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Key Technologies and Development Modes of Park Energy Internet in Data Centers

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Abstract: Data centers are an important direction of the New Infrastructure initiative, and the energy efficiency of data centers has been a focus of research. Park Energy Internet (PEI) is a system that emphasizes the consumption of clean energy and the promotion of energy efficiency. The "generation, grid, load, storage, and charging" coordination technology of PEI will be key aspects to improving the energy efficiency of data centers. Therefore, exploring the key technologies and development modes of PEI in data centers will be significant. However, the current studies on data centers and PEI have been conducted independently of each other. Therefore, in this study, the integration of data centers with a PEI system is analyzed and the key technologies in equipment planning, DC power distribution, waste heat recovery, multi-energy dispatch, load management, and energy storage dispatch are discussed. On this basis, we propose the infrastructure framework of the PEI system for data centers and explore potential business models. Finally, suggestions for the further development of PEI in the data centers in China are proposed, including technology integration, pilot practice, and policy support.
Keywords: Energy Internet; data center; equipment planning; operation optimization; business model

1 Introduction

With the continuous development and promotion of technologies such as fifth-generation mobile communications (5G) and cloud computing, the amount of data has increased exponentially. As the core aspect of data storage and processing, data centers are being constructed rapidly all throughout China. In March 2020, the Chinese government proposed speeding up the construction of the proposed New Infrastructure initiative, which includes 5G networks and data centers, indicating that, as one of the seven major areas of this initiative, data centers will enter a rapid development stage.

As entities of data storage, calculation, and interaction, data centers include computers, refrigeration, power supply, lighting, and machinery equipment. The data centers are also a data pivot and computing carrier of technologies such as 5G, artificial intelligence (AI), Internet of Things, and cloud computing. This means that data centers have become a significant part of the New Infrastructure. According to the clients they serve, data centers can be classified into the Internet data centers (IDCs), enterprise data centers, and national data centers.

The energy load of a data center differs from typical residential, industrial, and commercial energy loads. The server clusters and cooling systems contained in the data center are high-energy-consuming equipment that operate continuously. With the advancement of the New Infrastructure, the process of data center construction is accelerating. The overall energy demand of such centers will further increase, making the corresponding energy consumption

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issues an important research topic.

Chinese data center projects are mostly implemented in the form of industrial parks, such as the Zhangbei Cloud Computing Industrial Park, Nantong International Data Center Industrial Park, and Ulanqab Big Data Center. This type of construction mode provides application conditions for a Park Energy Internet (PEI) system, which is a multi-energy coupling system based on an electric power network and a natural gas network established on the consumer side. With the aim of optimizing the energy demand, PEI achieves an overall coordination of "generation, grid, load, storage, and charging" in the region based on the combination of Internet and communication technologies. A Park Energy Internet of a data center (PEI-DC) uses the coordinated technologies of "generation, grid, load, storage, and charging" to optimize the energy distribution structure of the park. At the same time, the capability of the center in terms of data search and mining can be used to create an energy portrait of energy users, which will free the potential of the load side. The combination of the two technologies will significantly improve the overall energy utilization efficiency of industrial parks and achieve the effect of 1 + 1 > 2.

At present, studies on both PEI and data centers are relatively independent, focusing on the planning and operating optimization of the PEI [1], data center load scheduling [2], and their perspective system designs. Current studies have not yet focused on combining the characteristics of both elements. The development mode of PEI-DC also lacks existing experience and guidance. Thus, we mainly discuss the key technologies in the planning and operation of PEI-DC, demonstrate its construction, business, and operation mode, and propose countermeasures and suggestions for its future development.

2 Demand analysis of PEI-DC development

The *2019–2020 China IDC Industry Development Research Report* shows that the market size of Chinese IDC business reached 156.25 billion CNY in 2019, with a yearly increase of 27.2%, and is expected to exceed 320 billion CNY in 2022. With the expansion of the market, IDC-related energy consumption is also rising. In 2017, the power consumption of the national data center was $1.2 \times 10^8 - 1.3 \times 10^8$ MWh, which is approximately 3.5-times that in 2009. The overall power consumption of the data centers in China is expected to reach 2.5×10^8 MWh in 2020. The increase in the total energy consumption means that the energy saving of the data center has become an important direction of current research.

The Ministry of Industry and Information Technology as well as the National Energy Administration set clear requirements for the power utilization efficiency (PUE) of data centers in China in the *Guidance on Strengthening the Construction of Green Data Centers*. By 2022, the average energy efficiency of data centers in China will reach the international advanced level, and the PUE value of newly built large/super-large data centers will be lower than 1.4. Meanwhile, old equipment with high energy consumption will be eliminated.

At present, the PUE value of data centers in China is mostly between 1.5 and 1.8, which is still some distance from the advanced international level. The high demand for stability of the power supply limits the efficiency of the data center absorbing clean energy, and the large amount of heat generated by the computers is not efficiently utilized after removal by the cooling system. Improving the ability of the data center to absorb clean energy and make full use of the waste heat will be key to solving its energy consumption problem.

The application of PEI technology will therefore be one of the effective countermeasures to solve this issue. The collaborative management of a PEI generated energy load should be applied to ensure the stability and reliability of the energy supply of the center while consuming clean energy. The waste heat in the data center can also be fully recovered owing to the comprehensive utilization of multiple energy sources such as cold, heat, electricity, and gas. Through the construction of PEI-DC, the "generation, grid, load, storage, and charging" in the park area can be efficiently coordinated to improve the overall energy efficiency of the data center. However, the current research on combining a PEI system and a data center has not been fully integrated, restricting the development of PEI-DC to a certain extent. The key factors of technology integration between a PEI system and a data center can be divided into two major parts: the construction and operation of PEI-DC, which can be subdivided into equipment planning, DC power distribution, multi-energy scheduling, waste heat recovery, load management, and energy storage scheduling.

3 Development status of Park Energy Internet

3.1 Foreign development status

After first proposing the concept of PEI in 2008, American scholars mainly focused on the architecture design of related systems. In the Future Renewable Electric Energy Delivery and Management System (FREEDM) project,

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the UNC research team proposed the concept of an energy router and built a system prototype that uses power electronics and communications technology to control power devices in the region as well as interact with it. The UC Berkeley team focused on the integration of information and power transmission protocols to make flexible use of electricity and price information in a distributed manner. The Purdue team paid further attention to the role of energy storage in the energy Internet. On the user side, Opower integrates energy and information networks using smart meters and smart grid technologies. Through big data computing and mining on the cloud platform, Opower integrates and analyzes data on the energy consumption of users, establishes household energy consumption archives, and provides users with personalized energy usage and saving suggestions.

Europe is also actively pursuing PEI. The Germen eTelligence project focuses on the utilization of wind energy in ports, and explores the improvement of regional energy efficiency through a combination of distributed clean energy resources, energy storage, and cogeneration of heat and power. The Manchester Demonstration Project is focusing on heating problems in the area, and is developing a comprehensive energy system for electric–heat–gas–water use and a user interaction platform. Efficient energy use is achieved through combined cooling, heating, and power supply as well as demand response. The E-DeMa project highlights multi-agent interaction in the region, integrating users, generators, e-commerce vendors, and operators through smart energy routers, which enable transactions of electric energy and reserve capacity within a unified system.

Japan is paying greater attention to the centralized dispatch of electric energy, managing its electric power through power routers. By allocating the corresponding "IP addresses" to generators, power converters, wind farms, solar cells, and other infrastructure, the power routers eventually complete the energy distribution within the grid.

3.2 Domestic development status

The practice of PEI in China is relatively late; however, the basic structure, planning, and operation of PEI have been explored. To implement the *Guidelines on Promoting the Development of Internet Plus Smart Energy*, the National Energy Administration launched the application of the Internet Plus smart energy (energy Internet) demonstration project in July 2017. The first batch of 55 Internet Plus smart energy (energy Internet) demonstration projects was announced, including the Beijing Yanqing Energy Internet Comprehensive Demonstration Area and Park Energy Internet Pilot Demonstration, indicating that PEI in China has entered a stage of practical demonstration. In December 2018, the National Energy Administration issued the *Notice on the Acceptance of the Development of Internet Plus Smart Energy (Energy Internet) Demonstration Projects* requiring accepted work to be completed by the end of April 2019.

Chinese PEI is developing toward multi-energy complementation. At present, Chinese PEI is mainly focused on the overall scheduling of electricity, gas, cold, heat, and other energy resources in park areas based on electric power and natural gas networks. Moreover, technologies such as combined heat and power generation, combined cooling heating, and power systems are used to realize the efficient utilization of energy. On this basis, the influence of distributed new energy resources, energy storage, and demand response during planning and operation have been further considered. Unlike Europe and Japan, China has a vast landmass with obvious differences in natural resources and social development among different regions. Therefore, PEI in China should be combined with the actual situation of each region to realize the integration of physical models and information structures in PEI. At the same time, multiple energy sources in PEI should be used efficiently, and multi-agents in the area should be able to participate. Furthermore, the potential of the demand-side market should be fully stimulated.

4 Key technologies and analysis of PEI-DC

4.1 Planning and building technology

4.1.1 Equipment planning technologies of PEI-DC

At present, most research in this field is aimed at completing the planning of energy equipment in the park through mathematical analytical calculations or modeling optimization solutions under the constraints of different indicators, thereby making the equipment planning scheme in the park more economical, environmentally friendly, and reliable.

(1) Empirical calculation planning method

According to engineering experience and various design principles, such as power determined by heat, heat determined by power, planning by area, and planning by proportion, the designer plans the energy equipment in the area. In [3], a combined cooling heating and power system was designed, the photovoltaic capacity was determined according to the roof area, and the equipment capacity was determined according to the requirements of the average heat load, average cold load, and 50% electric load. In [4], the cooling, heating, and electricity load of a station complex based on the principle of meeting the load demand was considered, and two different planning schemes were compared based on power determined by heat and heat determined by power. The empirical calculation method has a relatively intuitive calculation and a simple process. However, the economic and environmental indicators of the planning scheme are not strictly considered, and are only applicable to a small range of energy equipment planning within PEI-DC. There are certain problems in the overall planning, such as an over-simplification and an insufficient consideration of the interactive operation of various energy equipment.

(2) Modeling planning method

Modeling planning methods usually establish mathematical models for the overall programming objectives, construct objective functions based on different planning objectives, and solve the objective function to achieve the optimal configuration of the plan in terms of economy, environmental protection, and reliability as well as a mutual balance between multiple indicators. Compared with the empirical method, equipment planning by solving the model can usually find the optimal configuration under different indicators, but the results depends on the accuracy of the modeling. A model with more accuracy will increase the complexity of the model and the difficulty of solving it. In addition to planning indicators, uncertainty, as an important consideration of multi-time scale planning, is receiving increased attention. Through the interval optimization technology based on the worst condition [5] and the stochastic planning technology based on the scenes [6], the planning scheme becomes adaptable to uncertainty at different time scales.

Although the above research on planning lacks consideration of the energy usage and development characteristics of data centers, it provides a relatively complete technical basis for the construction of PEI-DC. In general, the planning of a data center needs to consider demand changes during the next 10 to 15 years. However, the Internet-based business structure of PEI-DC makes it difficult to make long-term load forecasting in traditional ways, which brings about a time-scale challenge to PEI-DC equipment planning. The significant variability of the data center’s power demand also tests the scalability of the planning scheme. Therefore, the planning of PEI-DC should give full consideration to information such as energy policy, regional characteristics, and regional supply demand characteristics, combined with information technologies such as big data and cloud computing to accurately portray the future development of the region to ensure the beneficial result of the planning scheme.

4.1.2 DC distribution technology in PEI-DC

In recent years, DC distribution systems (DCSs) have attracted attention owing to such advantages as a larger transmission capacity, better power supply quality, easy acceptance of distributed generation, and higher controllability [7]. Most of the electronic components of the data center are driven by DC power. At the same time, DCS has inherent advantages in the application of distributed generation, energy storage, charging stations, and flexible loads [8]. Therefore, studying DC distribution technology in PEI-DC will contribute to the wide access of new energy and energy storage in the park as well as support the realization of intelligent control on the load side. As an intelligent distribution system providing DC power based on a voltage source converter, DCS has the advantages of a high-quality power supply and is suitable for interactive access, but its reliability, stability, and economic problems should also be considered. At present, DCS research focuses more on technologies such as control and stability, fault identification and protection, topology, and networking. However, the above-mentioned studies focus on the independent operating environment of DCS, while less consideration is given to the operating environment with multiple energy sources such as PEI-DC.

Compared with the AC distribution system, DCS built in PEI-DC reduces the transformation steps in which all types of energy equipment are connected to the distribution system. At the same time, it reduces the cost while improving the power density and efficiency [9]. The distribution bus of DCS does not have the problem of phase and frequency synchronization, which supports the plug-and-play of generation, load, storage, and charging equipment in the park, simplifies the control and improves the reliability. DCS in PEI-DC should take full advantage of the close combination of physical and information networks in the park. At the same time, researchers should look deeply into real-time information acquisition and transmission technology as well as massive rapid data processing technology, and use these technologies in DSC control, operation, and protection to improve the flexibility and reliability of DCS.

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4.1.3 Waste heat utilization of PEI-DC

The energy consumption of the cooling system accounts for approximately 30%–40% of the total energy consumption of the data center, and is of great significance for effectively utilizing the heat generated by the cooling system. Constructing a PEI-DC waste heat utilization system, combined with PEI-DC multi-energy scheduling technology, will make full use of the waste heat recovered from the data center, which will effectively improve the energy efficiency of the park area, and further reduce the PUE of the data center. In [10], a data center is used as a node to establish a district heating model, and the energy-saving significance of waste heat utilization are analyzed and verified. In [11], the data center is considered as a heat generation in a district heating system, and its benefits of energy saving and economic operation are analyzed. In [12], a waste heat utilization scheme based on thermosiphon/vapor compression cycle composite refrigeration technology was proposed, and a time-based steady-state model was used to analyze the heating effect.

Most of the current research on data center waste heat utilization systems is based on the field of refrigeration, which is relatively complex and difficult to integrate with models from an electric power field. The combination of the current waste heat utilization system model and the PEI-DC planning and operation model still needs work. From the perspective of electric power engineering, the mathematical model of the waste heat utilization system should be simplified. The key data related to system cost, consumption, and efficiency should be extracted from the model, allowing a suitable waste heat utilization system model for the PEI-DC framework.

4.2 Operation and control technology

4.2.1 Multi-energy scheduling technology of PEI-DC

PEI-DC is a system containing multiple energy sources such as cold, heat, electricity, gas, and various types of energy equipment. Efficient scheduling of PEI-DC is the key to realizing the "generation, grid, load, storage, and charging" coordination in the park. There have been many studies on multi-energy scheduling, most of which take economy, environmental protection, reliability, and energy utilization as indicators to seek an optimal scheduling method for various types of energy equipment [13], and discuss the impact of equipment type, energy prices, user comfort, and various control methods on the scheduling results. As a system containing multiple forms of energy, PEI-DC is far more complicated in terms of uncertainty than a single system. Uncertainty may affect the PEI-DC energy production, energy transmission, energy transformation, energy consumption, and many other parts. Therefore, it is also important to study uncertainty handling in PEI-DC multi-energy scheduling. At present, relevant research mainly uses interval optimization [14], scene-based stochastic optimization [15], and various improved forms of robust optimization [16] to improve the system's ability to handle uncertainty. However, the research mentioned above does not consider the energy demand characteristics of the data center.

Multi-energy scheduling technology is a basic aspect of PEI-DC waste heat utilization, load management, and energy storage scheduling. Therefore, it is important to study an efficient scheduling method of PEI-DC and fully consider the PEI–DC business form under the current state of the Internet. By associating the business characteristics of a data center with the energy demand characteristics through a conversion model, PEI-DC can be a stable, efficient, and environmentally friendly approach.

4.2.2 Load management technology of PEI-DC

As a high-energy-consuming facility that runs uninterruptedly, the energy demand of a data center fluctuates significantly. The difference in energy consumption between the full load and no-load can reach 100%. The demand for energy supply stability restricts the consumption of uncertain new energy as well as adding standby redundant equipment. Through the optimized management of the data center load, the peak-to-valley difference in energy demand is reduced, renewable energy is absorbed, and the economy and environmental friendliness of the data center are improved. In [17], the workload of the data center is managed through an intelligent algorithm, which optimizes the start and stop of the server through load centralization, thereby reducing the energy consumption by more than 6.1%. On this basis, in [18], the energy purchase cost of the data center is reduced by shifting the load over time based on the real-time electricity price. In [19], access of renewable energy on the basis of real-time electricity prices is further considered, and the data center load is matched with renewable energy through scheduling strategies.

Looking at the entire PEI-DC, if the load control capacity of the data center is the only consideration in PEI-DC load management, it will greatly limit the operation optimization of the park. Other types of loads (e.g., industrial, commercial, residential, and electric vehicles) that may exist in the park should also be considered in the PEI-DC load management. For example, a centralized incentive demand response based on a dispatch center and a demand response based on energy price, as well as considering the influence of uncertainty, can ensure the economy and stability of PEI-DC multi-energy scheduling, while enhancing the controllability. By combining the methods mentioned above with the load management technology of the data center, a complementation of the two will significantly improve the load management of the park, enhancing the PEI-DC's ability to absorb clean energy and the reliability of the energy supply. Moreover, it will provide capacity support while equipment failure occurs, reduce the demand for data center reserve capacity, and improve the economy.

4.2.3 PEI-DC scheduling technology considering energy storage

As an important energy equipment in PEI-DC, energy storage can play a key role in the optimal scheduling of energy. Through the installation of multiple energy storage devices such as electricity storage, natural gas storage, hydrogen storage, cold storage, heat storage, and other types of energy storage devices, the ability of the PEI-DC to absorb clean energy and cut the peak energy expenditure is strengthened. At the same time, the economy and environmental friendliness of the PEI-DC are improved. The standby technology of energy storage is used to improve the stability of the system stability and balance the stability and economy of the energy storage scheduling. In [20], a hybrid hydrogen-natural gas energy storage system scheme based on renewable energy generation technology (i.e., power to gas, P2G) with intermediate buffer links was proven to be economical and environmentally friendly under scenarios with different levels of wind power penetration. In [21], heat storage is considered in a PEI system, and a multi-stage elastic scheduling strategy is proposed in an integrated electric and gas energy system, which can significantly improve the adaptability of the system to failures with the minimum reserve capacity. In [22], the authors considered the scheduling of multiple energy storage under multiple time scales, and minimized the energy purchase costs, penalty costs, and power adjustments through rolling control, which reduces the impact of uncertainty on the system while ensuring the economy of the system.

PEI-DC load management technology can also improve the economic benefits, provide reserve capacity, and improve the system stability when applied to optimal scheduling. Compared with energy storage, PEI-DC load management technology has the advantages of a lower unit cost and greater potential, while also having the disadvantages of uncertainty and a slower response under sudden failures. Combined with the energy storage characteristics of the determined power and a fast response, it can further reduce the reserve capacity in the data center and lower the equipment investment. Researchers should perfect the PEI-DC scheduling technology in the area of energy storage when considering the characteristics of the PEI-DC in terms of high demand for stability and a large reserve capacity.

5 Development model of PEI-DC

5.1 Construction model of PEI-DC

In the construction of PEI-DC, the advantages of a PEI system in a multi-energy interconnection and those of a data center used in data integration computing should be combined to realize the connection between the physical level and the information level of the entire park. First, the electric, gas, heating, and cooling networks in the park are coupled with each other through energy conversion equipment, and the PEI multi-energy scheduling technology is used to realize the complementarity between different types of energy. Second, the energy network connects with the data center at the physical level to realize the efficient power supply of the data center. Finally, through the intelligent sensors widely distributed throughout the park, massive data of the energy equipment and energy users can be collected and unified in the data center through the communication network of the park, which would realize the connection of the entire park at the information level.

PEI-DC coordinates the energy production, conversion, storage, and consumption within the park area, and integrates multiple kinds of energy, including cold, heat, electricity, and gas. Within the park area, the information network is closely connected to the energy network (Fig. 1). Compared with the industrial park of a general data center, PEI-DC has the following distinct characteristics:

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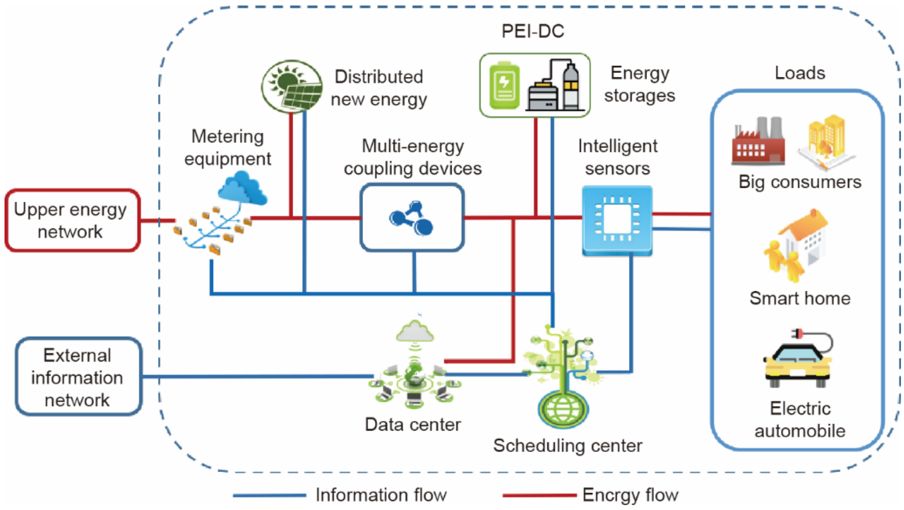

Fig. 1. Basic structure of PEI-DC.

(1) Massive access is given to newly distributed energy. The multi-energy supply and its scheduling technology of PEI-DC will significantly enhance the ability of the PEI-DC to absorb new energies, and the access of the newly distributed energy will effectively improve the environmental friendliness of the energy supply of the data center.

(2) Intelligent power terminals are widely available. The close combination of the physical level and information level enables all links in the park to interact more frequently. The efficient information flow between the sensor equipment and data center will help the intelligent power terminal to exert its potential for load management.

(3) Efficient and reliable energy supply. The PEI-DC is equipped with energy storage devices of various kinds of energy, which can quickly provide backup capacity through energy storage scheduling in the case of failure in the park, thus providing a stable and reliable energy supply for the data center.

(4) Data-driven park management. Massive information of the park collected by intelligent sensors is collected in the data center. Through big data mining technology, data-driven source/load forecasting, equipment monitoring, and load management are realized in the park.

According to the PEI-DC planning and building technologies, efficient equipment deployment and network design in the park should be carried out. Combined with the PEI-DC operation and control technology, the coordination of "generation, grid, load, storage, and charging" in the park should be realized, balancing the economy, reliability, and environmental protection of the park to achieve an efficient and green operation of a PEI-DC.

5.2 Business model of PEI-DC

Combined with the data mining and data processing functions of the data center, the operation of a PEI-DC can realize a combination of energy flow and information flow between the park and users, and make full use of renewable energy to improve energy efficiency. Meanwhile, it provides users with personalized services that create new business models. The exploration of business models can help PEI-DC realize the optimal allocation of resources and highlight its competitive advantages.

5.2.1 Clean energy supply services supported by big data

When numerous distributed clean energy devices are connected to the park, it not only provides a clean energy supply but also restricts the consumption of clean energy owing to its high volatility and uncertainty. Therefore, it is necessary to find an appropriate method to make fast and accurate output forecasts. The intelligent sensors in the park can collect massive amounts of data, which provide a foundation for the application of big data technology. Combined with data analysis and weather modeling technology, hybrid renewable energy forecasting can be carried out, which will enable rapid power assessment under massive data. Massive user data can be used for load forecasting, developing appropriate incentives according to the user's characteristics, which will promote new energy consumption as well as improve the overall cleanliness of the energy consumption in the park. On this basis, for users with special needs, PEI-DC can dig deep into their data, characterize their energy use, and perform source-load matching to provide users with more stable and reliable clean energy supply services.

5.2.2 High reliability power supply service based on big data analysis

Some energy users of PEI-DC have higher requirements for energy supply reliability, and thus providing high reliability energy for such users will be one of the service directions of PEI-DC. Using the massive data collected during the operation of the park, through a big data analysis and AI technology, the park can master abnormal problems and potential risks and control the running status in real time, allowing the risks to be avoided in advance. By using big data technology in macro- and micro-load forecasting, the accuracy of the forecast can be improved, and more accurate scheduling can be achieved, thereby improving the overall stability of the park. On this basis, PEI-DC can launch an analysis of value-added services for users based on a big data analysis. At the same time, combining a data analysis with scheduling, the energy storage scheduling and load management methods of the PEI-DC must meet customer-specific needs and provide a reliable energy supply.

5.2.3 Intelligent services powered by 5G and the Internet of Things

PEI-DC gives the data center more freedom in site selection. It is no longer limited to being built near a power plant that provides sufficient power, or a low-temperature climate that reduces the energy consumption of its cooling system. It can be built closer to the user side. This provides favorable conditions for intelligent services in and around the park. Through 5G technology, devices in or near the park will be able to interact with the data center efficiently. The stable and lower-than-1 ms latency connection from devices to the data center enables automatic vehicle driving, virtual reality, and augmented reality systems to maintain efficiency while saving the local data storage, and in turn, depends on the data center, which is stronger in data storage and computing. Combined with the Internet of Things, various terminals in the park can be connected to the cloud, and the 5G network can provide a stable and efficient connection. On this basis, PEI-DC can provide diversified intelligent value-added services.

6 Key points for the future development of PEI-DC

6.1 Data-driven operation method of Park Energy Internet

Intelligent sensors widely spread throughout the PEI-DC collect a large amount of information, including real-time and historical data of the park's weather, load, traffic, energy grid, and energy equipment. Through related data-driven technologies, these data can be effectively used, which will better support the running of the PEI-DC. There have been some studies on data-driven new energy output forecasting, short-term load forecasting, electric vehicle charging forecasting, and solving the thermoelectric coupling system power flow, although these studies are relatively independent. In a PEI-DC, as a tightly coupled system, all links from the energy production to consumption are interrelated and affect each other, and research from a single perspective will have insufficient consideration regarding the overall effect of the PEI-DC. The close connection between the PEI-DC and its information and physical levels enables the data-driven operation of the PEI-DC. Further research should start from the overall perspective of the PEI-DC, study the application of data-driven technologies in the generation, grid, load, storage, and charging of the park, making full use of the data integration, calculation, and distribution capabilities of the data center. Moreover, 5G, the Internet of Things, and other technologies should be adopted in PEI-DC to realize low-latency and high-frequency interaction from the data center to the edge devices as well as to promote the operation efficiency of the PEI-DC.

6.2 Multi-park coordinated operation considering the spatial characteristics of the data center load

With the acceleration of the digitization process and the promotion of relevant policies of the New Infrastructure initiative, industrial park projects of data centers will be continuously implemented, gradually forming a situation in which multiple industrial parks are closely interconnected in terms of energy and information systems. Under the background of Chinese electric power system reformation and an energy structure transformation, with the relaxation of market regulations, the electric power and energy market began to gradually increase. In an open energy market, multiple PEI-DCs in a region take the energy price as a guide and cooperate in the game according to their own interests, which will inevitably bring about challenges to the stability and economy of the entire region. At present, there have been studies on the optimal scheduling of multiple parks in the region based on energy price, but they have lacked consideration of the temporal and spatial characteristics of the load of the data center. The loads in the above studies are all local and can only be shifted or reduced in time according to the energy prices. Differently, the

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loads of the data center can be transferred between data centers through the Internet according to the difference in regional energy prices, and thus the spatial load transfer can be completed. Therefore, in the regulation of multiple PEI-DCs, the time and spatial characteristics of the data center load should be further considered to balance the load distribution in time and space within the region, and ultimately achieve an overall efficient operation of the region.

7 Suggestions on the development of PEI-DC

(1) Technical level - The technical barriers between the PEI and the data center should be prioritized. The models of the data center cooling system applied in current research are unsuitable for an electric power field, and the characteristics of the data center load have been rarely considered in the planning and scheduling research of the PEI. The key to the current study is to modify the two models or combine them through an interface design such that a unified PEI-DC planning/operation model can be established.

(2) Practical level - Different regions in China have obvious differences in natural resources, social development, load types, and levels, among other factors. Therefore, the construction of a PEI-DC should not be based on fixed standards, but should be considered in combination with the actual situation of the region. The region suitable for PEI-DC development should first be selected as a pilot project to carry out practical studies on a PEI-DC according to the local conditions, thus allowing the construction and operation experience of the PEI-DC to be gathered. Meanwhile, the practices should follow the New Infrastructure initiative and explore the mutual combination of PEI-DC, 5G, big data, Internet of Things, and other hotspot technologies.

(3) Policy level - Compared with a traditional power system, a PEI-DC requires a relatively high investment in terms of the initial construction. Relevant policies such as fiscal incentives and tax exemption can be introduced to promote the investment and construction of a PEI-DC. At the same time, the government should improve the regulatory system to ensure the scientific and fair development of PEI-DCs. Further, an energy market support mechanism should be established. Under a perfect market mechanism, each subject in the PEI-DC interacts and trades properly, activating the potential of the PEI-DC in terms of load management, source-load coordination, and multi-energy scheduling.

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