

Article

Identification of the Key Issues and Technical Paths for Intelligent Operation of Water Source Heat Pump Energy Stations Applying Digital Twin Technology

Jiaji Zhang ^{1,2,3} , Qiankun Wang ^{1,2,*}, Shuqiang Gui ^{4,*}, Junli Zhou ² and Jinlong Sun ^{5,*}

¹ Sanya Science and Education Innovation Park, Wuhan University of Technology, Sanya 572025, China; zhangjiaji@whut.edu.cn

² School of Civil Engineering and Architecture, Wuhan University of Technology, Wuhan 430070, China; jlzhou@whut.edu.cn

³ Birmingham Centre for Energy Storage & School of Chemical Engineering, University of Birmingham, Birmingham B152TT, UK

⁴ MCC Wukan Engineering Technology Co., Ltd., Wuhan 430080, China

⁵ School of Telecommunications and Information Engineering, Nanjing University of Posts and Telecommunications, Nanjing 210003, China

* Correspondence: wangqk@whut.edu.cn (Q.W.); 003117@wsgr.com (S.G.); sunjinlong@njupt.edu.cn (J.S.)

Abstract: To address the challenges posed by global climate change, developing green energy systems characterized by informatization, digitalization, and intelligence is crucial for achieving carbon neutrality. This article is a research report type paper on water source heat pump (WSHP) energy stations, aiming to use digital twin technology and other information technologies to resolve conflicts between clean energy development and efficient energy utilization. The primary objective of this study is to identify and analyze issues in traditional energy station operations and management systems. Based on this analysis, specific technical solutions are proposed, including pathways for technological research, methodologies, and content. The results provide a comprehensive theoretical framework for the intelligent transformation of energy station systems and essential technical support for the WSHP energy station project in the Hankou Binjiang International Business District. The findings have significant implications for the widespread adoption of WSHP energy stations and the achievement of national carbon neutrality goals.

Keywords: water source heat pump; energy internet; digital twin; IoT; intelligent operation; unmanned operation



Citation: Zhang, J.; Wang, Q.; Gui, S.; Zhou, J.; Sun, J. Identification of the Key Issues and Technical Paths for Intelligent Operation of Water Source Heat Pump Energy Stations Applying Digital Twin Technology. *Appl. Sci.* **2024**, *14*, 5094. <https://doi.org/10.3390/app14125094>

Academic Editors: Hugo Morais, Rui Castro and Cindy Guzman

Received: 10 May 2024

Revised: 4 June 2024

Accepted: 9 June 2024

Published: 12 June 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Energy is a critical foundation for social development. As global fossil fuel supplies dwindle and environmental protection pressures increase, comprehensive energy systems characterized by multi-energy flow coupling, multi-system integration, and multi-regional coordination are anticipated to mitigate the current pattern of extensive energy utilization and the conflicts between environmental protection and economic development [1]. In the resource-rich Yangtze River Basin, WSHP energy stations represent an innovative technological approach to the creation of a comprehensive urban energy supply. These stations utilize the Earth's water bodies as heat exchange sources and employ heat pumps to provide cooling and heating for buildings, offering advantages such as high operational efficiency and low costs. This method significantly contributes to large-scale carbon emission reductions in new urban developments [2–4].

However, the actual operation of WSHP energy stations presents numerous challenges. These include high specialization, complex systems, remote water intake, and a decentralized distribution of heat exchange stations, which collectively complicate operation and maintenance management and resource scheduling, significantly reducing energy

utilization efficiency. The traditional management mode of these stations typically involves the independent monitoring of electrical equipment within the system, relying on periodic manual inspections and data analysis for stage-based maintenance. This approach fails to ensure the safety and stability of the energy system. It is a deterministic operating management mode based on process flows and human experience, lacking proactive equipment wear prediction, dynamic energy consumption data statistics, accurate energy demand forecasting, and timely responses to demand in changing environments. Consequently, this results in passive management, low efficiency, and during long-term operations, numerous factors such as surface water temperature, water flow rate, and building load characteristics influence the energy utilization efficiency. Current energy information management methods provide insufficient guidance for future operational trends [5,6].

With the rapid advancement of technologies such as cloud computing, mobile internet, big data, 5G, and artificial intelligence, the energy sector is undergoing a digital transformation. Digital technologies are reshaping the production, operation, and transmission modes of traditional energy systems, forming a new energy network system that integrates new energy technologies with information technology. This new system aims to enhance management efficiency and production effectiveness while ensuring safe and stable operations, thereby facilitating an early transition to green and low-carbon energy solutions. By employing various digital methods, it is feasible to transition from the traditional deterministic operation of mechanical systems to intelligent operation under uncertainty management, ultimately achieving the goal of developing information-based, digitalized, and intelligent energy stations [7–9].

2. Developmental Overview

The concept of achieving energy interconnection through digital technology was first proposed by the American scholar Jeremy Rifkin in his seminal work *The Third Industrial Revolution* [10,11]. This idea has since captured the attention of governments worldwide. For instance, as early as 2002, Switzerland launched the VoFEN project to explore multi-energy transmission systems and the conversion and storage of distributed energy, aiming to develop ideal energy system facilities by 2050. Similarly, the German government initiated the E-Energy program in 2008 and the SINTEG program in 2016, focusing on the goals of low-carbon transitions and nuclear phase-outs. The U.S. government launched the FREEDM project in 2008, which employs advanced power electronics, information technology, and energy management technology to build future renewable energy transmission and management systems. In 2011, Japan formulated the “Digital Grid” strategic plan, researching technologies that could be used to integrate power routers with existing power grids and local networks to achieve a deep integration of energy and information networks. In 2016, China’s National Development and Reform Commission and National Energy Administration published the “Guiding Opinions on Promoting the Development of “Internet Plus’ Smart Energy”, emphasizing the necessity of building a green, low-carbon, safe, and efficient modern energy system [12]. The goal is to promote the deep integration of energy and information, accelerate the digitalization and intelligent upgrade of the energy industry, and establish smart energy demonstration projects. By 2025, the initial construction of the energy interconnection industry system is expected to be complete, forming a relatively comprehensive technical and standard system that promotes internationalization and leads global energy interconnection development [13,14].

Table 1 shows that multiple countries regard the application of energy interconnection industries as a national issue. The energy interconnection system, a novel type of energy system, serves as the physical carrier for realizing “Internet Plus Smart Energy”. It is the inevitable result of the deep integration of information and energy systems and the reconfiguration and optimization of systems once information becomes a new type of production factor. Countries around the world adopt slightly different technological pathways based on their own energy endowments and technological strengths. Existing concepts can be classified into three categories:

- (1) **Global Electricity Interconnection Focus:** This involves the spatial expansion of power networks by interconnecting different regional power grids to facilitate the cross-regional absorption of various types of new energy sources.
- (2) **Multiple Energy Sources Coupling Focus:** This involves interconnecting various energy systems, including electricity, heat, cold, gas, and water, to enhance comprehensive energy development and utilization and improve energy efficiency. Here, electricity is converted into different forms of energy such as cold, heat, and gas to harness renewable energy sources.
- (3) **Energy–Information Integration Focus:** This primarily utilizes technologies such as power electronics, information communication, and the internet for energy control and real-time information sharing, aiming to achieve energy supply–demand matching.

Table 1. A comparison of the initial energy internet planning forms used in major countries around the world.

National	Project	Time	Focus	Interconnection Type	Features
Sweeden	VoFEN	2002	Focus on the comprehensive interconnection of various energy sources	Physical interconnection	Integrates different types of energy such as electricity, heat, cold, gas, and transportation, on one hand, to achieve the transmission, conversion, and efficient utilization of various energy sources, and, on the other hand, to convert surplus electricity into other energy sources to complement, accommodate, and store electrical energy.
Germaý	E-Energy and SINTEG	2008 and 2016	Focus on the interconnection of information networks	Data interconnection	Built an information network based on information and communication technology (ICT) centered around information, utilizing the information network to collect, process, and provide real-time feedback on information from the production and consumption ends of electricity, thereby supporting the energy network in making decisions.
America	FREEDM	2008	Focus on the interconnection of energy networks	Physical interconnection	Drawing on the concept of open and equal peer-to-peer connectivity using the internet, combined with power electronics technology, formulated a new type of energy network comprising backbone networks, local area networks, and their connecting networks. With microgrids as the core, achieved energy supply balance, and realized plug-and-play, plug-and-store, and plug-and-generate capabilities.
Japan	Digital Grid	2011	Deep interconnection between information networks and energy networks	Physical interconnection Data interconnection	The deep integration of internet technology and energy networks divides the synchronous power grid into asynchronous autonomous and interconnected local area networks. Each basic unit in the power system is assigned an IP address, enabling bidirectional transmission of energy flow and information flow through power routers.

Table 1. Cont.

National	Project	Time	Focus	Interconnection Type	Features
China	Global Energy Inter-connection	2016	Focus on global electricity interconnection	Physical interconnection Data interconnection	Built a backbone network centered around electricity, continuously expanding the physical space of the power grid. Constructed a green, low-carbon, safe, and efficient modern energy system, promoting the deep integration of energy and information, accelerating the digitalization and intelligent upgrade of the energy industry, and establishing smart energy demonstration projects.

Due to China's well developed grid system and its global leadership in ultra-high voltage technology, research in China on energy interconnection focuses more on power system interconnection. However, urban comprehensive energy station systems, exemplified by WSHP, are more complex. They are based on power systems but also incorporate characteristics of multi-energy coupling and information fusion typical of energy interconnections. Research on the digitization and intelligentization of WSHP energy stations is relatively scarce. With the increasing number of WSHP energy station projects adopting the energy interconnection concept and utilizing technologies like digital twin (DT), information and communication technology (ICT), and artificial intelligence (AI), deep integration of energy and information can be achieved to accomplish energy-saving and carbon-reduction goals [15–17].

This has been a research hotspot in recent years. Many scholars have conducted in-depth research in this field. Li et al. [18] provided an overview of the correlation between information technologies such as artificial intelligence, big data, IoT devices, and blockchain, as well as their integration with smart energy management strategies. Mason et al. [19] reviewed the literature on the development of autonomous building energy management systems using reinforcement learning, and summarized methods for optimizing energy utilization by combining advanced sensor technology, communication and advanced control algorithms. Aguilar et al. [17] systematically reviewed the literature on the use of artificial intelligence technology to improve intelligent building energy management systems in recent years, and studied autonomous energy cycle management based on data analysis tasks to achieve the goal of improving energy efficiency. Li et al. [20] combined the advantages of knowledge-driven and data-driven methods and proposed a fault diagnosis method based on knowledge-guided and data-driven methods for building HVAC systems.

Through this research review, we believe that combining various information technology means to achieve load forecasting, fault diagnosis, and operation optimization of energy systems is an important direction for research in the field of energy and the internet. Research on the intelligent operation of the WSHP energy system has become more significant due to its complexity and dynamic user characteristics.

3. Research Decomposition and Analysis

3.1. Engineering Issue Decomposition

Traditional WSHP energy station operation and maintenance management systems are based on constant energy consumption. The system will set the operating instructions in advance to meet the energy conditions under different water temperatures in different seasons. These systems prescribe specific control strategies according to the design load of the energy station. The existing WSHP energy station operation and maintenance systems have the following issues.

Information Systems: Traditional management systems are incapable of acquiring accurate, comprehensive and real-time high-standard operational and maintenance data, and they fail to overcome the “information isolated island” that exists between energy supply and demand systems.

Energy Distribution: Traditional systems do not respond effectively to energy demands in a dynamic environment and lack precise management from the energy supply side to the demand side.

Management Decision Making: Traditional systems lack the ability to predict dynamic energy usage data. Therefore, it is impossible to make real-time, accurate, efficient, and scientific management decisions.

From the above discussion, it can be concluded that the root cause of these issues lies in outdated information management methods, which hinder intelligent coordination between energy supply and demand in the WSHP energy station.

3.2. Key Technical Issues and Solutions

This study identified the key technical issues that must be addressed to achieve the intelligent operation and maintenance goals of energy stations under uncertain energy consumption conditions during daily operation and maintenance processes. These key scientific issues include multiple aspects such as system logic and simulation, operational data processing, and energy system control. To overcome these challenges, the value of operational information systems, data assets, and operational logic can be harnessed through the use of digital tools, including DT, AI, data mining, and IoT technologies [21–23].

- (1) The problem of complex logic construction and the difficulty of real time simulation

DT is an important tool for logical construction and operational simulation. This study constructs a DT model for the WSHP energy station in the Building Information Modeling (BIM) space, and combines methods such as multi-source heterogeneous spatial data modeling and IoT perception data modeling to establish a digital twin model for the spatial physical entities and energy operation logic of the WSHP energy station. The model can reflect the time-varying state of energy flow during the operation of energy stations and is able to achieve multi-dimensional model unification for spatial information, operational information, and data information.

- (2) The problem of fragmentation and the redundancy of system operation data

The processing of energy station operation data is crucial for achieving intelligent operation of energy stations. This study conducts in-depth mining of energy station operation and maintenance monitoring data utilizing precise and comprehensive data key feature extraction techniques to adapt to monitoring dimensions such as the resource status, container status, and operational status of different edge and end devices. Then, based on massive amounts of monitoring data such as operational data, status monitoring, behavior recognition, and log analysis, a terminal operation knowledge graph is constructed to establish a complete device attribute, status, and event library. The study of this key scientific issue can provide IoT support to energy situation information and fault warning information.

- (3) The problem of low energy efficiency caused by imbalanced energy supply and consumption

Establishing an AI algorithm-based energy station operation situation awareness model is the key to solving the balance between energy supply and consumption. This study establishes an operational situational awareness model based on a logical correlation coupling model of multiple systems of energy stations, combined with the energy station group's control strategy. On the premise of meeting the energy needs of users, this model is constrained by energy conservation, carbon reduction, and economic reliability, and uses AI algorithms to analyze the operational situation of energy stations. By dynamically optimizing the system operation strategy, a balance between energy supply and consumption can be achieved, thereby improving the efficiency of system operation.

Based on the research decomposition and analysis discussed above, we formed the key issues and technical path analysis diagram of intelligent operation of WSHP energy station shown in Figure 1 [24–26].

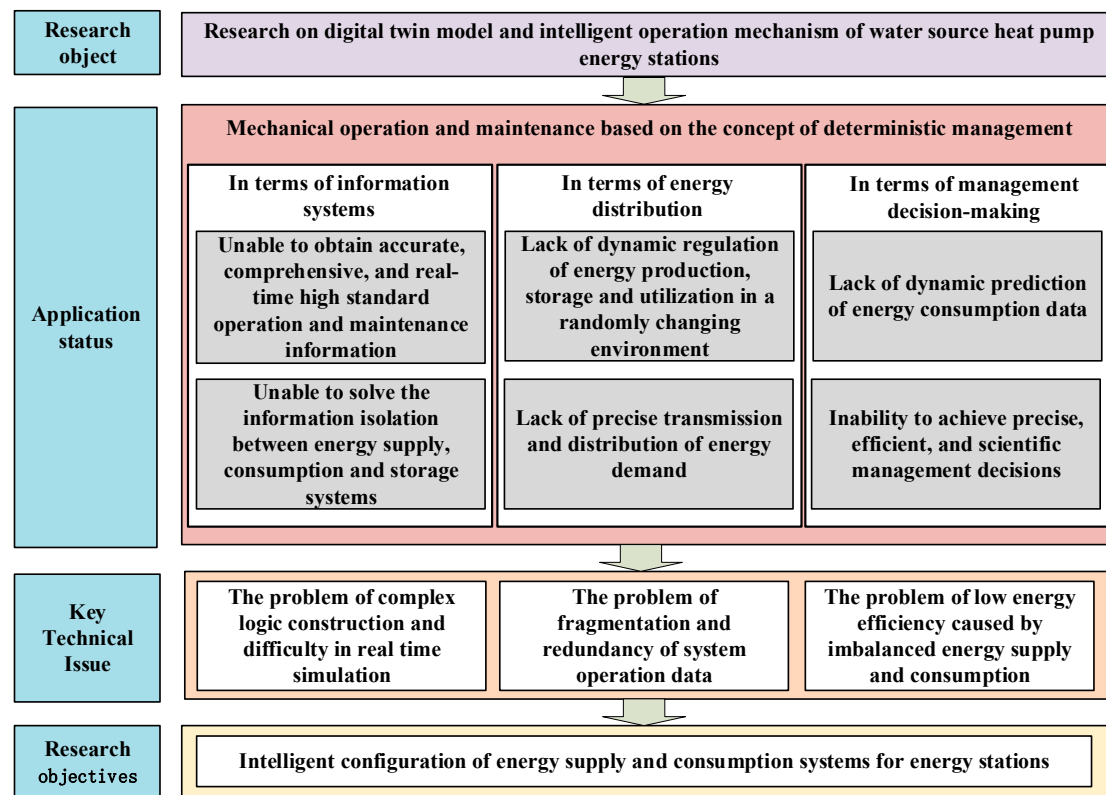


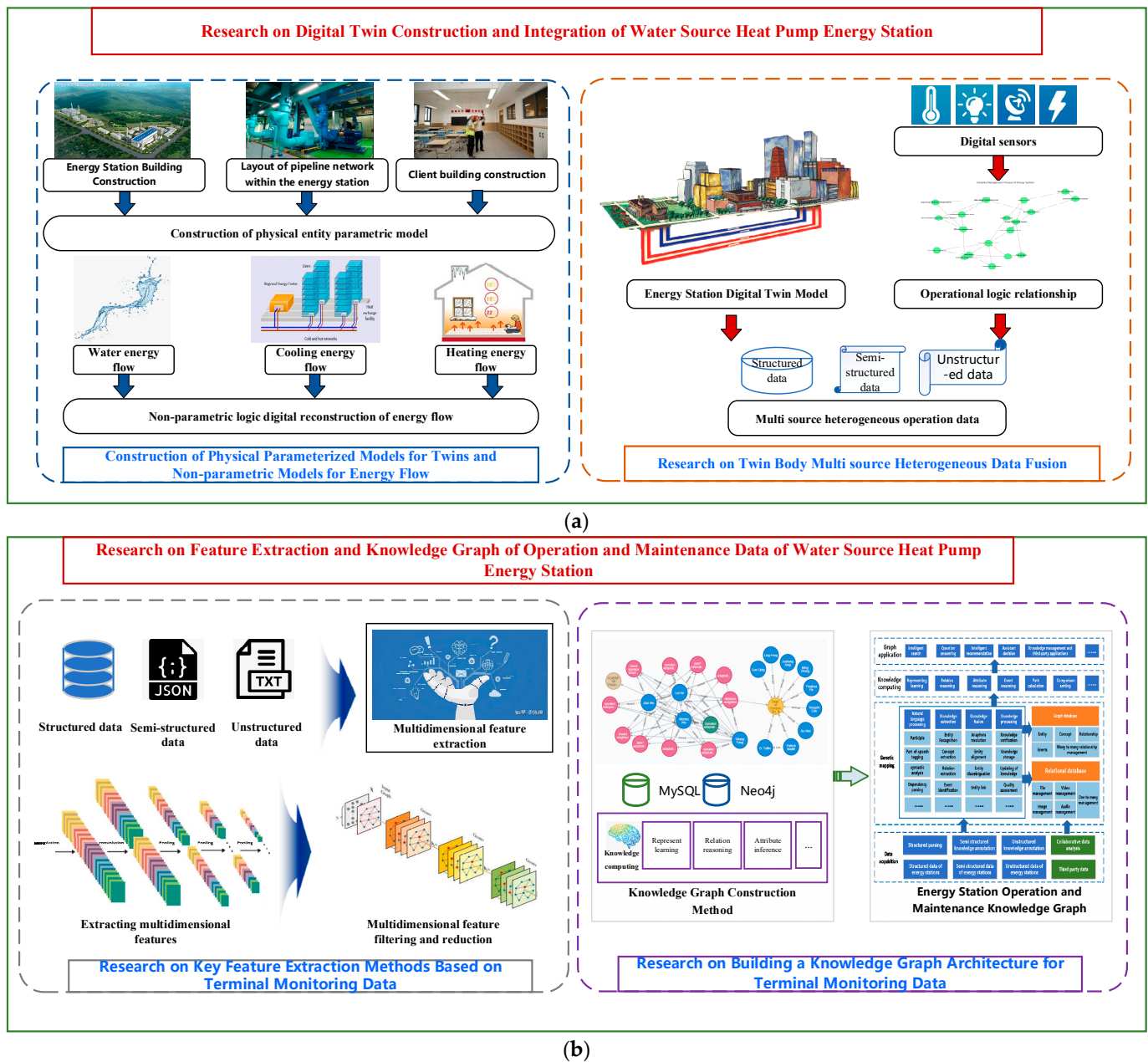
Figure 1. Decomposition and analysis of research issue.

4. Main Research Content

Following established scientific research methodologies, this study elaborates upon the DT model and the intelligent operation mechanism of the WSHP energy station from several aspects, including technical pathways, research methods, research content, and research objectives.

4.1. Technical Path

This study was conducted using three aspects, and the various research contents are interrelated. The technical path of this study is illustrated in Figure 2 [27–29]. Initially, the research establishes a physical parameterized model of the twin entity and a non-parameterized model of energy flow, forming a comprehensive three-dimensional DT model of the WSHP energy station (Figure 2a). The integration process includes aligning digital sensing devices within the energy station with operational logic relationships to incorporate diverse data sources during operation. Subsequently, multidimensional features are extracted from structured, semi-structured, and unstructured data from the energy station to create a knowledge graph based on terminal monitoring data (Figure 2b). Among them, the structured data have fixed data patterns and formats. Semi-structured data refers to data that do not fully conform to traditional relational database models, but still have a certain structure. Unstructured data refers to data without predefined formats or patterns. Finally, this study excavated operational data from energy stations and constructed a scenario prediction model. A hybrid AI algorithm based on a DT system has been developed to optimize the analysis of energy station operation (Figure 2c).

Figure 2. *Cont.*

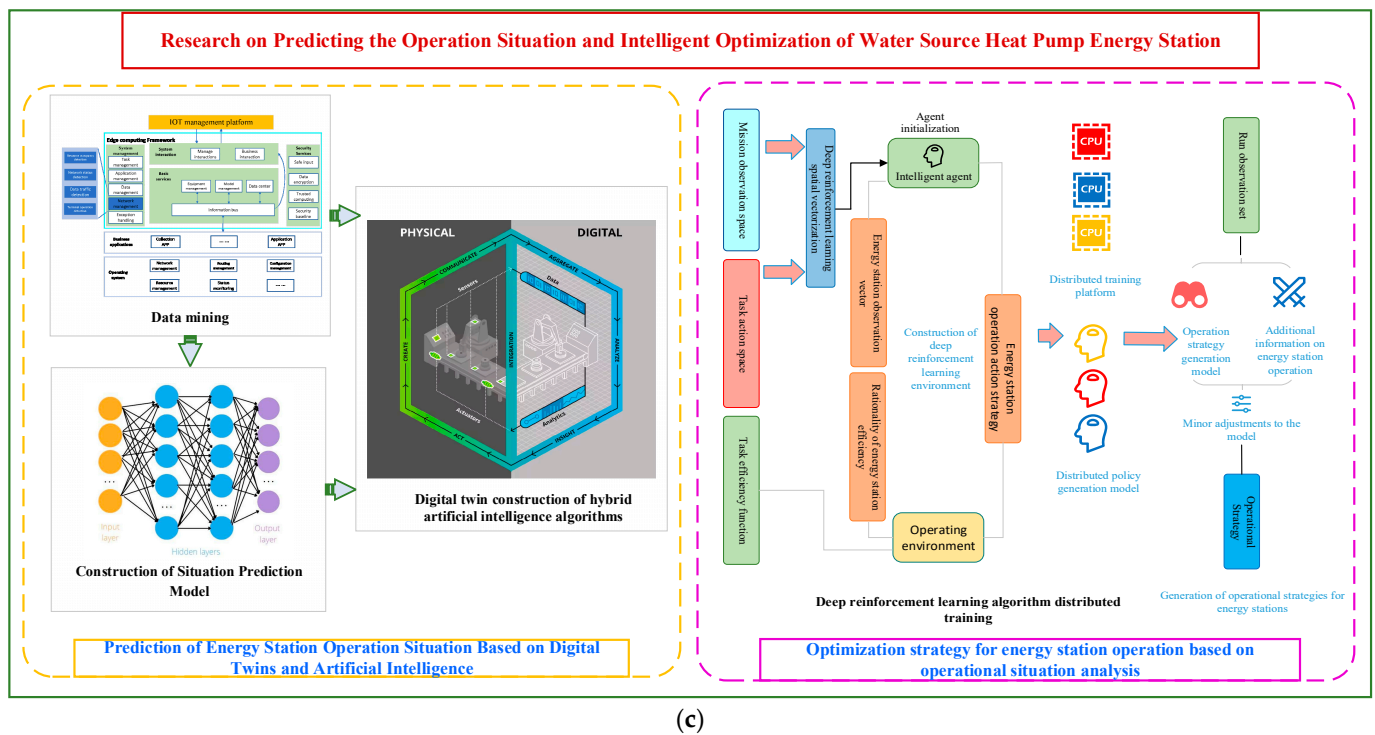


Figure 2. Technical roadmap of research content. (a) Graph of digital twin construction and integration technical path. (b) Graph of feature extraction and construction of knowledge graph technical path. (c) Graph of predicting the operation situation and intelligent optimization technical path.

4.2. Research Methodology

(1) Literature Review Analysis Method

In response to the current domestic and international research landscape in the field of the intelligent operation and maintenance of an WSHP energy station, this study employed a literature review analysis method. It involved a thorough review and analysis of both domestic and international literature to fully understand the latest research progress in integrating WSHP systems with the energy internet field. This process clarified the main content and research framework of the study, identified solutions that integrate related technologies such as “digital twin”, “knowledge graph”, and “situational awareness”, and provided a theoretical and methodological basis for the intelligent operation of an WSHP energy station.

(2) Digital Twin Model Construction Method

The method combined GIS information, IoT information, point cloud data, and other data based on the operation and maintenance BIM model of the WSHP energy station to construct a “BIM+” physical entity DT model. This achieved the integration of multiple sources of heterogeneous data in the twin body, including structured, unstructured, and semi-structured data. It also utilized methods such as finite state machines or process flow diagram theory to logically decouple energy flow information and generate a digital twin model that integrates static physical equipment parameters with dynamic energy information flow in a non-parameterized manner.

(3) Operation and Maintenance Monitoring Big Data Mining Method

The processing and analysis of energy station operation data are crucial for the achieving intelligent operation of energy stations. Through big data mining algorithms, research objectives can be effectively achieved. According to the operation and maintenance characteristics of energy stations, this method primarily consists of principal component analysis, association rule analysis, and attribute reduction feature extraction. Principal component

analysis, a classic method for feature extraction from high-dimensional data, helps to eliminate the correlation between data used for monitoring the statuses of energy station equipment, making the transformed factors mathematically independent of each other. Association rule analysis mines the relationships between state indicator variables from a large amount of equipment status monitoring data, identifying possible correlations hidden in different state indicators. Attribute reduction feature extraction extracts the simplest subset of attributes from numerous monitoring state attributes. By simplifying the attributes of energy station equipment status indicators, unnecessary attributes of energy equipment statuses are removed to reduce the difficulty and cost of handling energy system status monitoring data, decrease the storage volume of monitoring data, and improve the utilization rate of equipment monitoring data.

(4) Operation and Maintenance Monitoring Data Knowledge Graph Construction Method

This study combined text data such as daily operation and maintenance fault handling management regulations, fault handling plans, scheduling regulations, and abnormal monitoring manuals, as well as operational status data collected from equipment. Through concept extraction and relationship extraction methods, automated identification was carried out. The identification results were abstractly verified by business experts to form a bottom-up category system. Then, this system was integrated with the basic ontology architecture to build a knowledge ontology architecture for energy station equipment operation monitoring and fault handling. By storing the knowledge graph and its associated data in the field of energy station operation and maintenance, and using real-time operational data from smart IoT system equipment to update entity, relationship, attribute values and other information, the construction of a knowledge graph in the field of energy equipment operation monitoring and maintenance was achieved.

(5) Combining AI System Operational Trend Analysis Method

To achieve the goal of the intelligent operation of energy stations, this study combined deep reinforcement learning algorithms to establish an AI model with training capabilities, and analyzed the operation situation as a supplement. The research relied on the DT model of energy stations and an effective set of operation and maintenance monitoring data to complete the model configuration and adjust the parameters of the hybrid digital twins. At the same time, we determined the functional characteristics of the model using the optimal operating results for the energy station, completed model training, and made the model interpretable. Finally, based on the operation plan for the energy station, a dynamic parameter adjustment strategy for the energy station system under multi-objective constraints is studied to achieve intelligent optimization of the operation situation of the DT energy station.

(6) Research and Validation Method of Engineering Experiment Scenarios

We selected the WSHP Energy Station project in Hankou Binjiang Business District as an engineering case study to conduct research on the key issues and technical routes of the WSHP intelligent operation system based on DT. Because of the actual operation and maintenance needs of the energy station, the correlation between the input and output of digital resources in each system were considered. We selected high-value operation and maintenance application scenarios based around the key systems of WSHP energy station operation and maintenance. And based on this scenario, we established an energy station scenario model with a hybrid DT and AI, and completed an experimental engineering verification of our research on the WSHP energy station's intelligent operation mechanism.

4.3. Research Content

Research Topic 1: Research on the Construction and Integration of the WSHP Energy Station Digital Twin Model.

- a. Mechanism of Physical Parameterized Model of Twin Body and Non-parameterized Energy Flow Model Construction.

Due to the complexity of the electromechanical system of the energy station, as well as the phenomenon of insufficient spatial spacing in some pipeline networks and chaotic system logic, the difficulty of modeling digital twins has greatly increased. This study comprehensively characterized the geometric characteristics, physical characteristics, and energy operation laws of energy stations through the construction of parameterized physical models for energy stations and the digital reconstruction of non-parameterized energy flow logic, using methods such as BIM, GIS, and IoT. We analyzed the coupling and correlation mechanisms and dynamic spatiotemporal structures among various systems, achieved their parameterized analysis in digital space, and established a DT model of energy station embedded spatiotemporal characteristics and mathematical laws containing “physical, operation, logic, data” information.

- b. Mechanism of Coordination and Integration of Multi-source Heterogeneous Models of Digital Twin Bodies.

This study proposed a static DT model information and dynamic energy model information fusion method. This method explored the nonlinear and complex logical relationships of WSHP energy station systems, and explored multi-source heterogeneous data systems based on prior knowledge systems. At the same time, this study proposed a DT prototype system software and hardware design framework and a DT prototype system design method for cross operation platform integration in the intelligent operation and maintenance management process of energy stations. The precise matching between data and models is ultimately completed, achieving the collaborative fusion of DT models among the “model, operation, and data” of energy stations. The research content can support the mapping of and interaction between virtual space and real space.

Research Topic 2: Operation and Maintenance Monitoring Data Mining and Knowledge Graph Construction for WSHP Energy Station.

- a. Research on Key Feature Extraction Methods for Operation and Maintenance Monitoring Data from Energy Stations.

This study employed feature extraction methods such as principal component analysis, association rule analysis, attribute reduction, and deep neural networks. By mapping the source data space to a low-dimensional feature space, the correlation between variables is eliminated. The research results achieved key feature extraction and a reduction in energy station operation and maintenance structural and non-structural data while preserving the original data information to the greatest extent possible. Through this study, the problem of the redundancy or duplication of the monitoring data collected during the deep integration of IoT systems and energy systems has been resolved. Finally, by utilizing key feature extraction and mining methods from operation and maintenance data, we can better process and apply these data based on the real-time extraction of key information from energy station operation and maintenance data.

- b. Research on Knowledge Graph Construction Method for Operation and Maintenance Monitoring Data from Energy Stations.

This study solved the problems of complex intelligent cognition and large and complex operation and maintenance data from energy stations through the construction method of domain knowledge graph. We obtained corresponding knowledge from various heterogeneous multi-source data through specific extraction and mining techniques, and then represented it uniformly using graphs. At the same time, based on this method, the architecture design, graph parameter selection, and graph optimization mechanism of the relationship between the operational monitoring structure and structural features were completed. We studied the classification, connection, and weighting of various entities and attributes of energy stations based on the high-dimensional heterogeneous data characteristics and operational trends of IoT systems, ultimately achieving effective correlation and

feature mapping of entities such as equipment, users, buildings, and the environment in energy stations.

Research Topic 3: Predictive Operation State and Intelligent Optimization Mechanism of WSHP Energy Station.

- a. Energy Station Operation State Prediction based on Digital Twin and Artificial Intelligence.

We conducted research on the inherent mechanism and logical relationships within the intelligent operation of the WSHP energy station by introducing a virtual–real mapping model based on DT and non-linear mapping relationship mining based on AI. Based on the prediction model for equipment operation and energy consumption of the WSHP energy station, we designed an overall framework for energy station situational awareness and situational prediction. At the same time, we constructed a regional energy station operation situation prediction method based on hybrid DTs, and applied deep learning algorithms to solve the prediction results. The research results provide guarantees for achieving the optimal matching of energy station side and user (building) side operation, while improving the levels of automation and unmanned energy station operation.

- b. Energy Station Operation Optimization Strategy Based on Situation Awareness Analysis.

In response to the problems of excessive equipment configuration and low load rate caused by dynamic changes in the energy station system, we aimed to reduce manpower and achieve unmanned operation and maintenance goals in the long-term operation and maintenance process. We studied an energy station operation optimization strategy based on operational situation analysis to achieve the design goals of energy saving, efficient, and economical operation of the energy station. This study utilized information such as energy station operation situation prediction and load prediction, combined with the hybrid DT models constructed by the energy station knowledge graph and the logical relationship between the actual operation process of the energy station, to provide a decision-making basis for the capacity configuration of the energy station system. The study adopted multi parameter optimization algorithms and expert knowledge on unmanned operation systems, focusing on the two goals of maximizing energy efficiency and unmanned operation, to design a closed-loop optimization strategy that matches the multi-mode dynamic intelligent operation of energy stations. Finally, the research results were validated and analyzed based on real energy station scenarios.

4.4. Research Objectives Innovation

The construction of system logic and the difficulty of real-time simulation in the operation and maintenance management process of the WSHP energy station, as well as issues such as fragmented system operation data, data redundancy, and low energy efficiency caused by supply–demand imbalance, are discussed in this paper. In response to China’s “Internet+” smart energy development strategy in the era of carbon peaking and neutrality, this study utilized massive amounts of operation and maintenance data from energy stations and their operational logic combined with technologies such as DT, data mining, and AI to establish an operational state model of energy stations with hybrid DT capabilities. The research includes methods for constructing WSHP energy station DT models and integrating heterogeneous data from multiple sources, extracting key features from terminal monitoring data, and constructing knowledge graphs, as well as AI based operation state prediction methods and intelligent operation optimization mechanisms. The research results will contribute to achieving the goals of the informatization, digitization, and intelligentization of energy station construction, assisting in energy conservation and carbon reduction in building energy systems, thereby promoting the early realization of China’s carbon neutrality strategy.

The research outcomes will guide the development of smart energy systems for the WSHP energy station project in the Hankou Binjiang International Business District, assisting energy stations in achieving safe, stable, efficient, low-carbon, and cost-effective

operational goals. Additionally, it holds significant academic guidance and engineering reference value for the path selection towards China's carbon neutrality strategic goals. The innovative elements of this research are summarized as follows:

- (1) Establishment and Integration of WSHP System Digital Twin Models Combining Dynamic and Static Aspects.

In this study, we proposed a DT model establishment and fusion method based on "BIM + GIS + IoT" to address the problems of complex system logic construction and real-time simulation difficulties in the operation and maintenance management of WSHP energy stations. By constructing parameterized models for static physical devices and non-parameterized models for dynamic energy information flow, the digital unity of energy stations in different dimensions such as model, operation, and data can be achieved.

- (2) Construction of Knowledge Graphs Using Massive Terminal Monitoring Data with Key Feature Extraction Methods.

In response to the problems of fragmented and redundant operational data in the energy station system during the operation and maintenance management of a WSHP energy station, we proposed the use of key feature method to extract massive amounts of terminal monitoring data and construct a knowledge graph of the complex operation and maintenance status of energy stations. According to the knowledge graph, this strategy can help energy stations to achieve the digital expression of logical relationships under complex coupling effects of multiple systems.

- (3) Prediction and Optimization of Operational Situational Awareness Using a Hybrid Digital Twin Model Integrated with Artificial Intelligence Algorithms.

To address the issue of low energy efficiency caused by supply–demand imbalance in the operation and maintenance management process of the WSHP energy station, a hybrid DT model based on the mapping of digital twin and artificial intelligence dual models was proposed. Building upon this model, a dynamic analysis of energy station operational states can be conducted to assist energy stations in load forecasting and intelligent system optimization under various operating conditions.

5. Application Case Study

5.1. Project Introduction

This project is a demonstration of the WSHP energy station in the Hankou Binjiang International Business District, located in the Jiang'an District, Wuhan City. It provides centralized cooling and heating for buildings in the Hankou International Binjiang Business District. It has a total designed energy capacity of 2.11 million m² and uses river water from the Wuhan Yangtze River section as a cold and heat source. The project's designed air conditioning cooling load is 164.14 MW, and the heating load is 78.84 MW. A map of the location of each system in the project and an internal sectional view of the energy station are shown in Figure 3. The construction of the smart energy station management and control system in this project includes a centralized energy monitoring and management software system, a hardware system, a regional centralized cooling and heating centralized group control system, a power monitoring system, a digital twin platform, an energy billing system, an energy expert service system, etc.

Through the discussion of key issues and technical paths for the intelligent operation of the WSHP energy station, we have designed a scientifically efficient, comprehensive, and fully functional smart energy station control platform construction plan to achieve the goal of fully automated operation with long-term unmanned intervention throughout the year. This plan includes functions such as equipment monitoring, energy regulation, energy management, energy efficiency analysis, and load forecasting. On the basis of meeting the cold and hot needs of users, this plan reduces the number of operation and maintenance personnel, lowers operation and maintenance costs, improves system energy efficiency, and increases system reliability. The functional design of the project system is shown in Figure 4.

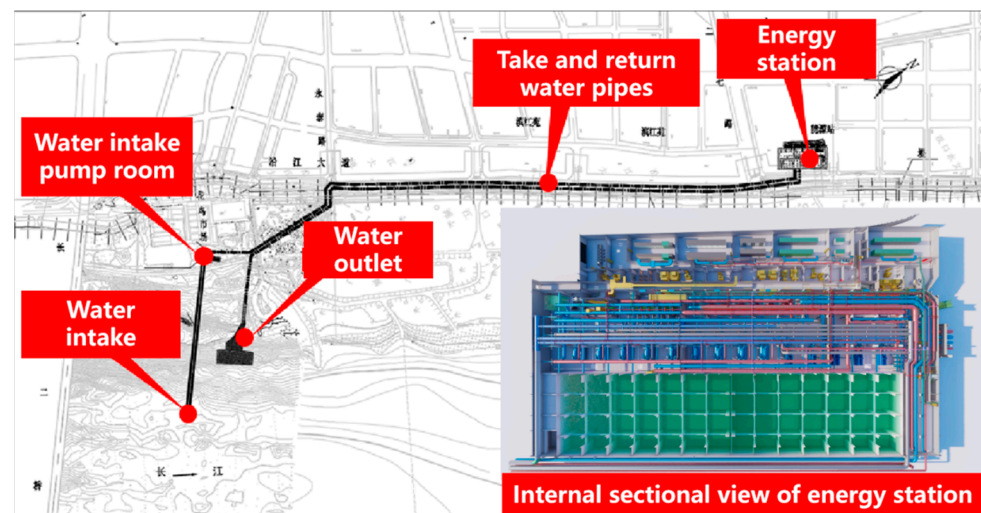


Figure 3. Location of each system in the project and internal sectional view of the energy station.

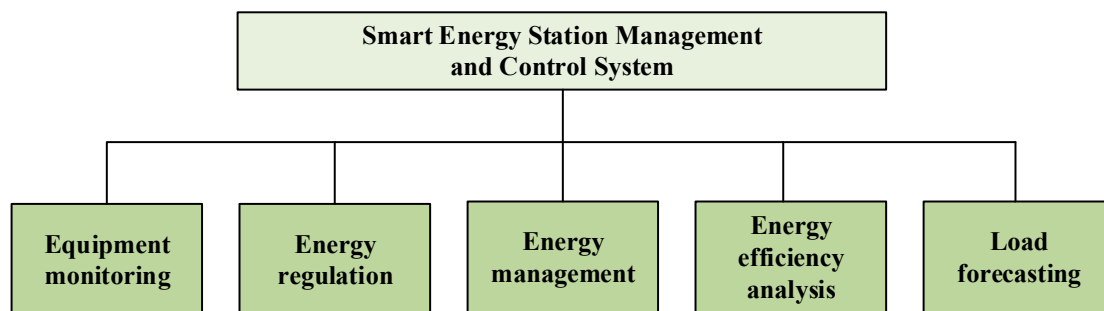


Figure 4. Project system functional design diagram.

5.2. System Architecture and Software Development

The functional architecture of the projected system includes multiple aspects, including a perception layer, network layer, data layer, twin layer, application layer, and user layer. The perception layer collects real-time energy station operation and maintenance information through IoT devices. The network layer is responsible for transmitting information within the system. The data layer is responsible for organizing, storing, and analyzing spatiotemporal data. The twin layer presents the actual operational status of energy stations in digital space. The application layer is a functional application that revolves around the intelligent operation of energy stations, including operation condition monitoring, load forecasting, energy-saving analysis, and other functions. The user layer sets different permissions for different users such as energy investment units, government management agencies, and social public organizations to achieve the effective utilization of the system. A diagram of the projected system's architecture is shown in Figure 5.

At the software development level, this study first used the Revit 2023 software to establish the BIM model of the energy station. Then, based on the low code twin engine, we achieved the fusion of digital twin models. To acquire the real-time operation status of energy stations, energy information within the system is collected through IoT. At the same time, we utilized the API interface of the low code twin engine, integrated AI algorithms, and processed and analyzed the energy operation data. The ultimate goal was to achieve real-time, dynamic, and intelligent construction of the intelligent operation and management platform for digital twin energy stations. Taking the WSHP energy station in Hankou Binjiang International Business District as an example, the system development process is shown in Figure 6.

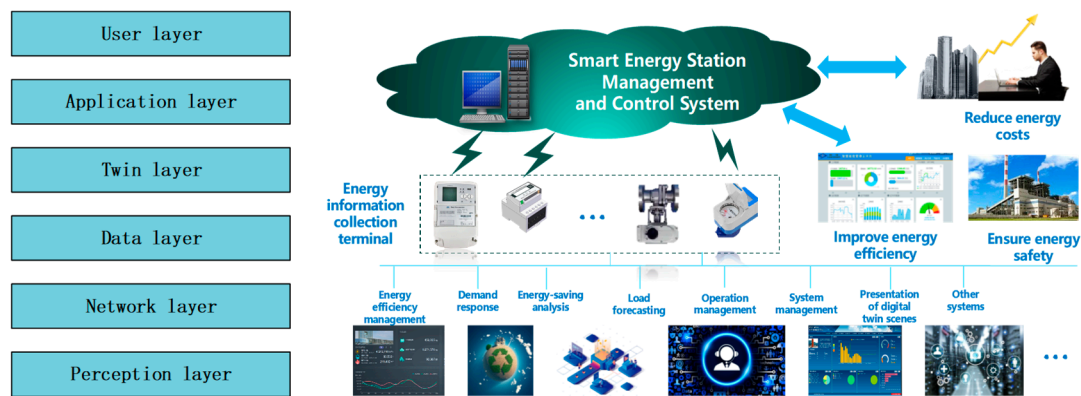


Figure 5. Project system architecture diagram.

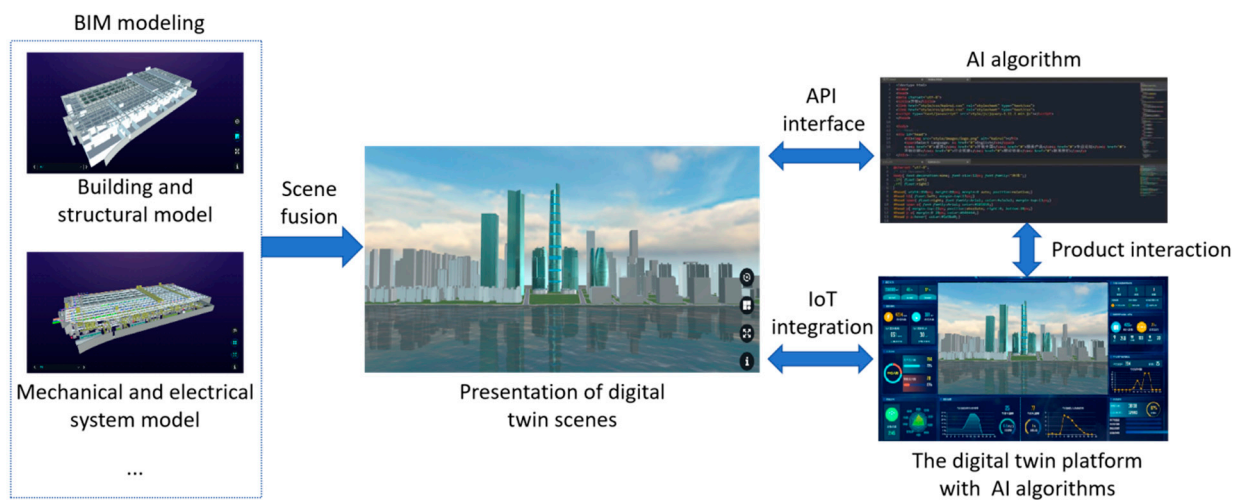


Figure 6. Software system development process.

6. Research Significance

6.1. Theoretical Significance

This study focused on the operation and maintenance phase of the WSHP energy station and proposed an intelligent energy management framework system with the main technical route of “digital twin, knowledge graph, situational awareness”. Through digital twin modeling, knowledge graph construction, and operational prediction optimization, the research examined the DT model of the WSHP energy station and intelligent operational logic from various aspects such as virtual multidimensional space, intelligent operation standards, and intelligent operation mechanisms. The research outcomes will lead to the development of multidimensional digital twin modeling and multi-source heterogeneous data integration methods for the WSHP energy station, as well as key feature extraction from terminal monitoring data and knowledge graph construction methods, and AI-based operational state prediction methods and intelligent operation optimization mechanisms. This research will help reveal the coupling laws acting on multi-source energy flows in energy stations and the intrinsic mechanisms of intelligent operation and maintenance, assisting in addressing a series of issues caused by the mismatch between energy supply and demand in traditional operation and maintenance management systems in energy stations.

6.2. Practical Significance

This study focuses on the WSHP energy station project in the Hankou Binjiang International Business District of Wuhan. Through in-depth engineering demonstrations and experimental validations in practical scenarios, the study aimed to assist the WSHP energy station in optimizing system operation strategies and improving operational efficiency to

achieve the objectives of safe, stable, efficient, low-carbon, and cost-effective operation and maintenance management. Compared with the traditional energy operation management system, the technical scheme proposed in this research is more vivid, accurate, and intelligent in the digital management of the energy system. The research outcomes will help energy stations achieve the goals of informatization, digitization, and intelligentization, significantly enhance the level of intelligent operation management of energy stations, effectively alleviate the contradiction between the development of clean energy and extensive energy utilization, and contribute to the early realization of China's goal of peaking carbon emissions and achieving carbon neutrality.

7. Conclusions

The study has identified the problems inherent in traditional operation and management systems of WSHP energy stations, particularly in information systems, energy allocation, and management decision making. It introduces the concept of intelligent operation and maintenance management for energy stations under uncertain conditions. A smart energy management framework system based on the main technical route of “digital twin, knowledge graph, situational awareness” is established. The research explores the logical relationship between the digital twin model of the WSHP energy station and intelligent operation, providing the system architecture and engineering development methods. Based on theoretical research, this study proposes a digital twin operation and maintenance management system architecture and explores the basic process of system development. These research outcomes will guide the development of smart energy systems for the WSHP energy station project in the Hankou Binjiang International Business District, helping the energy station achieve safe, stable, efficient, low-carbon, and cost-effective operations. As this study is still ongoing, we will carry out the construction, simulation, and experimental verification of the WSHP energy station digital twin platform in the future. Furthermore, the study offers significant academic guidance and engineering reference value for China's path towards achieving its carbon neutrality strategic goals.

Author Contributions: Conceptualization, J.Z. (Jiaji Zhang) and Q.W.; Methodology, J.S. and J.Z. (Jiaji Zhang); Software, J.Z. (Jiaji Zhang) and J.Z. (Junli Zhou); Validation, S.G.; Formal analysis, J.Z. (Jiaji Zhang); Resources, Q.W. and S.G.; Data curation, J.Z. (Jiaji Zhang) and S.G.; Writing—original draft, J.Z. (Jiaji Zhang); Writing—review & editing, J.Z. (Jiaji Zhang); Visualization, Q.W.; Supervision, Q.W. and J.Z. (Junli Zhou); Project administration, J.Z. (Jiaji Zhang) and J.Z. (Junli Zhou); Funding acquisition, Q.W., S.G. and J.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Wuhan Key R&D Plan, grant number 2023020402010590, Major R&D projects of China Metallurgical group corporation, grant number 2022 No. 14, The PhD Scientific Research and Innovation Foundation of Sanya Yazhou Bay Science and Technology City, grant number HSPHDSRF-2022-03-002, Major science and technology projects in Hainan Province, ZDKJ2021024. We thank Yangdong Peng, Lijun Dong, Meiliang Ku, and Sen Chen for their assistance in the data collection.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data generated or analyzed during the study are available from the corresponding author upon request. The data are not publicly available due to privacy.

Conflicts of Interest: Author Shuqiang Gui was employed by the company MCC Wukan Engineering Technology Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Reddy, V.J.; Hariram, N.P.; Ghazali, M.F.; Kumarasamy, S. Pathway to Sustainability: An Overview of Renewable Energy Integration in Building Systems. *Sustainability* **2024**, *16*, 638. [\[CrossRef\]](#)
- Jung, Y.; Oh, J.; Han, U.; Lee, H. A comprehensive review of thermal potential and heat utilization for water source heat pump systems. *Energy Build.* **2022**, *266*, 112124. [\[CrossRef\]](#)
- Ren, Z.; Yang, S.; Zhang, J.; Wang, Q.; Gui, S.; Zhou, J.; Tang, Y.; Zhu, K.; Shen, C.; Xiong, Z.; et al. Source Heat Pump Energy Station. *Water* **2024**, *16*, 470. [\[CrossRef\]](#)
- Shen, C.; Lei, Z.; Wang, Y.; Zhang, C.; Yao, Y. A review on the current research and application of wastewater source heat pumps in China. *Therm. Sci. Eng. Prog.* **2018**, *6*, 140–156. [\[CrossRef\]](#)
- Noye, S.; Mulero Martinez, R.; Carnietto, L.; De Carli, M.; Castelruiz Aguirre, A. A review of advanced ground source heat pump control: Artificial intelligence for autonomous and adaptive control. *Renew. Sustain. Energy Rev.* **2022**, *153*, 111685. [\[CrossRef\]](#)
- Wu, Y.; Wu, Y.; Guerrero, J.M.; Vasquez, J.C. A comprehensive overview of framework for developing sustainable energy internet: From things-based energy network to services-based management system. *Renew. Sustain. Energy Rev.* **2021**, *150*, 111409. [\[CrossRef\]](#)
- de Wilde, P. Building performance simulation in the brave new world of artificial intelligence and digital twins: A systematic review. *Energy Build.* **2023**, *292*, 113171. [\[CrossRef\]](#)
- Wang, P.; Luo, M. A digital twin-based big data virtual and real fusion learning reference framework supported by industrial internet towards smart manufacturing. *J. Manuf. Syst.* **2021**, *58*, 16–32. [\[CrossRef\]](#)
- Wang, Y.; Kang, X.; Chen, Z. A survey of Digital Twin techniques in smart manufacturing and management of energy applications. *Green Energy Intell. Transp.* **2022**, *1*, 1–11. [\[CrossRef\]](#)
- Chen, Z.; Deng, Q.; Ren, H.; Zhao, Z.; Peng, T.; Yang, C.; Gui, W. A new energy consumption prediction method for chillers based on GraphSAGE by combining empirical knowledge and operating data. *Appl. Energy* **2022**, *310*, 118410. [\[CrossRef\]](#)
- Guo, M.; Xia, M.; Chen, Q. A review of regional energy internet in smart city from the perspective of energy community. *Energy Rep.* **2022**, *8*, 161–182. [\[CrossRef\]](#)
- Feng, C.; Liao, X. An overview of “energy+ internet” in China. *J. Clean. Prod.* **2020**, *258*, 120630. [\[CrossRef\]](#)
- Wang, W.; Yang, X.; Cao, J. Energy internet, digital economy, and green economic growth: Evidence from China. *Innov. Green Dev.* **2022**, *1*, 100011. [\[CrossRef\]](#)
- Ji, Z.; Wang, X.; Wu, D. Research on task scheduling and concurrent processing technology for energy internet operation platform. *Glob. Energy Interconnect.* **2022**, *5*, 579–589. [\[CrossRef\]](#)
- Song, Y.; Xia, M.; Chen, Q.; Chen, F. A data-model fusion dispatch strategy for the building energy flexibility based on the digital twin. *Appl. Energy* **2023**, *332*, 120496. [\[CrossRef\]](#)
- Xie, Y.; Hu, P.; Zhu, N.; Lei, F.; Xing, L.; Xu, L.; Sun, Q. A hybrid short-term load forecasting model and its application in ground source heat pump with cooling storage system. *Renew. Energy* **2020**, *161*, 1244–1259. [\[CrossRef\]](#)
- Aguilar, J.; Garces-Jimenez, A.; R-Moreno, M.D.; García, R. A systematic literature review on the use of artificial intelligence in energy self-management in smart buildings. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111530. [\[CrossRef\]](#)
- Li, J.; Herdem, M.S.; Nathwani, J. Methods and Applications for Artificial Intelligence, Big Data, Internet-of-Things, and Blockchain in Smart Energy Management. *Energy AI* **2022**, *11*, 100208. [\[CrossRef\]](#)
- Mason, K.; Grijalva, S. A review of reinforcement learning for autonomous building energy management. *Comput. Electr. Eng.* **2019**, *78*, 300–312. [\[CrossRef\]](#)
- Li, T.; Zhao, Y.; Zhang, C. A knowledge-guided and data-driven method for building HVAC systems fault diagnosis. *Build. Environ.* **2021**, *198*, 107850. [\[CrossRef\]](#)
- Liu, X.; Jiang, D.; Tao, B.; Xiang, F.; Jiang, G.; Sun, Y.; Kong, J.; Li, G. A systematic review of digital twin about physical entities, virtual models, twin data, and applications. *Adv. Eng. Inform.* **2023**, *55*, 101876. [\[CrossRef\]](#)
- Huang, X.; Liu, Y.; Huang, L.; Onstein, E.; Merschbrock, C. BIM and IoT data fusion: The data process model perspective. *Autom. Constr.* **2023**, *149*, 104792. [\[CrossRef\]](#)
- Zhang, H.; Qi, Q.; Tao, F. A consistency evaluation method for digital twin models. *J. Manuf. Syst.* **2022**, *65*, 158–168. [\[CrossRef\]](#)
- Tao, F.; Xiao, B.; Qi, Q.; Cheng, J.; Ji, P. Digital twin modeling. *J. Manuf. Syst.* **2022**, *64*, 372–389. [\[CrossRef\]](#)
- Ehrhardt, J.M.; Hoffmann, C.T. The digital shadow: Developing a universal model for the automated optimization of cyber-physical production systems based on real-time data. *Procedia CIRP* **2020**, *93*, 304–310. [\[CrossRef\]](#)
- Shen, T.; Zhang, F.; Cheng, J. A comprehensive overview of knowledge graph completion. *Knowledge-Based Syst.* **2022**, *255*, 109597. [\[CrossRef\]](#)
- Chen, Y.; Huang, Z.; Zhou, N. An advanced framework for improving situational awareness in electric power grid operation. *IFAC Proc. Vol.* **2011**, *44*, 12162–12170. [\[CrossRef\]](#)

28. Mariano-Hernández, D.; Hernández-Callejo, L.; Zorita-Lamadrid, A.; Duque-Pérez, O.; Santos García, F. A review of strategies for building energy management system: Model predictive control, demand side management, optimization, and fault detect & diagnosis. *J. Build. Eng.* **2021**, *33*, 101692. [[CrossRef](#)]
29. Yu, W.; Patros, P.; Young, B. Energy digital twin technology for industrial energy management: Classification, challenges and future. *Renew. Sustain. Energy Rev.* **2022**, *161*, 112407. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.