Technologies and Applications of Digital Twin for Developing Smart Energy Systems

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Abstract: Smart energy strategies can facilitate the development of an energy-sharing platform that is interconnected, transparent, and mutually beneficial. Digital twin technology can circumvent technical and market barriers associated with the implementation of smart energy policies. However, this technology is still in its infancy and there is insufficient research on its development and application; a systematic research framework has not yet been formed. This study aims to promote the application of digital twin technology to the smart energy industry by examining the development of this approach in China and abroad, in addition to discussing its future development paths. We compare the definitions and applications of digital twin technology in different fields, define digital twin for smart energy systems, and discuss its general architecture, key technologies, and ecosystem construction. Moreover, application cases are briefly analyzed. Furthermore, countermeasures are proposed based on three aspects: technology development, ecological construction, and policy establishment. This study aims to provide a reference for engineering applications of digital twin technology in the smart energy industry.

Keywords: smart energy; digital twin; general architecture; energy ecosystem

1 Introduction

With the advancement of digital technology and the deepening of China's power system reform, the acceleration of energy transition has become an industry consensus. However, there are institutional, technological, and market barriers in the energy industry that impede the energy transition process. The National Energy Administration has proposed a smart energy strategy to build an energy-sharing platform that is interconnected, transparent, open, and mutually beneficial to address the common barriers in the energy industry [1]. Digital twin technology can facilitate a precise connection between the physical world and the digital world, and is a potential solution to the technical problems associated with the development of smart energy. Moreover, it supports accurate simulation and control of energy interconnection networks from multiple angles. However, the definition and application architecture of digital twins in the smart energy industry requires further investigation. Furthermore, the application test of digital twins for energy systems is only in the preliminary verification and exploration stage, which involves research on digital twin modeling of the energy systems of substation equipment, power transmission networks, and thermal power plants [2–4].

This research focuses on digital twins for the development of smart energy systems, investigates the demand for digital twins in the field of smart energy in addition to the research status and trends in China and abroad, explores the definition and general architecture of digital twins for smart energy systems, and analyzes the key technologies and ecological construction of digital twins for smart energy systems. On this basis, deployment and application case studies of digital twins for the smart energy industry are investigated, and the development direction and application

trend of digital twins for the smart energy industry are predicted.

2 Demand analysis of digital twin for smart energy systems

2.1 Macro demand analysis

The *Decision of the Central Committee of the Communist Party of China on Several Major Issues Concerning Upholding and Improving the Socialist System with Chinese Characteristics and Promoting the Modernization of the National Governance System and Governance Ability* that was proposed on November 2019 requires the promotion of the energy revolution and the building of clean, low-carbon, safe, and efficient energy systems. The *Thirteenth Five-Year National Strategic Emerging Industry Development Plan* proposes to cultivate new businesses and formats based on smart energy, and to build a new energy consumption ecology and industrial system. As such, the ecosystem of the energy industry is undergoing profound changes in China.

At present, COVID-19 has negatively affected the development of the economic and energy industry in China. Specifically, coal, natural gas, electricity, and new energy industries have been affected to some extent. This does not change the requirements of China's energy systems with respect to achieving the goal of energy transition. The fundamental changes in energy production and utilization methods urgently require a new generation of digital technologies as key support.

2.2 Technical demand analysis

Energy supply in China is shifting toward decentralized production and network sharing, but there are still institutional, technical, and market barriers in the energy industry. Moreover, there are many problems associated with opacity and the lack of information sharing on the energy supply, transmission, and consumption side. The Internet Plus smart energy strategy proposed by the National Energy Administration aims at using modern information technologies to develop an interconnected, transparent, open, and mutually beneficial information network platform, obviating the existing asymmetric information relationship between production, transmission, distribution, and use of energy to advance the revolution of energy production and consumption patterns, and to reconstruct the ecosystem of the energy industry. The implementation of this strategy requires energy systems to implement in-depth digital transition. Moreover, the use of new technologies to facilitate digital transition is an urgent need.

Emerging technologies such as cloud computing, artificial intelligence (AI), big data, and digital twins have introduced new momentum to the innovation and transition of the energy industry, which supports the acceleration of the digital transition of energy systems.

The development of a smart energy ecosystem is the trend of China's energy industry, and the digital twin technology system that integrates the Internet of things (IoT), communication technology, big data analysis technology, high-performance computing technology, and advanced simulation analysis technology is key to solving the problems associated with the development of smart energy. Based on existing energy system modeling and online monitoring technology, the digital twin technology system further involves state perception, edge computing, intelligent interconnection, protocol adaptation, intelligent analysis, and other technologies, providing more abundant and authentic models for the smart energy system, thus fully serving the operation and control of the systems.

3 Research status and trends in digital twin for smart energy systems

In recent years, there has been rapid development in research on the theory and application of digital twins [5]. General Electric (GE) and the University of Cincinnati have applied digitization to the entire process from design to maintenance and the optimization of production. However, they have not achieved a unified model for digital twins [6]. The American ANSYS company proposed the ANSYS twin builder to create a digital twin that can be quickly connected to the industrial IoT, which is used to improve product performance, reduce the risk of unexpected downtime, and optimize the next generation of products [7]. A digital twin reference model has been proposed [8], which facilitated a comprehensive description of the product lifecycle at the conceptual level. In related studies, a multi-mode data acquisition method was employed, which coupled a production system with a database, and facilitated state perception and analysis in digital twins [9].

Compared to the rapid development in foreign countries, research in China on digital twins is still in its infancy [5]. A digital twin design framework has been proposed to describe complex products and to explore the key

technologies in the development process [10]. Researchers have also introduced the concept of a five-dimensional model and considered its application in ten different fields [11]. Moreover, the similarities and differences between big data and digital twins from multiple angles have been analyzed, in addition to the promotion of the realization of intelligent manufacturing [12]. In another investigation, the key technologies of digital twins in cyber-physical systems were summarized, and a realization approach for digital twins in the product lifecycle was proposed [13].

The application of digital twins in various fields is developing rapidly. However, in the energy industry, this technology is primarily in the exploration and verification stage. Dassault is committed to research on digital twin simulation modeling of electrical equipment, and has built an interactive platform between users and designers [14]. The research team of Shanghai Jiao Tong University established a power flow model of the power grid in a digital twin and verified its technical feasibility [2]. Based on the Flownex software, the Pera Global Digital Twin Laboratory established a digital twin thermal power plant model [3], which served as a technical reference for the engineering design and maintenance of thermal power plants. A team from Tsinghua University used the digital twin CloudIEPS platform to implement a digital twin integrated energy system model, which facilitated enhanced functionality and cost reduction [4].

It is generally believed that digital twin technology is suitable for modeling complex systems with asset-intensive and high-reliability requirements. This technology has gradually been applied to many industrial fields, especially in manufacturing. The smart energy system is a comprehensive and complex system that integrates multiple energy sources, which is highly compatible with the application of digital twins. However, the current application and development of digital twin technologies in smart energy is relatively fragmented, and there is no established framework for their application and implementation.

4 Definition and architecture of digital twin for smart energy systems

4.1 Definition of digital twin technologies for smart energy systems

Digital twin technologies were initially utilized in the military and aerospace industry. Its basic concept was proposed by Professor Greives in the product lifecycle management course at the University of Michigan in 2003 [15]. Digital twins can be traced back to the aircraft fuselage digital twin definition proposed by the Air Force Research Laboratory (AFRL) in 2009. The definitions of digital twins by scientific research institutions in 2009–2019 are shown in Table 1.

Table 1. Comparison of the definitions of digital twin.

Organization (Year)	Definitions
AFRL (2009)	Fuselage digital twin is an integrated system of data, models, and analysis tools to represent a fuselage over its entire lifecycle to provide actionable information for making decisions now (diagnosis) and for the future (prognosis) on a fleet-wide and individual tail number basis considering all sources of uncertainty.
GE (2015)	Digital twin is a software representation of assets and processes that are used to understand, predict, and optimize performance in order to achieve improved business outcomes. Digital twin consists of three components: a data model, a set of analytics or algorithms, and knowledge.
IBM (2017)	A digital twin is a virtual representation of a physical object or system across its lifecycle, using real-time data to enable understanding, learning, and reasoning.
Pera Global (2019)	Digital twin is a digital model of existing or future physical entity objects to perceive, diagnose, and predict the state of physical objects in real time through measurement, simulation, and data analysis, regulate the behavior of physical objects through optimization and instruction, use mutual learning between relevant digital models to evolve themselves, and improve the decision-making of stakeholders in the lifecycle of physical objects.

IBM: International Business Machines Corporation.

Based on a wide variety of descriptions, the definition of digital twins for smart energy engineering applications is summarized as follows: Digital twins exploit refined physical models, intelligent sensor data, and operation and maintenance history data, and integrate the simulation of multi-disciplinary, multi-scale, and multiple probabilities in electromagnetism, heat, fluid, and other disciplines, to complete the mapping of smart energy systems in a virtual space. Digital twins reflect the entire lifecycle process of corresponding smart devices, which can be updated and dynamically evolved in real time, thereby realizing the true mapping of smart energy systems.

4.2 Architecture and characteristics of digital twin technology for smart energy systems

This report presents an architecture utilizing digital twins for smart energy systems. The architecture is divided into five layers according to the characteristics of smart energy systems (Fig. 1): the physical layer, data layer, mechanism layer, presentation layer, and interaction layer. The data layer first collects a large amount of data from the physical layer, preprocesses and transmits the data; the mechanism layer receives multi-scale data (including historical and real-time data) from the data layer, which is inputted into the simulation model via the "data chain" for data integration and simulation operation; the presentation layer obtains the simulation results from the mechanism layer and presents this information to users in an immersive manner. The interaction layer can realize precise human–computer interaction. The interactive instructions can be fed back to the physical layer to the control equipment and also act on the mechanism layer to realize the update and iterative growth of the simulation model. The characteristics of the corresponding layers are described as follows:
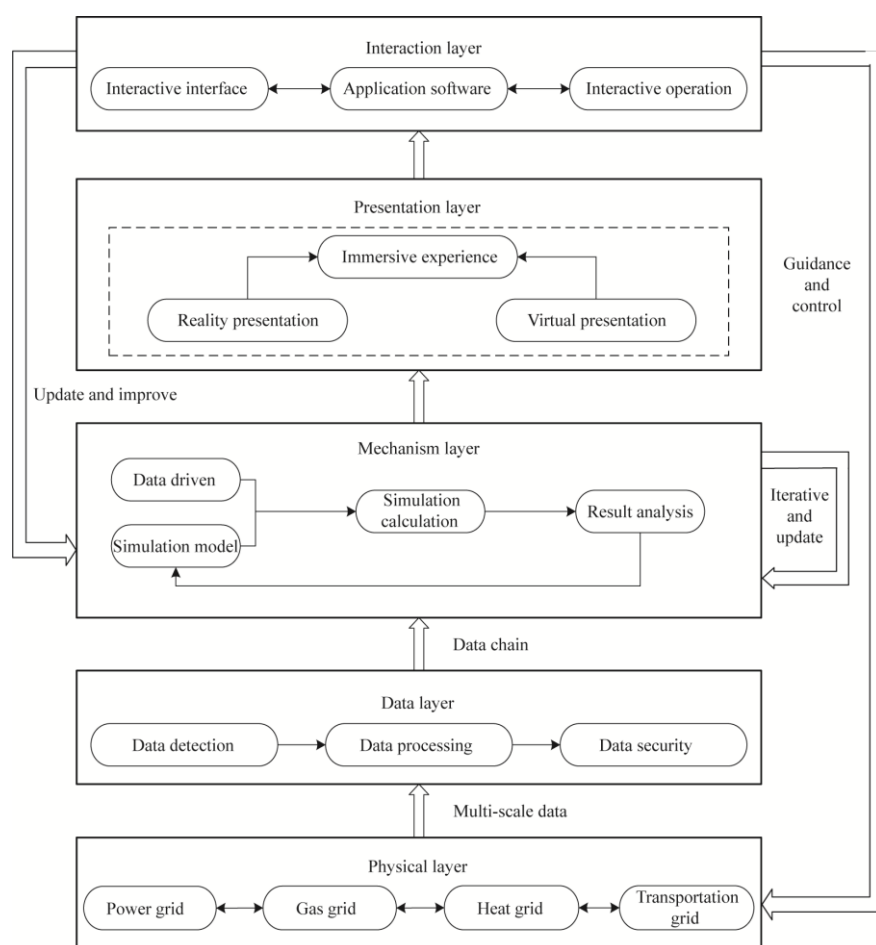

Fig. 1. Digital twin architecture for smart energy systems.

4.2.1 Physical layer

In conventional condition monitoring, sensors are installed on energy equipment, and data are collected via acquisition software. However, it is difficult for decentralized data acquisition systems to interact. Based on the energy IoT platform, the physical layer collects multi-mode and heterogeneous data by applying advanced sensor technologies in various intelligent devices, and integrates massive datasets such as physical perception data, model generation data, and virtual reality fusion data. It also supports cross-interface, cross-protocol, and cross-platform interaction, which can realize interconnection and intercommunication among various subsystems in energy systems.

4.2.2 Data layer

Conventional condition monitoring only focuses on sensor data, whereas digital twins consider multi-dimensional data throughout the life cycle of intelligent devices. The data layer realizes the data cleaning and normalizing in real time on the local side of each intelligent device, and uses high-speed, high-capacity, low-delay communication lines

for transmission. Moreover, by utilizing cloud computing and data centers, it can dynamically meet various computing, storage, and operational requirements.

4.2.3 Mechanism layer

The smart energy system simulation model constructed based on digital twin uses the hybrid modeling technology of "model-driven + data-driven," adopts the modeling methodology of system engineering, utilizes "data chain" as the main line, and combines AI to update and iteratively optimize the system model to realize real virtual mapping. The model has guiding values for the selection, design, and manufacture of smart devices, which is not limited to decisions related to repair or replacement based on data changes.

4.2.4 Presentation layer

Digital twins apply the 3R technology of virtual reality (VR), augmented reality (AR), and mixed reality (MR) to establish a virtual model of energy systems with high visualization capability, which improves the visual display effect [16]. The use of computer-generated visualization, listening, olfactory, and other sensory signals to integrate real and virtual information can enhance the user's experience and participation, and technicians gain more intuitive and useful insight into the information and connections of smart devices.

4.2.5 Interaction layer

The virtual model of smart energy systems based on digital twins is not only a traditional planar or a simple three-dimensional display, but also facilitates real-time deep interaction between users and models. Using voice, posture, visual tracking, and other technologies, a channel between users and smart devices is established. This can realize accurate interaction via multiple channels to support efficient, accurate, and interactive control of multi-energy coupling energy systems including the power grid, gas grid, heat grid, transportation grid, and water grid.

Overall, digital twins are neither a simple numerical simulation tool, a conventional state perception method, nor a simple data analysis technique such as AI or machine learning. Instead, it is a technology that integrates these three aspects organically. The approach facilitates digital modeling of energy systems and realizes information interaction between the digital space and the physical space. First, it makes predictions by applying complete information and a clear mechanism. It then develops to speculate on future outcomes based on incomplete information and the uncertainty mechanism, and finally realizes twins' wisdom among the digital twin models for energy systems.

5 Key technologies of digital twin for smart energy systems

5.1 Digital twin service platform based on cloud–edge interaction

By including a large number of physical equipment in many fields, the development of data collection for smart energy systems can be diversified, and the amount of data is exponentially increased. A conventional data service platform can no longer meet the requirements of rapid and accurate data processing. Therefore, a cloud–edge collaborative digital twin service platform is necessary. The edge side uses smart devices to perform local calculations, whereas the cloud side integrates various data for calculation. Using the "data chain", general algorithm libraries, and model libraries, it can realize the efficient and collaborative analysis of multi-source heterogeneous data, which lays the foundation for applications of digital twin.

5.1.1 Design of "data chain" for smart energy systems

The structure, manufacturing process, performance, and operating parameters of each equipment component of smart energy systems influence the services of systems operations. The entire "data chain" design based on acquisition, transmission, analysis, and output, needs to determine the mapping relationship between the "data chain" and the entire lifecycle process. By studying the relationship between the "data chain" and the design cloud, production cloud, knowledge cloud, detection cloud, and service cloud of the entity and virtual model, the description and design methods of the entire lifecycle "data chain" can be determined using the database and machine learning. Fig. 2 shows the collection, transmission, and analysis process of the "data chain", which is used to realize vertical penetration of the data and the closed-loop accurate interaction of knowledge.

5.1.2 General intelligent algorithm library for cloud–edge services

Establishing an accurate and dynamically expandable intelligent algorithm library for cloud–edge services can accelerate the speed of distributed computing in smart energy systems to achieve efficient use of network, computing, storage, and other computer resources. The algorithm library is under a generic design framework that is thoroughly

tested and sufficiently verified. This includes data cleaning algorithms, performance degradation feature extraction algorithms, and state trend prediction algorithms. In particular, professional algorithm application deployment based on the edge–cloud collaborative system can realize instantiation verification and iterative growth of professional algorithms.
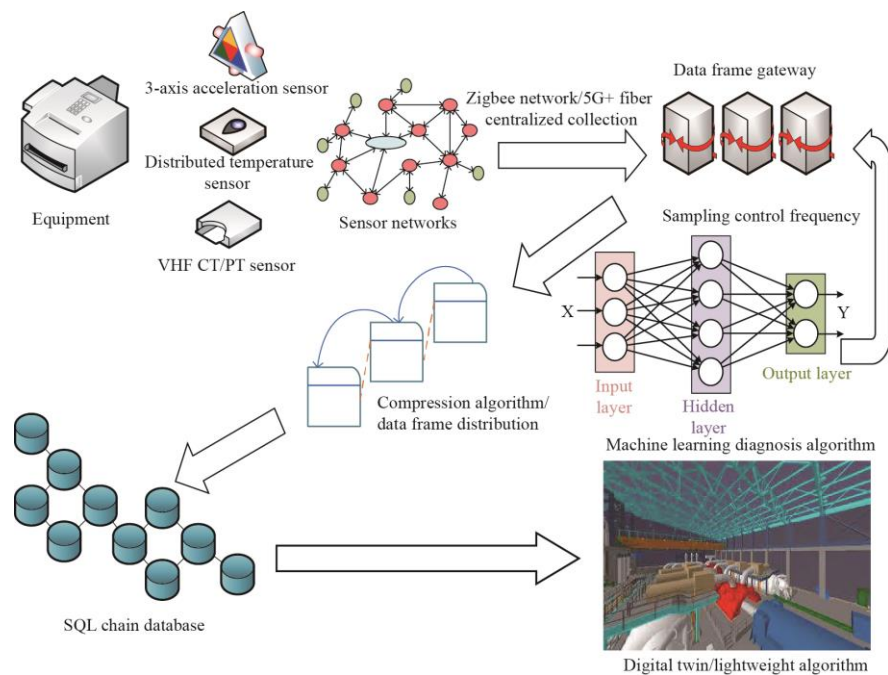

Fig. 2. Collection, transmission, and analysis of the equipment data of the "data chain."

5.1.3 General detailed model library for smart energy systems equipment

The detailed model library of smart energy system equipment can facilitate detailed and personalized modeling. The cloud–edge data interaction mechanism is constructed to provide the required data and interactive interface for digital twin models that realize vertical penetration of data. It is essential to investigate cloud and edge multi-dimensional data reduction and merging technologies, design complex event processing engines, and develop energy system model libraries, to realize horizontal integration of services.

5.2 Efficient simulation and hybrid modeling technologies for smart energy systems

A smart energy system is composed of multiple systems including mechanical, electrical, and information systems, which requires comprehensive and realistic models and simulations from the perspective of multi-physics and multi-scale. During the transmission and loading of virtual and real information onto various digital twin models, the hybrid driven mode of "model-driven + data-driven" should be adopted for high precision simulations. Under complex working conditions, it can predict and analyze the performance of energy systems from the component and system level in a virtual environment.

5.2.1 Modeling and simulation based on multi-physics and multi-scale technologies

Due to the complexity of smart energy systems, researchers should not only consider the effects of a single physical field or one-dimensional scale data, but should also consider the coupling relationship between multi-scale and multi-physical fields. Finite element simulation methods can be applied to build multi-physical and multi-scale simulation models, including electricity, heat, magnetism, and force, which can reflect historical, real-time, and future effects. It supports engineers in analyzing and evaluating the simulation models of smart energy systems from different perspectives.

5.2.2 "Model-driven + data-driven" modeling technologies

The uncertainty and complexity of smart energy systems are well-known. However, existing state analysis normally establishes a simplified mechanism model in advance, and simplified constraints are introduced in a practical application. As such, it is impossible to obtain models that meet the performance requirements in a complex environment. The conventional data-driven method cannot describe the objective physical law constraints, so the single use of model-driven or data-driven methods cannot satisfy the intelligent and temporal requirements of energy

systems. Based on the "model-driven + data-driven" hybrid modeling technique, the problems related to the imbalance and lack of original data categories can be addressed using category balancing algorithms, strategy networks, and value network data learning. The inversion and parameter identification method based on cost-sensitive learning and machine learning can overcome the shortcomings that it is hard to model using the mechanism mode and some features are easy to be ignored. The integrated learning algorithm of such a hybrid modeling technique can improve the generalization ability of system operation state evaluation.

5.3 Information security defense mechanism of digital twins

The subsystems in smart energy systems are connected via a cyber network, which is highly network dependent. The reliability of information exchange determines whether the system can operate normally. Any equipment security issue may cause data leakage of the entire system. Considering potential malicious attacks and tampering risks encountered by smart energy systems, it is necessary to study network attack detection and defense technologies to enhance the security of smart energy system operations.

5.3.1 Multi-model detection technique based on low-level classification module

Based on the multi-source sensor information transmitted by smart energy system terminals, the ability of AI to extract and measure attack characteristics can be improved, and the generalization ability of the model can be strengthened. For the underlying incremental classification library of multiple classification models, the integrated output modules of the classification results can be constructed to achieve accurate detection of data integrity attacks.

5.3.2 Constructing characteristic attribute sets related to data integrity attacks

For smart energy systems, the temporal and spatial coupling physical characteristics of digital twin models and parameters can be extracted. By targeting the network data that contains multi-source heterogeneous information transmitted via terminals, AI-based feature extraction algorithms can be developed to dynamically optimize the selection of the optimal feature attribute set related to data integrity attacks, which can extract its embedded model features.

5.3.3 Establishing an access mechanism for security risk assessment

By using AI, statistics, and information theory, the access mechanism for security risk assessment can be established. The big data technique can be applied to analyze each subsystem connected to the smart energy systems, and to quantify its information security risk. If the risk value of a subsystem is higher than a set threshold, the access of the subsystem is restricted, which can realize access control based on security risk assessment.

5.4 Immersive visualization and interactive technologies of smart energy systems

In contrast to the conventional mathematical simulation model, a digital twin model emphasizes the interaction between the virtual world and the real world, which is updated and dynamically evolved in real time to realize dynamic and realistic mapping of the physical world. The immersive visualization technique can help users to observe the real world more vividly, thoroughly, and richly. It can be divided into algorithm visualization and model visualization.

5.4.1 Visualization techniques of algorithm application results for smart energy systems

Digital twin visualization techniques include not only typical visualization techniques, such as graphical displays, queries, parameter update interfaces, but also graphical displays of component attribute data, status data, prediction data, and evaluation data. Based on the properties and the graphical interface associated with components, it can facilitate visualization and interaction with its component model interface.

5.4.2 Human–computer interaction based on 3R technique

The conventional simulation model is typically displayed in a 2D format, which is limited to displaying the state of physical entities to users via charts. Based on the 3R interactive technique and the use of visual display components, a 3D virtual space can be simulated, which can present the physical equipment to users in a pseudo-real environment. During the operation on a virtual entity, it can realize the control of the physical entity, information network, and simulation model indirectly, which greatly expands the users' sensory experience and obtains real feedback from system operations.

5.5 New application mode of scalable digital twin technology

The implementation of digital twin interaction technology improves the interaction between humans and computers. This technology can add new capabilities or expand existing functionality for physical entities by combining the simulation results, in addition to realizing the feedback and control of the design, operation, and maintenance process. Moreover, it can achieve an accurate description and behavior prediction of physical entities and virtual simulation models. On this basis, a series of new application modes for digital twins can be provided.

5.5.1 New operation and maintenance mode for smart energy systems based on digital twin

Based on the scalable "virtual and real synchronization" operation and maintenance service platform for smart energy systems, the typical operation and maintenance requirements of the entire lifecycle can be obtained. In response to individual needs, mobile applications (APPs) can be developed using customized operation and maintenance services, thus to form a variety of new remote operation and maintenance modes. For example, targeting the problems of the long development cycle and the high testing cost of new products in smart energy systems, research, and development of remote virtual simulation test techniques can be developed to explore new models for testing and inspection services.

5.5.2 APPs for the application of smart energy systems

Smart energy systems are multi-dimensional and heterogeneous, and have multi-domain, multi-level, and multi-unit characteristics. A deep interactive APP can improve the management and optimization control capabilities of smart energy system equipment.

5.5.3 Equipment management APP of smart energy systems

The equipment management APP includes equipment setting, map, data management, maintenance management, and other modules. It performs the functions of equipment registration, parameter configuration, positioning, status display, historical data query, alarm query, maintenance history record, maintenance order distribution, service quality management, system alarm setting, system logging, and other functions, to realize entire lifecycle management for system equipment.

5.5.4 Equipment optimization control APP of smart energy systems

The equipment optimization control APP includes equipment data source modules, asset analysis modules, state maintenance intelligent auxiliary decision modules, state evaluation modules, and control instruction issuing modules. Such an APP performs real-time control according to the load of the energy equipment, which increases intelligent efficiency and improves equipment utilization and system stability. Considering the energy equipment as an object, cluster management can be used to provide value-added services, such as life prediction and fault diagnosis.

6 Digital twin ecosystem construction for smart energy systems

The digital twin for smart energy systems encompasses the areas of energy production, transmission, storage, consumption, transaction, and other links that assist in breaking the time and space constraints of the energy industry, and promoting the all-round integration and unified scheduling management of various businesses. It can horizontally unite the business between entities in the energy industry to improve energy efficiency. The digital twin ecosystem for the smart energy industry is presented in Fig. 3 according to the entire lifecycle process of energy systems, which is divided into six parts: energy production, transmission, distribution, consumption, storage, and market. With the deepening of the interaction between the various parts, the sustainable development of the smart energy industry based on digital twins has been gradually implemented. Considering the objective of the application of digital twins, the six participants in the smart energy industry are summarized as follows [17,18]:

6.1 Energy production

Using a digital twin service platform based on cloud–edge collaboration, efficient conversion of energy production can be achieved. Through the establishment of virtual and real mapping simulation models, real-time operating status monitoring and environment simulation for energy production units can be performed, and the optimal operation strategy of the units can be formulated. The features extracted from the operating data can be used to optimize equipment production design, such as digital twin wind turbines, multi-physics photovoltaic models, and digital power plants.
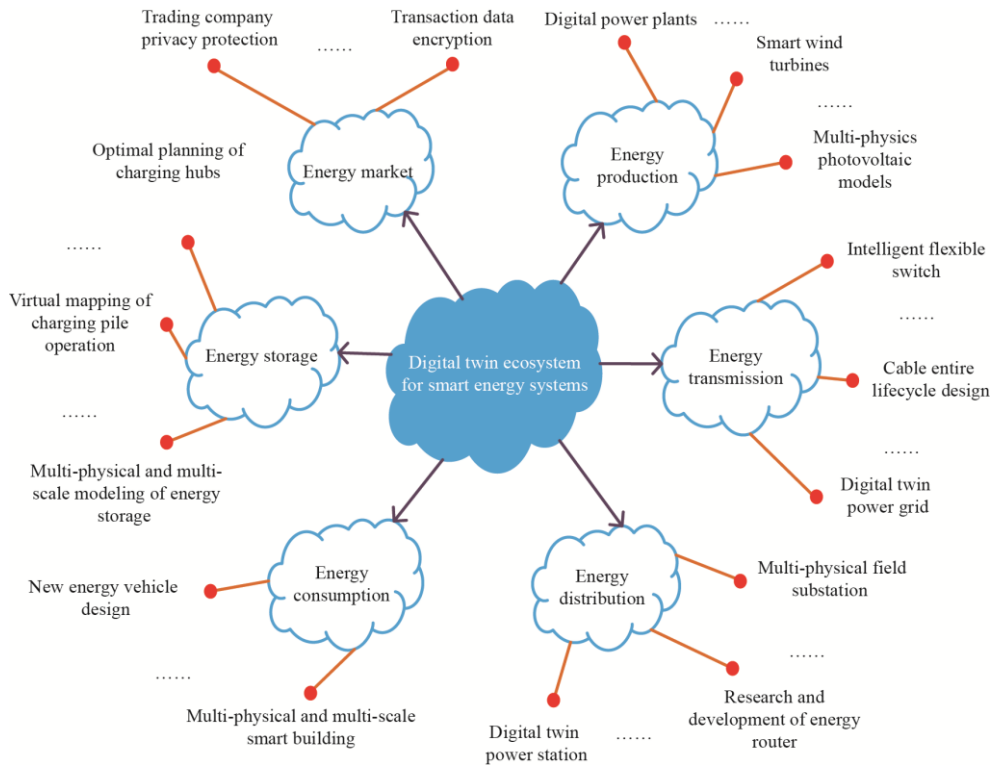
Fig. 3. Digital twin technology ecosystem for the smart energy industry.

6.2 Energy transmission

Due to the imbalance of the spatial distribution of energy, some regions in China are energy deficient, so appropriate transmission schemes are required to ensure energy security. Digital twins can improve the control and optimization ability of energy transmission [19]. The digital twin model of a flexible and direct modular multi-level converter in an HVDC transmission network can realize the optimization and upgrading of energy transmission. For cables and other equipment used for power transmission, digital twins can be applied to develop models of virtual and real mapping to guide the entire lifecycle design of a cable, which can improve the operational performance and increase the service life of such equipment. Digital twin power grids can realize multi-physics and multi-scale virtual simulations, which allow managers to better understand the operating status of transmission equipment and the load of each energy node. Using big data and AI techniques, real-time monitoring and early warning of possible faults can be realized.

6.3 Energy distribution

The research and development of energy routers are still in their infancy. Using digital twins to build a virtual model of an energy router and perform big data simulation analysis can guide the production design process, and significantly reduce the development cycle. By targeting substation equipment in the energy distribution link, a digital twin model can be used to instantiate the substation equipment. With the assistance of intelligent robots and intelligent safety monitoring equipment, massive data and physical equipment can be associated and mapped, which can be displayed in real time on a visualization platform. This results in a digital twin transformer substation, which improves the economy and safety of the energy distribution process.

6.4 Energy consumption

The concept of digital twins from virtual to real enables advanced designers to circumvent the limitations of traditional manufacturing processes for developing new designs, such as establishing digital twin models for new energy vehicles, digital twin mapping, and updating of design models to improve their performance. As an important component of smart energy systems, smart buildings are typical manufacturers and sellers. Digital twins can be used to establish multi-physical and multi-scale simulation models for smart furniture, cooling, and heating systems in smart buildings, and to collect information on the building's temperature, humidity, in addition to the number and

location of personnel. In a visualization platform, managers can easily control the subsystems of smart buildings based on IoT technology, and use AI techniques to realize operational trend prediction and formulate an optimal operational strategy.

6.5 Energy storage

In the planning stage of EV charging hubs, to meet the charging needs of users and the requirements of municipal planning, the layout of charging hubs can be simulated and planned based on digital city models, so that the optimal distribution of charging hubs can be realized. After building, simulation, and modeling of each charging hub, the status information is presented in a virtual scene, which is monitored and fed back to the actual operation and maintenance management to guide the timely repair of faults. Multi-physics and multi-scale digital twin models of energy storage equipment (such as batteries and supercapacitors) are then performed, and these models are used to monitor and predict their operation to achieve an optimal configuration.

6.6 Energy market

The rapid development of the energy industry has created diversified demand for new financial market services. As a result, energy trading companies that participate in energy market transactions have access to a large amount of private data. The information security defense mechanism of digital twins can be used to determine the characteristics of network attacks, construct the optimal feature attribute set related to data integrity attacks, establish an access mechanism for security risk assessment, and minimize the security risk of energy trading.

7 Application prospects of digital twin

7.1 Deployment strategies

Represented by cloud computing, big data, IoT, AI, and blockchain, the new generation of digital technologies is being rapidly developed and applied. Digital twins have broad development prospects in the smart energy industry. According to the operational requirements of smart energy systems, digital twin APPs are developed. With the advent of 5G and big data, the digital twin APPs of smart energy systems will provide robust and flexible technology support for the transition and upgrading of China's energy industry.

The digital twin APPs of smart energy systems should first support common deployment configurations that contain the Browser/Server (B/S) or Client/Server (C/S) architecture, and support mobile phones, tablet computers, personal computers, and other access terminals. Deployed on cloud platforms, services such as multiple simultaneous access, collaborative operations, and remote expert guidance can be provided. Using service and model innovation, the working efficiency of smart energy ecosystems can be significantly improved, the cost of energy production and sales can be reduced, and the quality and efficiency of smart energy systems planning, operation, and control can be improved.

7.2 Application cases

Although the investigation of digital twins for smart energy systems is in its infancy, it has broad application prospects ranging from a single device to a multi-agent complex energy system.

7.2.1 Digital twin substation equipment

A large-scale pumping station is used to extract water resources, which is a complex system that integrates electricity, information, and control. The subsystems of a pumping station include power transformation systems, water pump systems, and monitoring systems. Based on digital twins, the pumping station equipment uses a "data chain" to establish a multi-physics and multi-scale simulation model of multiple coupled components. The visual management system of digital twin pumping stations can be used to realize the seamless connection between a simulation in a virtual environment and a real operation, which improves the transparency of enterprise management and operation. Considering the substation equipment as an example (in Fig. 4), a multi-time and multi-physical digital twin model can be developed and coupled with electricity, magnetism, and heat to provide a refined model for equipment selection and operation of large-scale pumping stations.
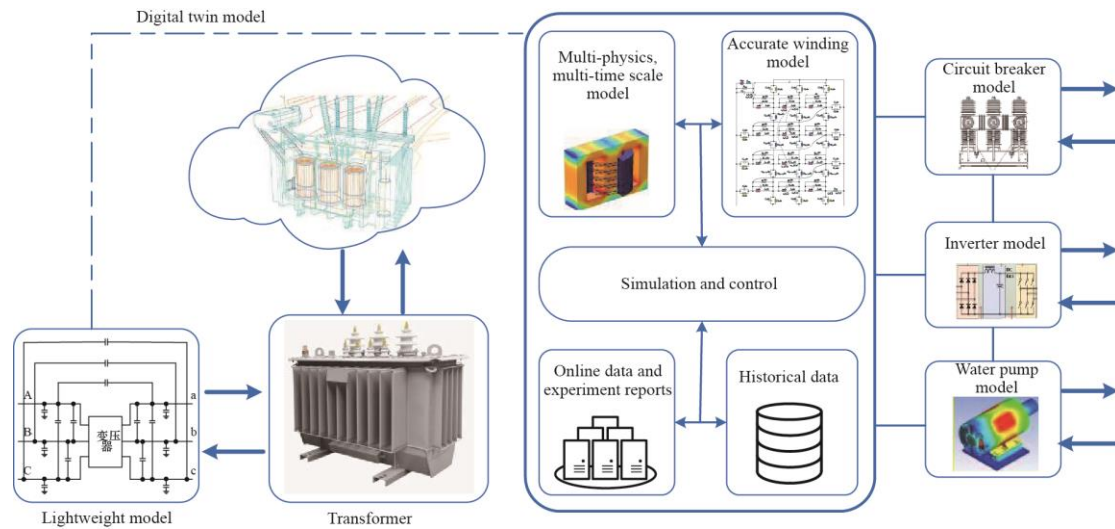
Fig. 4. Digital twin model of substation equipment.

7.2.2 Digital twin power grid

A digital twin power grid first collects data from intelligent devices, and then establishes digital twin models to realize the real-time perception of power grid operational status to evaluate and predict the health of the power grid (such as abnormal detection, weak link analysis, and disaster warning). A research team from Shanghai Jiao Tong University analyzed and verified the feasibility of the digital twin power grid by comparing the two driving modes of the power flow equation (with admittance information) and the data-driven mode (without admittance information). It was demonstrated that the data-driven mode could still satisfy the actual operational requirements when the mechanism model was insufficient. Moreover, the feasibility of the digital twin grid was also examined [2]. The design framework of the corresponding digital twin grid is shown in Fig. 5.
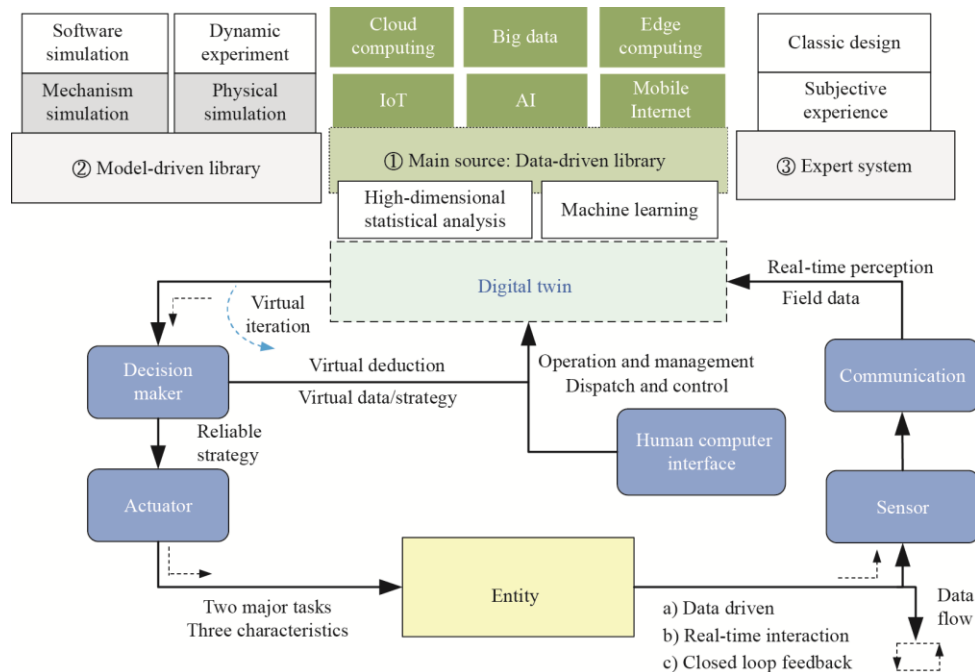

Fig. 5. The design frame of the digital twin grid [2].

7.2.3 Digital twin integrated energy systems

The concept of an integrated energy system originated in the field of coordinated operation of heat and power, and has been developed into a system that integrates multiple energy sources in a certain district [20]. Pera Global Digital Twin Laboratory constructed a digital twin application case for thermal power plants [3], and the

corresponding model can accurately predict the operating performance of these plants. It can be employed to address management failures and system bottlenecks based on system constraints, provide forward-looking guidance for daily maintenance or replacement, and evaluate work priorities after shutdown. In this case, the assessment of the impact on condenser structure is considered as an example to determine the probability that fouling adversely affects the backpressure of the main condenser. This serves as an effective reference for the design and operation of relevant equipment. With the assistance of the digital twin CloudIEPS platform, a research team from Tsinghua University established a digital twin integrated energy system model [4]. This included an electrical load, cooling load, heat load, gas generators, absorption chiller, gas boiler, photovoltaic, battery, ice storage air-conditioning systems, and other subsystems. These models were used to optimize the capacity of various devices to reduce the system's operational cost.

As such, digital twin integrated energy systems can realize "source–grid–load" connection of equipment via the Industrial Internet. The digital twin model of an energy system can be constructed using multi-physical fields, multi-scale modeling and simulation, and industrial big data, to facilitate state monitoring, fault diagnosis, and operational optimization of energy systems to realize the "twins' wisdom" of integrated energy systems.

8 Countermeasures and suggestions

In the context of energy transition and Internet Plus, policy barriers in various energy industries should be circumvented. As a result, the physical connection and interaction of various energy systems should be developed, and smart energy systems with multiple optimized and coordinated sources should be established. For the implementation of digital twins, it is first necessary to build a support platform for closed-loop feedback, optimization, and decision making with cloud–edge bidirectional data and information interaction. The platform is the core of the application of digital twins to smart energy systems, and helps to address the technical and market barriers encountered during development. This is useful for achieving continuous innovation of services, immediate response to demand, and industrial upgrading and optimization. Based on these concepts, we propose the following recommendations for the development of digital twin technology in the smart energy industry based on three aspects: technology development, application ecosystem, and policy establishment.

8.1 Building technology and resource sharing platform and jointly tackling technical development challenges

Participants in the smart energy industry (such as companies, universities, and research institutes) not only need to accelerate the key research technologies of architecture and the supporting platforms of smart energy systems, but also need to improve exchanges and cooperation between all participants. The development of technology and resource sharing platforms is beneficial to research units, and facilitates the sharing of breakthrough progress and the development of bottleneck judgments during the implementation of digital twin applications. This leads to the improvement of the cooperation between universities and enterprises, and collaborative investigation of the key technical elements and difficulties encountered during the implementation of digital twins.

8.2 Integrating the disciplinary characteristics of energy ecosystems and building comprehensive digital twin application systems

To better promote the application of digital twins in the entire lifecycle of the energy industry, value creation, value-added information, business innovation, and overall benefits should be improved. First, the advantages of various fields should be organized in the smart energy ecosystem. Moreover, the characteristics of multi-disciplinary integration should be combined to develop a comprehensive digital twin application system that integrates different fields and has strong universality, including the "data chain" design technology, digital twin modeling technology, and dynamic interaction technology. Through the establishment of preliminary pilot projects and gradual advancement to the entire smart energy industry, the barriers between various fields can be reduced, and the comprehensive effect of digital twins can be fully realized in the ecosystem development for smart energy systems.

8.3 Promoting standards formulation for digital twin development

The formulation of digital twin standards is still in its infancy. A few international organizations have initiated the compilation of these standards. The compilation of digital twin standards in China has not been initiated. As such, the lack of standards references such as digital twin-related terms and applicable guidelines has affected the

development of digital twins for smart energy systems. There is an urgent need to initiate the formulation of standards related to digital twins in China. Moreover, educational and research institutions should develop relevant personnel training programs as soon as possible, allocate relevant resources to promote the development of digital twins for the smart energy industry, and cultivate talent in the field of digital twin applications. Personnel training and technical exchange should be implemented from a global perspective, to gradually narrow the gap with developed countries. This will provide a strong foundation for the digital transition of China's energy systems.

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