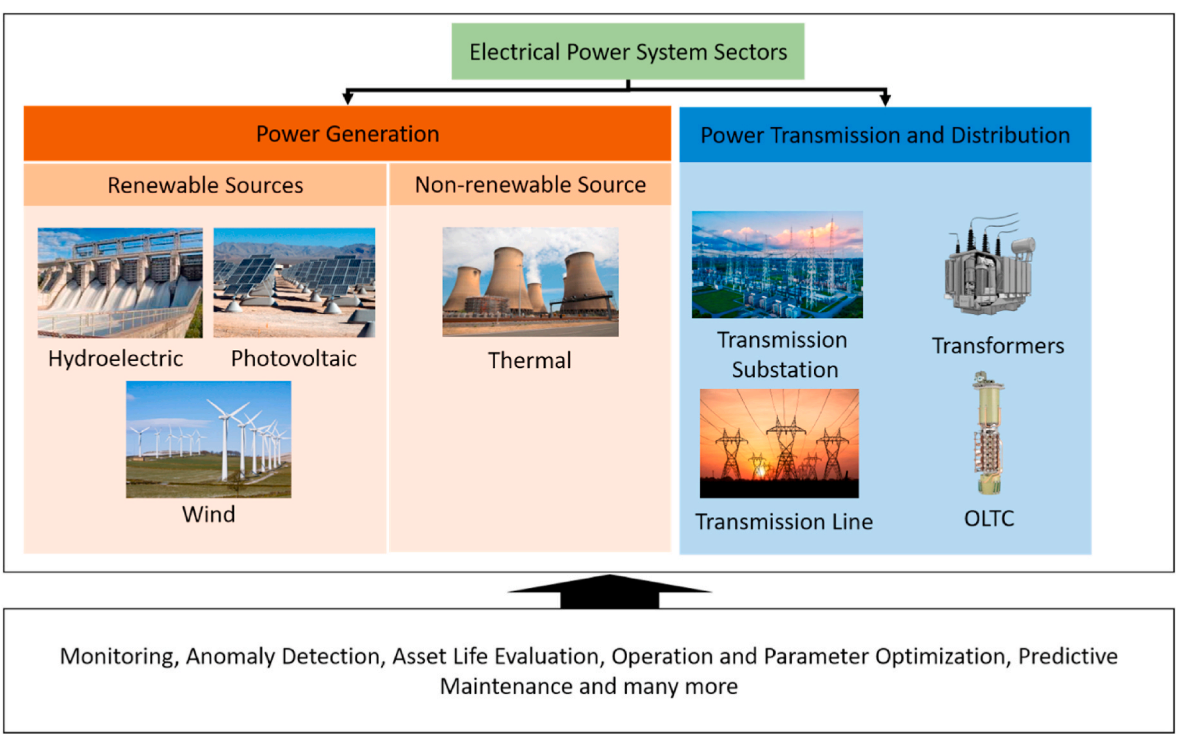

Fig. 6. Digital twin implementation for different electrical power system sectors.

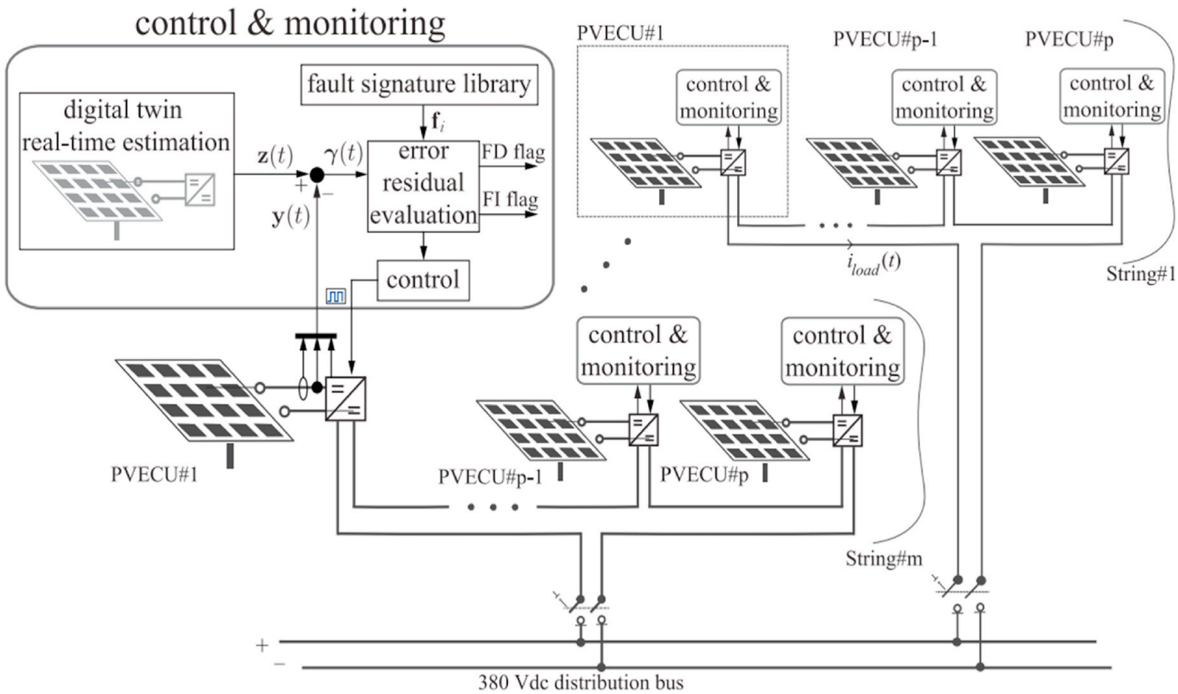

Fig. 7. *Example DT Architecture in a PV system based on* [40].

diagnostics locally for each PVECU. The fault diagnosis approach consists of three main elements: 1) a digital twin that estimates the measurable output characteristics z(t) of the PVECU in real time; 2) a fault residual vector γ(t) that represents the difference between the estimated outputs z(t) and the measured outputs y(t), and a fault diagnosis (FD) method that activates an FD flag; and 3) an analysis of the residual error vector γ(t) to accurately identify the faulty subcomponent and the fault mechanism (indicated by a FI flag). It is worth noting that the fault signature library contains prior knowledge about potential fault events and consists of a collection of analytically computed fault signatures fi ∀ i ∈ {1, 2. … n}. The digital twin successfully differentiated between different fault kinds by analyzing the input energy source of power converters and electrical sensors.

Reference [43] presents a novel approach for implementing a cloud-based monitoring and control system specifically designed for photovoltaic (PV) power plants, as shown in Fig. 8. The technology employs a digital replica, known as a digital twin, to simulate and forecast the operational characteristics of the PV plant. The digital twin

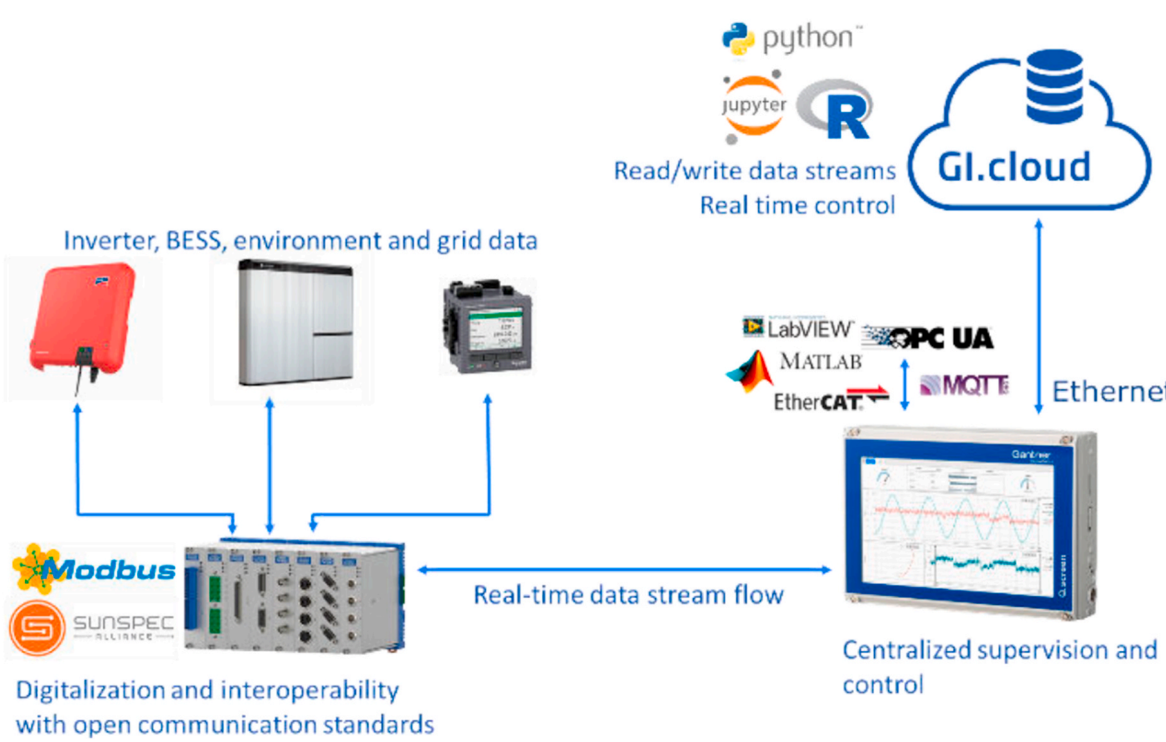

Fig. 8. *Multi-service monitoring system architecture for grid-edge control and AI-driven smart grid service by* Ref. [43].

is educated using past data and can identify flaws to enhance the facility's operating efficiency and overall performance. The system has been deployed on cloud infrastructure, enabling remote access from any location. This characteristic renders it very suitable for deploying expansive photovoltaic installations encompassing a vast geographical expanse. The system employs artificial intelligence (AI) algorithms for health-state diagnostics and analytics. This enables the system to detect and resolve issues early, mitigating the potential for significant interruptions. This study offers the findings derived from the experimental verification of the system. The results indicate that the system can effectively simulate the PV plant and accurately forecast its operational outcomes. Additionally, the system demonstrated the capability to identify and rectify malfunctions while enhancing the efficiency of the plant's functioning. The study's findings suggest that the suggested system has significant potential as an effective means of monitoring and regulating photovoltaic power facilities. The system exhibits characteristics of scalability, reliability, and efficiency. The utilization of this technology has the potential to enhance the efficiency and productivity of PV facilities, hence reducing operational expenses.

One notable aspect of this study is its reliance on a substantial volume of data from the PV plant. It is essential to acknowledge that the collection of such data might be a costly endeavour. To ensure the accuracy of the digital twin, the data quality utilized for its training must be of a high standard. Small and medium-sized PV facilities may have difficulties deploying and operating the digital twin due to the substantial computational resources required for training and execution. Finally, the data utilized for the training and operation of the digital twin must be safeguarded and kept confidential since it may contain confidential information about the PV plant.

7. Digital Twin Architecture in Hydropower Plant

A virtual platform called Digital Twin for Hydropower System (DTHS) is being developed to enable utilities, end-users, OEMs and other stakeholders to gain valuable insights into the behaviour of actual assets and improve operational performance through simulations and predictive or prescriptive analytics. Due to the open and innovative platform, the cost of implementing and using DTHS is expected to be low. As the electricity market becomes more complex, digital twins are expected to provide a valuable service to hydropower plants seeking to improve their operations while maintaining their reliability as a renewable energy source.

Fig. 9 shows that implementing the digital twin in a hydropower plant has numerous advantages. Firstly, it helps the operator optimise the unit/plant [44]. The advances in sensors, communication and technologies in the last decades have made data-driven condition monitoring with the digital twin possible [45] by collecting real-time data using the digital twin. It is possible to display all variables in the distributed control system (DCS) and internal dynamic 3D images, such as turbulent flows in the turbine chamber.

In reference [47], the authors propose constructing a digital twin model for a hydroelectric plant via a data-driven methodology, as shown in Fig. 10. The model is employed to mimic the behavior of the plant and forecast its performance across various operational circumstances. The data-driven method uses machine learning techniques to acquire knowledge about the correlation between the inputs and outputs of a plant. The variables that may be considered as inputs are the water level, the turbine speed, and the generator voltage. The potential results encompass the power output, efficiency, and emissions. The machine learning algorithms undergo training using previous data obtained from the plant. This study then validates the proposed technique by simulating the plant's behavior across various operating situations. The findings indicate that the model has a high level of accuracy in forecasting the plant's performance, achieving about 92%. The study's findings suggest that the methodology holds significant potential for developing a digital twin model for a hydropower facility. The utilization of the model has the potential to enhance the plant's operational efficiency, optimise its overall performance, and mitigate its emissions.

This research looks at various issues that must be addressed to properly build and deploy data-driven digital twin models for hydropower plants. The obstacles encompass data collection and preparation, the intricacies of constructing the digital twin, model validation and

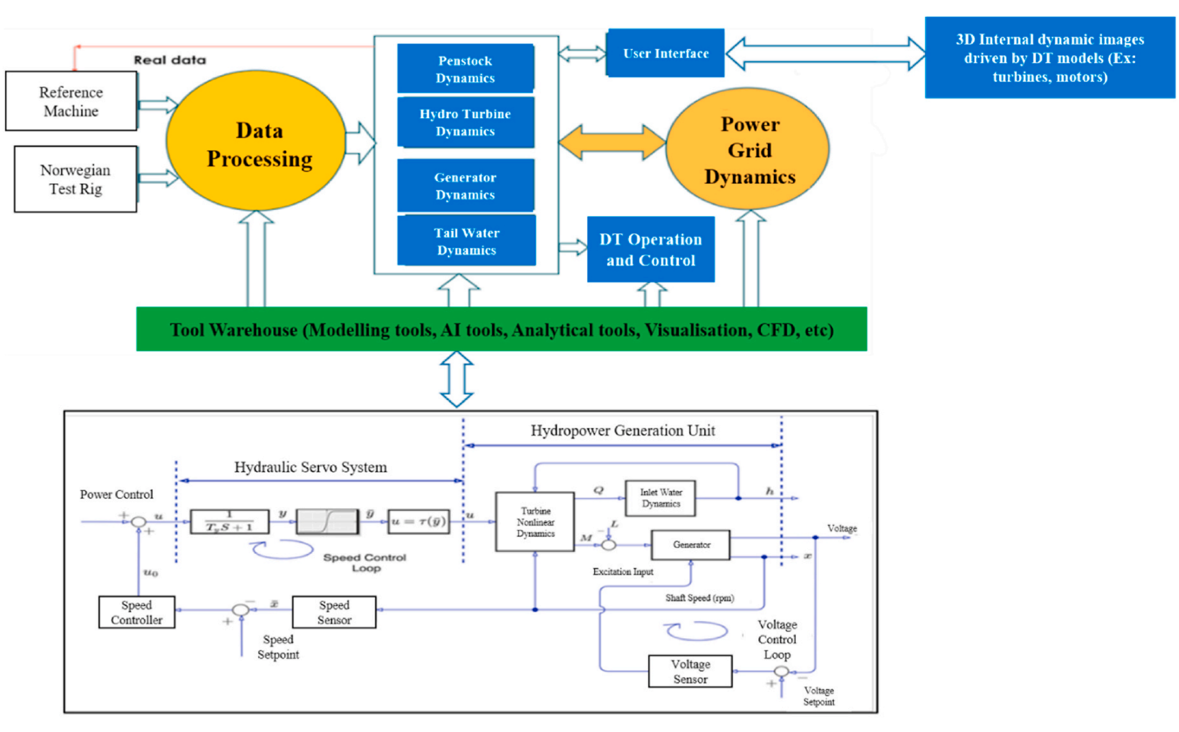

Fig. 9. *Example DT architecture for hydropower plant based on* [46].

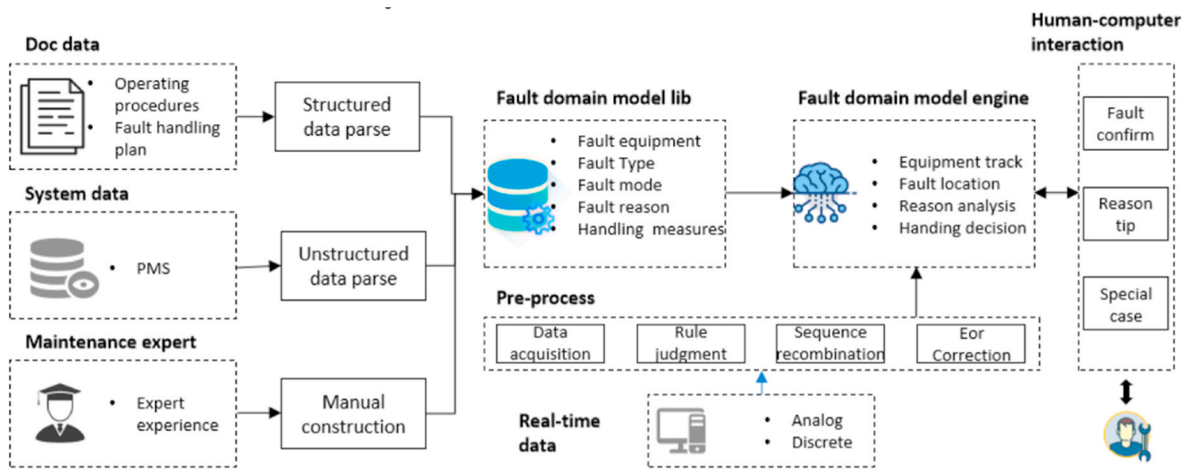

Fig. 10. *Architecture of the hydropower plant fault diagnosis application* [47].

maintenance, and the creation of applications. However, the study does not provide a definitive answer to overcome the challenges above. Moreover, the study lacks a comprehensive analysis of a particular case study demonstrating the successful implementation of a data-driven digital twin concept in a hydroelectric facility.

4. Digital twin in wind power plant

In reference [48],the authors proposed a more accurate and reliable digital twin model of the wind power plant. In Fig. 11, data sets are collected from the physical twin, while control and scheduling directives are afterwards sent as needed, facilitating monitoring and operation. The data that has been captured, perhaps in real-time and from comparable or legacy sources, is utilized in conjunction with numerical models and physical test beds. These test beds may incorporate additional online devices, systems, or databases in order to provide the necessary simulation capabilities. The coordination of these distinct parts is facilitated by a process which further offers users visual representation and quantitative feedback.

In reference [49], the author proposes developing a predictive digital twin platform specifically designed for offshore wind farms, as shown in Fig. 12. The platform utilizes data from several sources, including sensors, SCADA systems, and weather predictions, to create a comprehensive model that accurately represents the operational characteristics of the wind farm. The model is subsequently employed to forecast the wind farm's performance across various operating scenarios. The study starts by addressing the inherent difficulties associated with the operation and maintenance of offshore wind farms. The real-time data collected by the sensor is sent to the cloud. They are visualised in the user interface developed in Unity 3D assets like the turbines. The platform can be designed in any computer-aided design software (CAD), such as SOLIDWORKS [50], Creo Parametric [51] and Autodesk [52]. The obstacles included in this situation are the inhospitable environmental conditions, the isolated geographical setting, and the substantial financial burden associated with repairs. The study subsequently introduces a proposed predictive digital twin platform to tackle these difficulties effectively. The suggested platform is then validated by simulating a wind farm's performance across various operational scenarios. The findings indicate that the platform can effectively forecast the wind farm's performance. Although the work was a success, there were challenges that needed to be addressed to replicate this kind of work. Firstly, the cost of collecting and processing data from offshore wind turbines is exorbitant. Next, the need for a reliable and secure communication network to transmit data between the digital twin and the wind turbine is crucial.

Modelling and estimating anomalies based on wind turbine bearings' vibration and temperature development over long periods is possible. In Fig. 13, the Fast Fourier transform (FFT) method can detect vibration anomalies. The FFT is widely used in audio and image processing, communication systems and scientific computing. It has applications in spectral analysis, differential equation solving, encryption and data compression [53]. FFT is an efficient approach for computing a sequence's discrete Fourier transform (DFT). The DFT is useful for signal analysis because it decomposes a series of values into a sum of sine functions with different frequencies. Cooley and Tukey invented the FFT

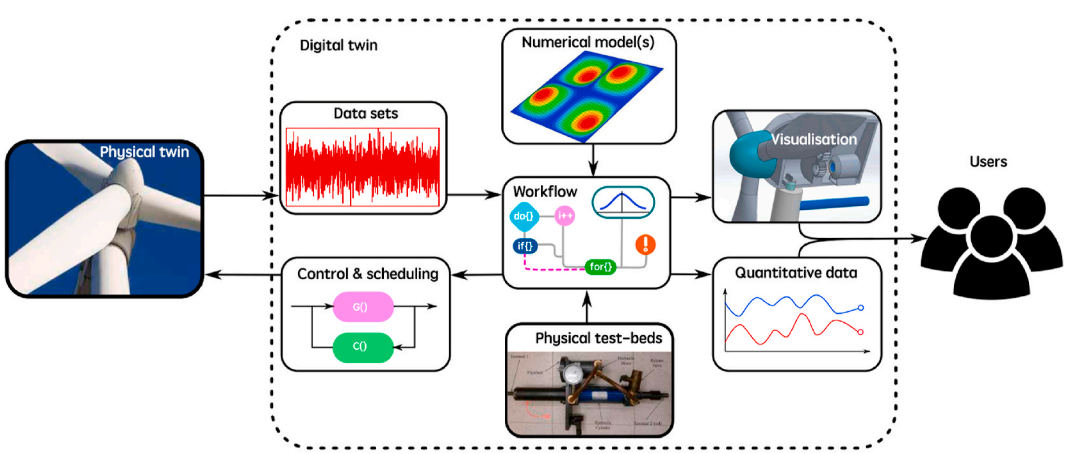

Fig. 11. *Example DT for a wind farm based on* [48].

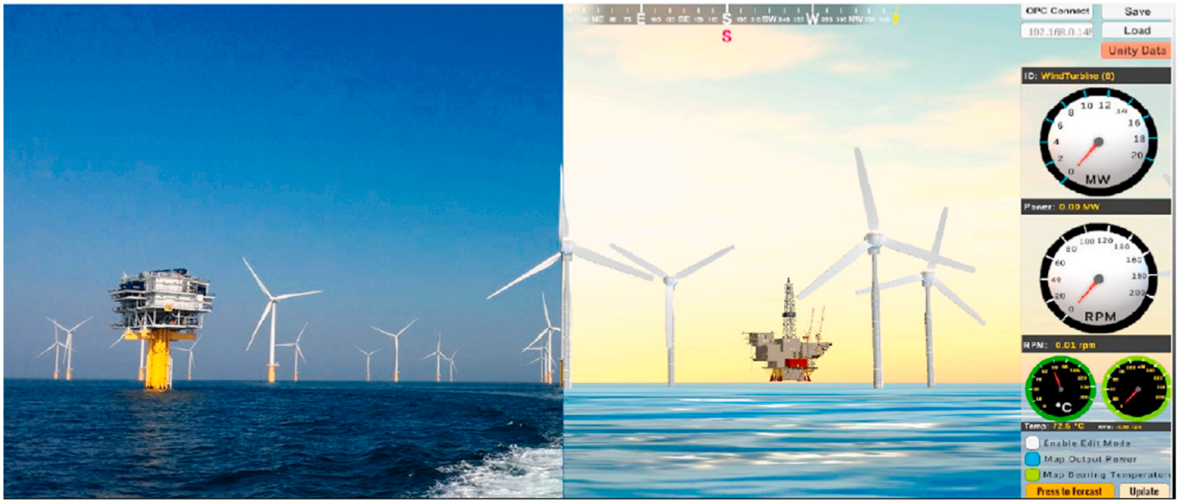

Fig. 12. *Predictive Digital Twin of Wind Farm by* Ref. [49].

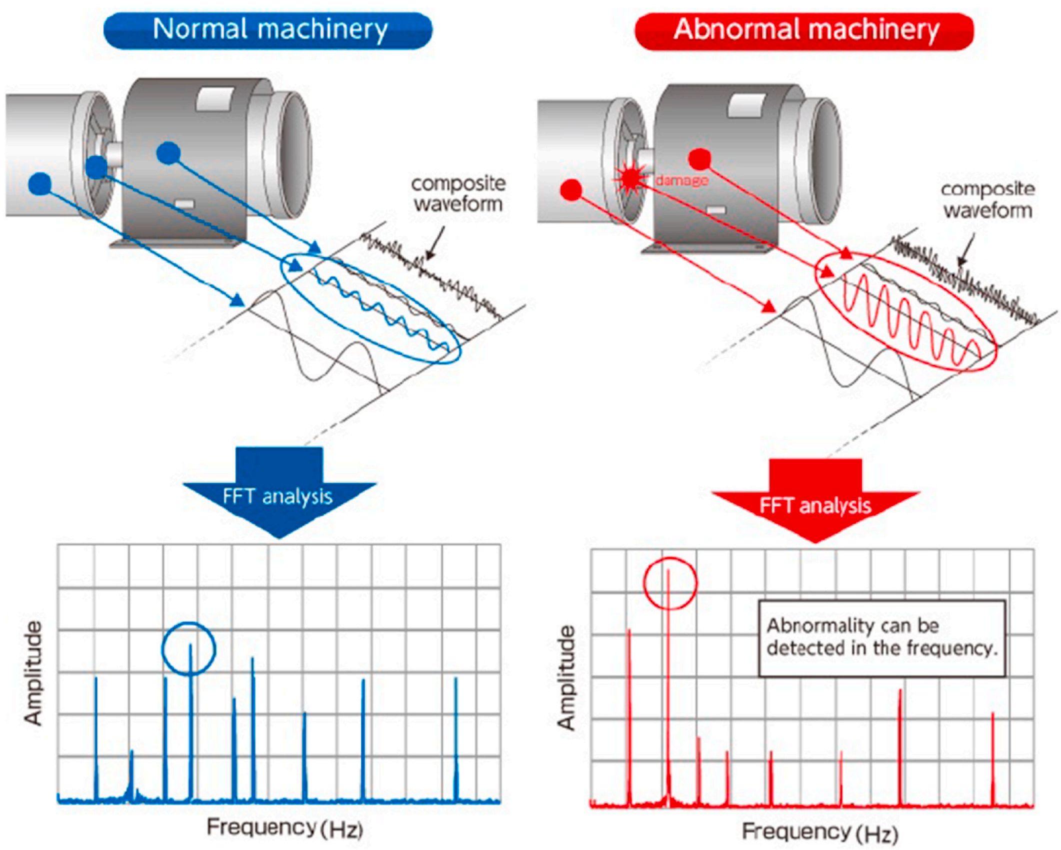

Fig. 13. *Example of showing abnormalities using the FFT method based on* [54].

technique in the 1960s. They used symmetries in the DFT calculation to minimise the required calculations.

5. Digital twin in thermal power plant

This section will explain how the digital twin is employed in thermal power plants. A digital twin model was constructed to exemplify the concept of a digital twin by simulating a coal-fired thermal power unit. This digital twin aimed to assess the power plant's operational performance and propose potential optimization methods to enhance the facility's economic performance [33].

Fig. 14 depicts a comprehensible digital twin, a physics-based numerical model capable of simulating the thermodynamic performance of a plant system. It can also compute the heat and mass balance of the entire system, as well as its subsystems and primary components, across various operating situations. In this study, the ThermoflowTM software suite is employed by the researcher. This software suite encompasses boiler, steam turbine, and emission control equipment models, which comprise selective catalytic reduction, electrostatic precipitator, and sea-water flue gas desulphurisation scrubber [32]. The digital replica was first set up and dimensioned to accommodate a 320 MWe base load, relying on the design specifications provided by the original equipment

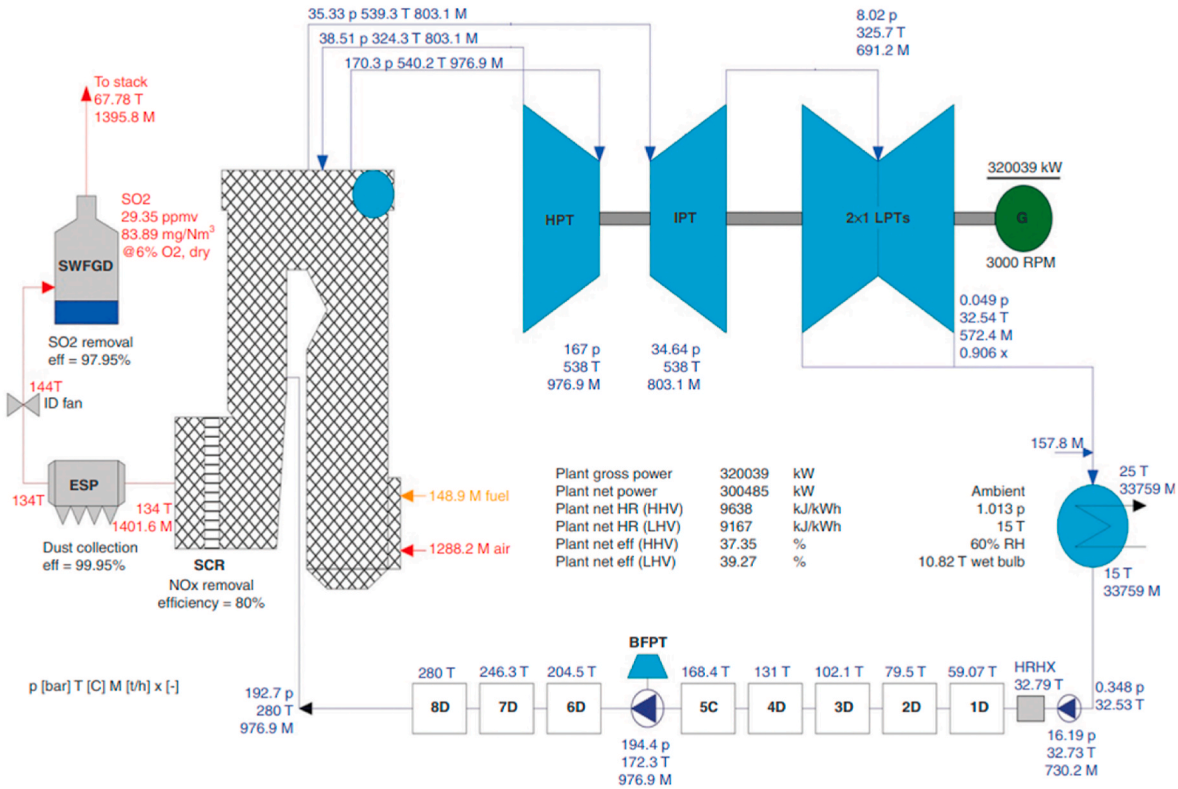

Fig. 14. *Example of DT architecture for thermal power plant by* Ref. [33].

manufacturer. Subsequently, it was fine-tuned by including real-time operational data obtained from the distributed control system of the power plant. The accuracy of the calibrated digital model was assessed by conducting simulations of different part-load operating scenarios, and it was found to closely match the power plant's actual performance. Consequently, the calibrated digital twin can replicate the power plant's operational performance across various operating situations.

Based on reference [55], a digital twin of the Nuclear Power Plant (NPP) was developed for fault diagnosis in a nuclear power plant. The digital twin of this NPP can generate deterioration data for machine learning. The use of the simulator as a dynamic reference was introduced in previous research by Cilliers and Mulder [56], who studied the behaviour of the control system of a nuclear power plant and used the data from the NPP simulator for fault detection. The framework of the digital twin of the NPP of [55] is shown in Fig. 15. The research outcome is that the digital twin could diagnose the faults related to nuclear power plants with minimal errors. Due to the lack of nuclear power plant data, the data is generated, representing more or less the actual plant data. Developing another framework to send sensor data into the simulator in future work is possible.

10. Digital Twin in the Power Transmission and Distribution Sector

Fig. 16 shows the communication system of the electrical digital twin network, which allows continuous connection between the individual components of the digital twin so that the performance and status of the power grid can be checked in real time [57]. The many sensors and data-gathering devices are linked to a central data acquisition card. These sensor nodes are interconnected by wired or wireless connections, employing several communication topologies. The communication network management system's responsibility is collecting and aggregating all data, functioning as a cloud platform for the digital twin network. The communication architecture effectively preserves the comprehensive digital twin framework as a SCADA workstation, wherein real-time data on the network's condition is methodically gathered. The gathered and organized data is transferred to the digital twin network's analysis, decision-making, and forecasting nodes. The updated data sequence is continually transmitted to the Programmable Logic Controller (PLC) and network control unit. The digital twin network employs dedicated data transmission methods within each data

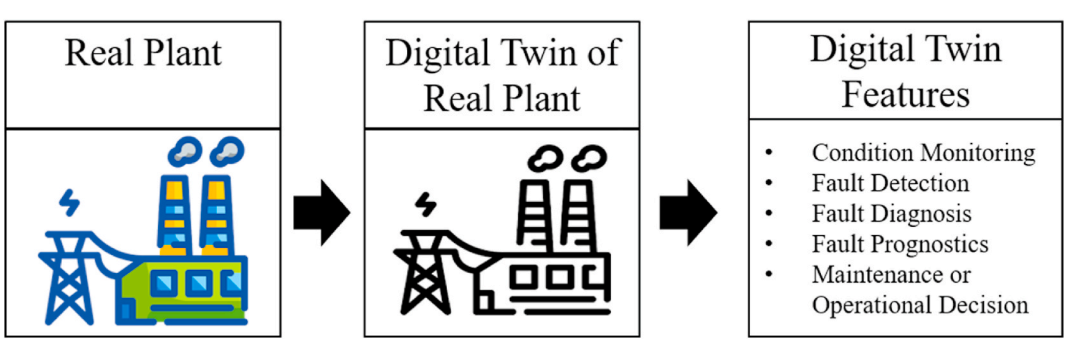

Fig. 15. *Framework for digital twin in a nuclear power plant by* Ref. [55].

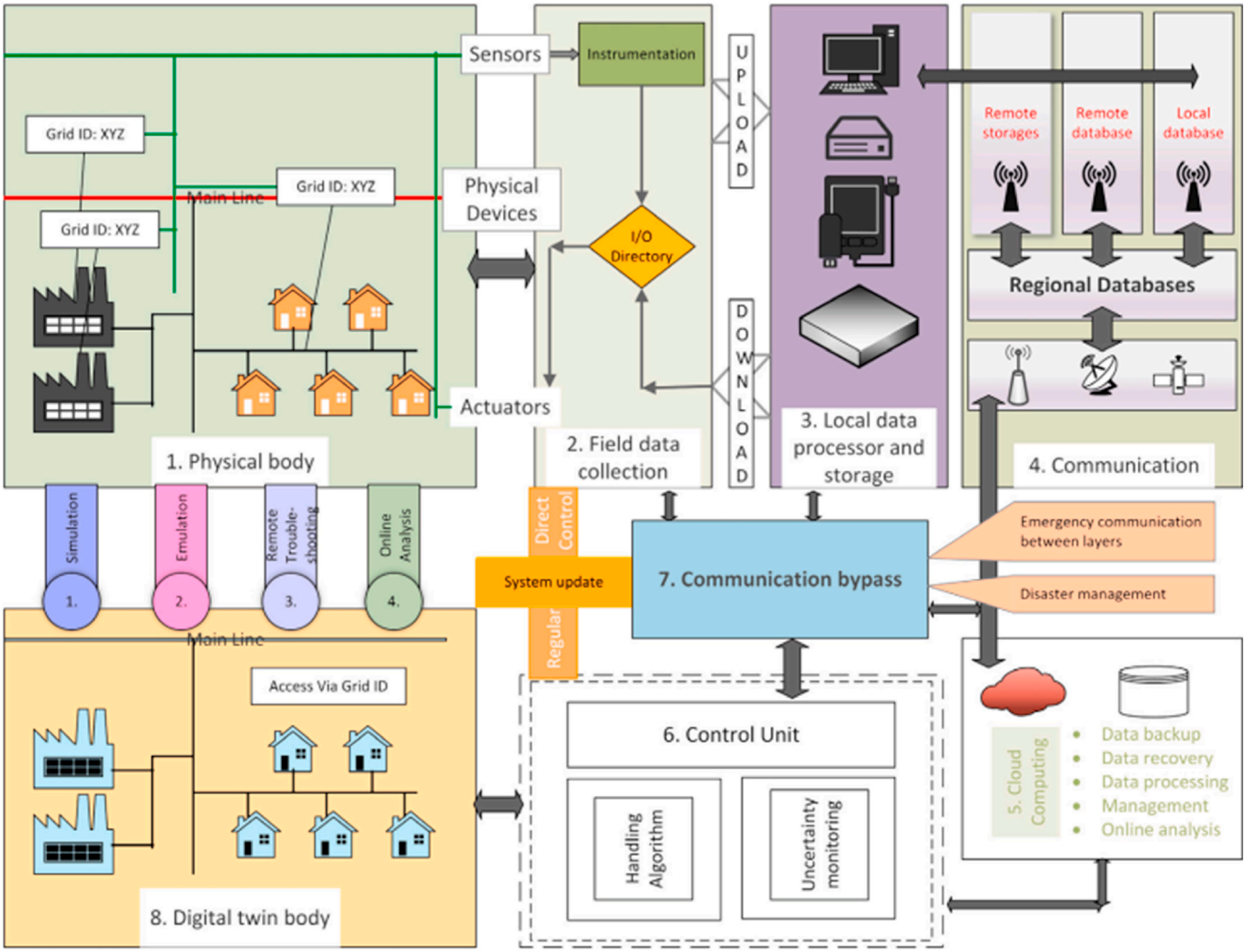

Fig. 16. *Conceptual framework of electric digital twin grid* [57].

bus to ensure the secure processing of real-time data.

Fig. 16 depicts the comprehensive conversion process from the physical realm to the digital twin network, encompassing all intermediary layers between the physical and digital twin networks. Conceptually, this is possible, but integrating with multiple sensors and communicating with multiple hardware and systems can be quite complex and requires experts to develop it.

Table 3 shows the protocols often employed for transmitting large-scale data, including MQTT, MMS (IEC61850), GOOSE, and OPC.

Table 4 shows a further explanation of these four protocols. MQTT is a good choice for applications where lightweight messaging and low bandwidth are essential. MMS (IEC61850), GOOSE, and OPC are good choices for industrial automation and process control applications where high speed, low latency, and reliability are essential.

The concept of twinning technology in electrical network management systems is illustrated in Fig. 17 [57]. The comprehensive conceptual framework of the digital twinning network illustrates the expected characteristics of the electrical digital twin, the methods for its operation, optimization and management of the power system, and the numerous adjustments that need to be made in the power system. This framework provides security for the grid, minimises transmission and distribution losses, reduces the likelihood of power outages, incorporates smart demand management, enables interaction between customers and consumers on a cloud platform, and enables rapid system restoration in the event of an outage while maintaining robust cyber

Table 3
Comparison table of the communication protocols.

Protocol	Description	Use cases
Message Queuing Telemetry Transport (MQTT)	The messaging protocol under consideration is specifically intended to cater to devices with limited resources and networks characterized by low bandwidth and high latency.	Telemetry and monitoring systems
Manufacturing Message Specification (MMS) IEC61850	A protocol used for the effective operation of substation automation systems.	Substation automation, energy management systems, and grid monitoring systems
Generic Object Oriented Substation Event (GOOSE)	A communication protocol designed specifically for substation automation systems, characterized by its high-speed and low-latency capabilities.	Protection and control systems in substations
Open Platform Communications (OPC)	The communication mentioned above protocols are designed to facilitate industrial automation and process control systems.	Data exchange between industrial devices and applications

Table 4
Detailed comparison of the protocols.

Feature	MQTT	MMS IEC61850	GOOSE	OPC
Lightweight	Y	N	N	Y
High speed	N	Y	Y	Y
Low latency	N	Y	Y	Y
Reliable	N	Y	Y	Y
Secure	N	Y	Y	Y
Scalable	Y	Y	Y	Y
Open source	Y	N	N	N

security measures. Although the concept is feasible, the author would face some challenges, such as accessibility to the energy utility company's network and assets and integrating the multiple sensors for all the relevant parameters. Cybersecurity issues need to be addressed first, as potential hackers may disrupt the digital system and cause severe damage to the company's assets.

Researchers in the field have developed numerous examples of various use cases of the digital twin. In 2022, Reza set up a digital twin of the power transformer protection relay with SIMULINK MATLAB that can sensitively and selectively detect internal faults [39]. The outcome of the work is that the system demonstrates the ability to detect turn-to-turn defects with a magnitude of three percent, even in the presence of substantial additive disturbances, within a brief timeframe.

Moutis has developed a digital twin system for monitoring the distribution transformer that focuses on the two most important parameters: voltage and current [38]. The system exhibits high calculation accuracy and effectively detects various system problems and harmonics content. The precision of the digital twin improves with higher sampling rates of the input LV waveforms and is similar to that of an instrument.

Power transformer life prediction has been developed based on current, voltage, flux leakage density and winding hotspot temperature [58]. It was found that the digital twin system could predict the remaining life with a 95% accuracy rate. Two researchers focused on a digital twin for simulation by creating a mathematical model using ANSYS Maxwell [35,36]. Through theoretical validation results, the simulation had an error rate of less than 5%. Another researcher also developed a digital twin of the transformer to evaluate the equipment online [59]. Next, the author [60] considers the condition of power transformers based on the gas composition in the insulating oil, the insulating oil test parameters and the electrical test parameters. Using finite element software, Delong could digitally visualise the three-phase voltage and current [61]. A virtual twin of an ultra-high voltage nuclear power plant was developed to visualise and optimise the plant [62]. Researchers utilizes digital twin to simulate their energy management layout (EML) for household DR employing Reinforcement Learning (RL) and Fuzzy Reasoning (FR) [63]. Table 5 summarizes the different purposes of the digital twin and related research.

11. Challenges and Limitations in Implementing Digital Twin Technology

Although digital twins can benefit energy power from diverse sectors, some known challenges and limitations need to be addressed first and are still a problem for researchers. Some of the main challenges and limitations of using digital twins in the energy supply industry are the following:

Table 5
DT application in the Power Transmission and Distribution Sector.

No	Digital Twin Use	References
1	Simulation	[35,36,39,62,63]
2	Asset Monitoring	[36,38]
3	Asset Health Evaluation	[58–60]
4	Visualisation	[61,62]

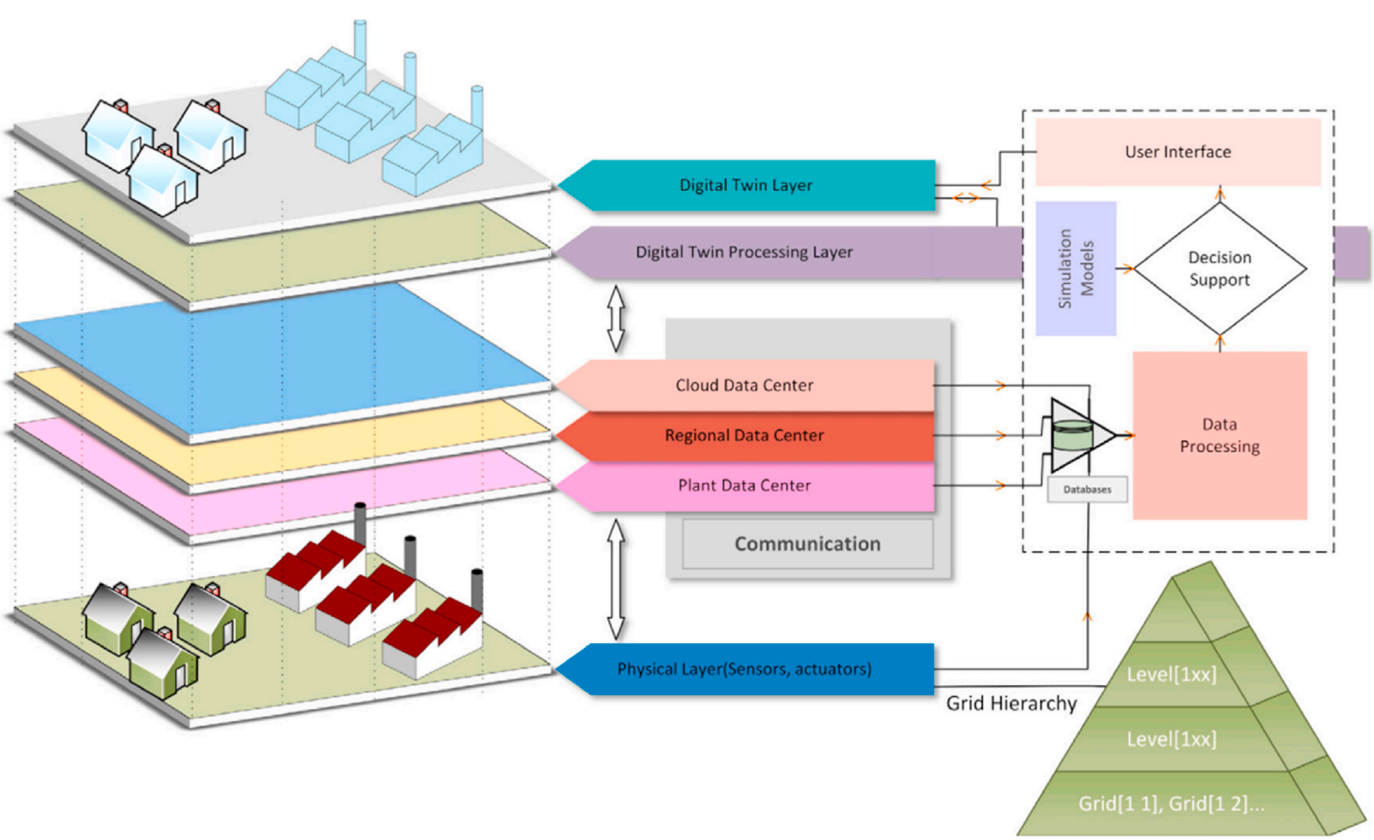

Fig. 17. *Electric digital twin grid concept by* Ref. [57].

- Cost and complexity [64]: Establishing and sustaining a digital replica of a power transformer may be intricate and labor-intensive, necessitating specialized software and knowledge. Consequently, it might incur significant costs and may not be viable for all power transformers, particularly those older or smaller. The cost associated with the digital twin is contingent upon several factors, including the digital twin software, the integrated software, as well as training and education [65].
- Data quality and availability [66]: The efficacy of digital twins relies on the presence of accurate and up-to-date data, enabling the accurate execution of simulations and predictions. The accuracy of the digital twin may be compromised if the data employed for its construction is insufficient, outdated, or of inferior quality. Furthermore, the effectiveness of the digital twin might be limited if there is a lack of access to real-time data. Data collection was one of the challenges faced during the deployment of the DUET Digital Urban Twin project. The initiative had challenges obtaining some data as private firms owned it, and there was limited accessibility to real-time data from the federal government [67,68].
- Integration with existing systems [69]: To optimise advantages, combining digital twins with other systems, such as monitoring and control systems, may be necessary. Implementing this endeavor might have intricacies and substantial financial implications, necessitating significant system modifications.
- Liability and legal issues [70]: The use of digital twins may raise legal and liability considerations, especially when the twin is utilized to make decisions that affect the operation of the power transformer. Therefore, it is crucial to exercise prudence and get advice from legal experts in order to resolve these issues effectively. Currently, airports are acquiring personal data to utilize it to foster the digital environment. However, this situation raises legal considerations since it is essential for individuals to understand the particular data they are collecting and the intended goals for its use [71].

Although digital twins can benefit power transformers, their use has challenges and limitations. These issues must be carefully addressed to ensure digital twins' successful implementation and use in the power industry.

Table 6
Interrelations summary of digital twin application for various sector in the energy industry.

Aim	Reference	Research Gaps
Asset operation optimization	Photovoltaic Power Plant- [27] Hydro Power Plant- [19,44] Wind Power Plant-NA Thermal Power Plant- [33] Power Transmission and Distribution- [57,62,72–74]	Lack of research on asset operation optimization for wind power plants.
Asset Fault Diagnostics	Photovoltaic Power Plant- [40] Hydro Power Plant-NA Wind Power Plant-NA Thermal Power Plant- [55,56] Power Transmission and Distribution-NA	Lack of research on asset fault diagnostics for hydropower plants, wind power plants and power transmission and distribution. This could be due to a lack of faulty data for research.
Asset Monitoring	Photovoltaic Power Plant- [43] Hydro Power Plant- [45] Wind Power Plant-NA Thermal Power Plant-NA Power Transmission and Distribution- [38,57,58]	Lack of research on asset monitoring for wind and thermal power plants. Integrating sensors into the system could be quite challenging.
Asset Controlling	Photovoltaic Power Plant- [43] Hydro Power Plant-NA Wind Power Plant- [48] Thermal Power Plant-NA Power Transmission and Distribution- [57]	Lack of research on asset monitoring for hydropower plants and thermal power plants. Integrating sensors into the system could be quite challenging.
Asset simulation	Photovoltaic Power Plant- [28,29] Hydro Power Plant-NA Wind Power Plant- [48,49] Thermal Power Plant- [20] Power Transmission and Distribution- [35,36,39,59–62]	Lack of research on asset simulation for hydropower plants. Getting raw data for simulation is scarce and thus can only generate data for testing.

12. Further Research Insights

In order to offer a cohesive understanding of the current trajectory of digital twin applications for diverse sectors in the energy industry, an interrelation summary is conducted and shown in Table 6. This table captures the seminal studies that have redefined the narrative around digital twin applications for diverse sectors in the energy industry. Different energy sectors have other objectives when it comes to applying digital twins. In addition, the analysis below shows what researchers have not covered in using digital twins in various sectors. Hence, it was essential to highlight these gaps along with the researchers' aim to clarify further and motivate this work.

In summary, the findings from the analysis of Table 6 indicate that the creation of a digital twin for asset simulation is deemed viable based on the research papers referenced [18,26,27,33,34,37,46,47,57–60], except the Hydro Power plant sector. The potential reasons for this phenomenon may be attributed to a lack of available data or concerns around data confidentiality. Authors from Refs. [36,55,56], and [55] have the potential to collaborate in the power transmission distribution sector by integrating the functionalities of monitoring and controlling through the utilization of digital twin technology. This would augment the existing research gap and ultimately contribute to developing a more optimized and robust system within that specific industry. The primary finding derived from Table 6 indicates that implementing digital twin technology is feasible across several energy sectors. Numerous researchers have made valuable contributions in this area, resulting in favorable outcomes. Table 6 provides insights into the potential deduction that can be made for the development of strategies aimed at ensuring a successful application of digital twin technology, which is descripted as follows:

- To begin, it is essential to establish a well-defined vision and set of goals. What are your anticipated objectives in using your digital twin? Would you like to enhance operational efficiency, decrease expenses, or enhance asset performance? Once an individual comprehends their objectives, they may start formulating a strategy for execution.
- One must ascertain the appropriate data sources. Digital twins rely on data; hence, it is crucial to ascertain relevant data sources and guarantee the accuracy and timeliness of the data. Data can be obtained from diverse sources, including sensors, meters, and SCADA systems.
- Select the appropriate digital twin platform. Various digital twin platforms exist, so selecting a platform that aligns with one's specific requirements is crucial. When choosing, considering many elements, such as pricing, features, and scalability, is essential.
- One should endeavor to create a digital replica of the system. After identifying appropriate data sources and selecting a digital twin platform, the subsequent step involves developing a digital twin of the power distribution system. The procedure will entail the development of a digital representation of the system, followed by incorporating real-world data into this model.
- Undertake the process of validating and refining the digital twin. After creating a digital twin, it becomes imperative to undertake the

process of validation and refinement in order to ascertain its accuracy and currency. The process involves comparative analysis between the digital twin and the actual real-world system and implementing necessary modifications.
- The utilization of the digital twin might enhance the performance of your system. After successfully validating a digital twin, it becomes feasible to leverage its capabilities in improving the power distribution system. The digital twin may be utilized to simulate various situations and determine the optimal operational approach for the system. The digital twin can also identify and forecast issues before their manifestation.

6. Conclusion

This study conducts an in-depth analysis of the current advancements in digital twin deployment and underscores the anticipated surge in research and development efforts in the near future. Furthermore, it observes that several prominent corporations are actively championing the adoption of digital twin technology across various industries by offering compatible software solutions. This article explains the extensive utilization of digital twins in diverse domains within the electric utility sector, emphasizing the imperative need to embrace this technology for achieving operational and economic benefits.

Section 1 introduces the energy sector and the concept of digital twins. Section 2 provides a comprehensive overview of the methodologies employed in the systematic evaluation presented in this study, with a specific focus on the application of digital twin technology within the energy industry. Addressing question 1, Section 3 demonstrates substantial client base growth for several firms through the implementation of cutting-edge digital twin software in various domains. Additionally, Section 4 highlights the availability of commercially viable digital twin software solutions catering to diverse aspects of power systems. Researchers can potentially leverage this software in both academic and industrial settings to advance their digital twin implementations.

Section 5 underscores the favorable reception of digital twin technology across various domains of power systems, with a particular emphasis on power transmission and distribution. Addressing question 2, Sections 6 through 10 detail the implementation of digital twin technology across renewable and non-renewable energy sectors. Finally, question 3 is addressed in Section 11, which delves into the obstacles that must be overcome for the successful utilization of digital twin technology.

In response to these findings, the authors of this paper put forth several recommendations for researchers or companies aiming to establish their digital twin within their respective industries.

First and foremost, it is crucial for researchers or organizations to clearly define their objectives when developing their digital twin application. Moreover, creating an open-source database containing information on power plants would prove beneficial to researchers, particularly when they require validation of the operational efficacy of their digital twin. This encompasses the integration of advanced analytics, exploration of decentralized energy systems, implementation of enhanced cybersecurity measures, and alignment with sustainability objectives.

The authors seek to contribute to the power distribution industry by proposing the development of a digital twin-based monitoring and control system for on-load tap changers in transformers, recognizing the lack of existing literature on this specific topic. The feasibility of this task lies in the precise identification and monitoring of crucial parameters governing the operational condition of on-load tap changers in transformers. The mechanical components will be regulated based on sensor data through relay signals.

By adhering to the suggestions outlined above, understanding inherent limitations, and aligning with emerging research trends, it is imperative to recognize that these actions will play a pivotal role in fully harnessing the capabilities of digital twins. This, in turn, will facilitate the optimization of energy supply operations and promote sustainability within this vital and ever-evolving industry.

Declaration of competing interest

The authors declare no conflicts of interest.

Data availability

No data was used for the research described in the article.

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