China's green data center development: Policies and carbon reduction technology path

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Abstract

Data center is a very important infrastructure to support the development of information technology, and its development and increment are very remarkable. However, with the rapid and large-scale development of data centers, the problem of energy consumption turns to be also very prominent. Under the background of global carbon peak and carbon neutrality, developing green and low-carbon data centers has become an inevitable trend. This paper reviews and analyzes the policies and their roles in promoting China's green development of data centers in the past 10 years, summarizes the current situation of the implementation of green data center projects in China and gives the changes of PUE limits of data centers under the policy constraints. Application of green technologies is an important measure for energy-saving and low-carbon development of data centers,

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so encouraging innovation and application of green technologies in data center is also a priority task in relevant policies. This paper points out the green and low-carbon technology system of data centers, further summarizes energy-saving and carbon-reducing technologies in IT equipment, cooling system, power supply and distribution system, lighting, intelligent operation and maintenance, and provides an outlook on the future green development of data centers.

Keywords: Data center; Green development; Green data center; Energy saving; Low carbon

1. Introduction

With the rapid development of 5G, cloud computing, artificial intelligence and other new generation information technologies, data center is an indispensable infrastructure in the era of digital economy. The number of data center cabinets in China has increased rapidly, from 1.08 million cabinets in 2015 to 2.39 million cabinets in 2020 (Wang et al., 2022). With the increase of the number of data center cabinets, there is also a huge power consumption. At the global level, data center energy consumption accounted for 0.9% of global energy consumption in 2015, and is expected to reach 4.5% in 2025 and 8% in 2030 (Wang et al., 2020). China's data centers accounted for 2.71% of the national electricity consumption in 2020 and are expected to account for 4.05% in 2025 (Zhang et al., 2021). Among them, the energy consumption of IT equipment accounts for a relatively large proportion, about 30-50%; the energy consumption of cooling system is about 25-45%; the energy consumption of power supply and distribution system and lighting system accounts for about 13-25% (Liao and Wu, 2014; Hong, 2018; Liu, 2015; Han et al., 2021; Shao et al., 2022; Hu et al., 2019; Qian, 2015). With the gradual increase in energy consumption of data centers, carbon emissions also increase, posing a threat to the environment. According to statistics, data centers produce carbon emissions amounting to 98.55 million tons of carbon dioxide in 2018; data centers produce 94.85 million tons of carbon emissions in 2020 (Liu et al., 2021). The problems of high energy consumption and high carbon emission of data centers are becoming more and more prominent, and accelerating the construction of green and low-carbon data centers has become an important development goal.

Some countries in the world have studied the green development of data centers. The United States, the European Union and other countries have stipulated the energy efficiency indicators that indicate the energy-saving level of green data centers, and formulated the evaluation standards of green data centers to carry out the rating of data centers (Li, 2013; Gong and zhao, 2021). Similarly, green data centers have been studied in China. In terms of data center standard evaluation system, the Ministry of Housing and Urban-Rural Development released the *Technical Rules for Green Data Center Building Evaluation* in 2015; Chinese Institute of Electronics released the *Green Data Center Evaluation Guidelines (T/CIE 049-2018)* in May 2018; China Academy of Building Research released the standard *Green Data Center Evaluation Standard (T/ASC 05-2019)* to evaluate and grade green data centers in 2019. In terms of data center policies, the policy of promoting green data centers was proposed in 2012, and a series of policies and measures were introduced in the following years, which standardized and guided the green development of data centers.

This paper firstly analyzes the policy context of China's data center green development in the past 10 years and the current situation of green data center development. This paper also studies the limit change and current situation of PUE, an index for measuring data center energy efficiency, and finally proposes the technical path of data center energy saving and carbon reduction in order to provide reference for data centers in realizing green and low carbon development.

2. Policy development of green data centers in China

2.1 Promoting policies and roles

In the face of the rapid growth of carbon emissions and energy consumption in data centers, relevant departments have issued policies to promote the green development of data centers to support the construction of new-generation green data centers(Li, 2011). As early as 2011, the *"12th Five-Year" Plan for Energy Conservation in Public Institution* proposed to actively promote the construction of green data centers, and in 2012, the Ministry of Industry and Information Technology assumed the role of "government first" and released the *"Twelfth Five-Year" Plan for energy saving in industry*, which included green data center as one of the key promotion work and started the green construction of data center in China.

Through a series of policies issued by the state, the development trend of applying, innovating and promoting the green technologies of data centers, innovating and promoting the efficient energy utilization and new energy technologies, formulating and improving the standards and evaluation system of data center, and carrying out the pilot work of data center is formed, which actively guides the green development of data center. The policies have played three significant roles in guiding and promoting the development of green data centers:

（1）Spawning green data center technical standards

Both the construction industry and the IT industry have realized the importance of green data centers, and many discussions have been triggered around green data centers. Although foreign countries have standards related to green data centers (Song ang Zhang, 2014; Yang et al., 2016), there is no measurement standard for green data centers in China at the early stage of green data center development. Industry practitioners realize that "the essence of a green data center is not simply to purchase new generation products, and the most efficient data center is not necessarily green" (Lv, 2009), but there is no universally accepted answer to the questions of what is a green data center and what standards should be used for the design and construction of a green data center.

In January 2013, China's Ministry of Industry and Information Technology and other relevant departments issued the *Guiding Opinions on the Construction and Layout of Data Centers*, which called for strengthening the standardization of data centers, studying and formulating standards and corresponding evaluation methods on energy efficiency, security and other aspects, so as to promote the development of green data centers to standardization. Subsequent policies such as the *National Green Data Center Pilot Work Plan* in March 2015, the *Guiding Opinions on Strengthening Energy Conservation and Emission Reduction in the "13th Five-Year" Plan for Information and Communication Industry* in April 2017, the *Guiding Opinions on Strengthening the Construction of Green Data Center* in January 2019, and the *Three-year Action Plan for the Development of New Data Center(2021-2023)* in July 2021, have gradually formed the technical standard planning of green data centers, and constantly put the major task on the evaluation system and technical standard of green data centers.

Under the combined promotion of technology development and policy support, industry practitioners and researchers have formed a relatively complete and applicable set of technical standards for green data centers through continuous research and practice. Policy guidance has laid an important foundation for the standardized development of green data centers in China.

（2）Promoting the implementation of green data center projects

The *National Green Data Center Pilot Work Plan* released in March 2015, with the goal of establishing the promotion mechanism of green data centers and guiding the overall improvement of energy-saving and environmental protection level of data centers, identifies a number of tasks such as technology innovation and promotion, green operation and maintenance system, index monitoring and evaluation system, etc, and clearly requires the creation of data center pilot work, supported by technology innovation and promotion, guaranteed by standard development and technical evaluation, so that the green data center pilot plays a radiation leading role, forms a replicable promotion model, and guides the data center to take the road of green development. This policy has opened the curtain of green data center development, which is of great significance to the development of green data centers for the better.

In accordance with the requirements of the *Notice on the Evaluation of National Green Data Center Pilot Units* issued in June 2017, relevant departments jointly carried out pilot evaluation of data centers, mainly evaluating the work of data centers in the promotion and use of advanced applicable technologies, the construction of operation and maintenance management systems, energy efficiency improvement, water resources utilization, control of hazardous substances, disposal of waste electrical and electronic equipment, renewable energy and clean energy application, etc, and announced the list of the first batch of green data centers in December 2017, thus guiding more data centers to take the green development path. This work has promoted the leap of green data center projects from non-existence to existence, and realized the great transformation of green data centers from green concepts to actual projects. Based on the accumulated experience of green data center development, the *Guidance on Strengthening Green Data Center Construction* was issued in 2019 to further strengthen and guide the development of green data centers at the policy level.

（3）Improving the level of green energy saving and emission reduction in data centers

Data center related policies have long focused on "green, energy saving and emission reduction". The Opinion on *Promoting Innovative Development of Cloud Computing and Cultivating New Business Forms of Information Industry* issued in January 2015 supports the use of renewable energy and energy-saving and emission reduction technologies to build green cloud computing centers. In 2017, the *Guiding Opinions on Strengthening Energy Conservation and Emission Reduction in the Information and Communication Industry in the "13th Five-Year Plan"*, the policy requires promoting the efficient use of electric energy, innovating and promoting green energy-saving technologies and equipment, and increasing the proportion of new energy sources such as wind and solar energy; the *Guiding Opinions on Strengthening the Construction of Green Data Centers* issued in January 2019 specifies the energy-saving and low-carbon technology application direction, requiring upgrading the green development of new data centers, encouraging the use of clean energy utilization systems such as natural cooling sources, waste heat recovery and utilization or renewable energy power generation, strengthening the green operation and maintenance transformation of in-use data centers, and accelerating the innovation and promotion of green technology products, etc.

In 2020, China set the goal of "peak carbon dioxide emissions in 2030 and carbon neutrality in 2060", which means that the total annual carbon dioxide emissions reached the highest value in a certain period of time, and then gradually decreased after reaching the peak value. If the man-made carbon dioxide is offset by planting trees, saving energy and reducing emissions, carbon capture and carbon sequestration in a certain period of time, the net emission of carbon dioxide will be zero, thus achieving "carbon neutrality". Environmental policies to control carbon emissions mainly include carbon tax and carbon emission trading system. Among the current carbon tax policies in

China, the emission reduction policies are mainly divided into two categories. One is the taxes that are conducive to reducing fossil energy consumption and related policies, such as imposing resource taxes on crude oil, natural gas and coal. The other is the preferential tax policies that are conducive to promoting the development of low-carbon technologies, such as the reduction and exemption policies for promoting low-carbon development in corporate income tax and the credit policies for investment in energy-saving equipment, the reduction and exemption policies for contract energy management projects in value-added tax, and the preferential policies for taxpayers to sell their own power products generated by wind power.

Under the goal of "double carbon", the relevant policies of data center also conform to the background of the times, starting with the *Three-Year Action Plan for the Development of New Data Centers (2021-2023)* released in July 2021, highlighting the construction of green low-carbon data centers, accelerating the use of advanced green and low-carbon technology products, continuously improving the level of efficient and clean use of energy, and optimizing green management capabilities; *Several Opinions on Strict Energy Efficiency Constraints to Promote Energy Saving and Carbon Reduction in Key Areas* released in October 2021, which encourages energy saving and carbon reduction in infrastructure such as green data centers in the field of data centers. *Implementing the Carbon Summit Carbon Neutral Target and Promote Green and High-Quality Development of Data Centers and 5G and Other New Infrastructure Implementation Plan*, which requires innovative energy-saving technologies, optimization of energy-saving modes and utilization of green energy, as a way to promote green and low-carbon development of data centers and enable data centers to actively join the ranks of carbon reduction.

2.2 Current situation of green data center construction in China

Based on the evaluation technical standards of green data center, 153 green data centers have been constructed, which are widely distributed in various provinces and cities in China (as shown in **Fig.1**). Among them, Guangdong, Beijing, Jiangsu, Shanghai and Hebei have more green data centers, followed by Sichuan, Guizhou, Chongqing and Inner Mongolia, fewer green data centers located in Fujian, Shanxi, Liaoning, Jilin and Tibet.

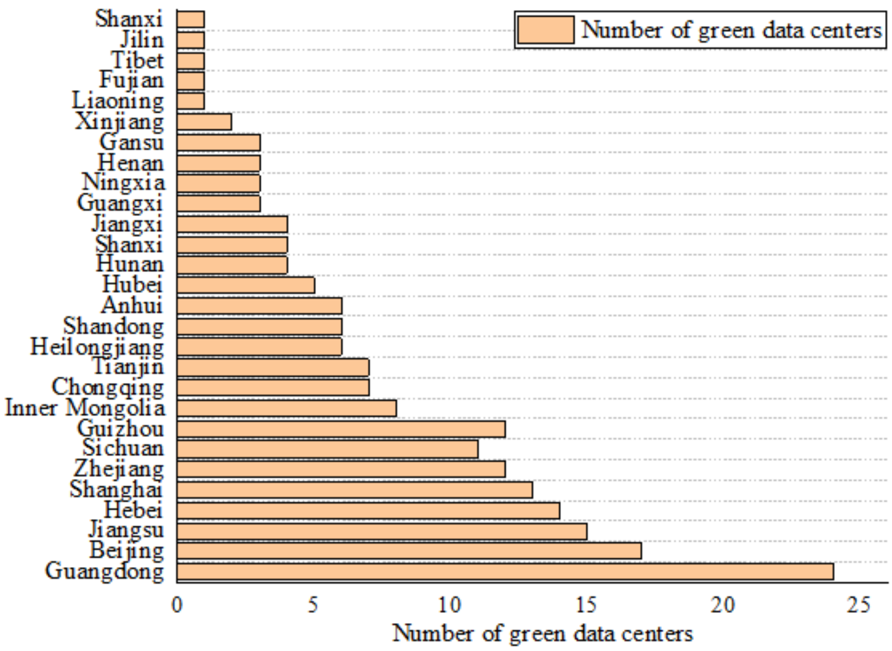

Fig.1. Distribution of green data centers in China.

The green development of data centers is inseparable from the support of green technologies. **Table 1** gives some green data centers and the green technologies they use. It can be seen that the green technologies used in these green data centers mainly focus on cooling systems, power supply and distribution, renewable energy utilization and operation and maintenance management.

Table 1

Green technologies used in some green data centers.

Data center name	Region	Green technology
Capital Ring - Taihang mountain energy information technology industry base	Shanxi	Adopt prefabricated integrated calculation module; use indirect evaporative cooling equipment for cold source; give priority to renewable energy generation; use waste heat recovery to provide office heating, etc.

Global data solutions limited (Shanghai No.4 data center)	Shanghai	Adopt one way utility + one way high voltage direct current (HVDC) supply and distribution system; increase the proportion of green power usage; AI intelligent empowered operation and maintenance management, etc.
China telecom cloud computing inner Mongolia information park A6 data center	Inner Mongolia	The power supply mode is mainly one way utility + one way high voltage DC; improve the chiller chilled water temperature, adjust the pump frequency to save energy, optimize the operation of the air conditioning end, use plate exchange to achieve natural cooling, etc.
Shurong cloud computing data center	Beijing	Implanting artificial intelligence (AI) control technology into building automation control systems; maximizing the use of natural cooling throughout the year; actively participating in renewable energy procurement, etc.

3. Data center PUE development under the policy driven

3.1 Data center PUE targets

For the safe operation and energy-saving evaluation of data centers, it is very important to select appropriate energy efficiency evaluation indicators (Zhang et al., 2022). Among them, PUE (Power Usage Effectiveness), as a common indicator to measure the efficiency of energy utilization in data centers, was first proposed by Malone et al in 2006. In 2007, TGG (The Green Grid) gave the definition and calculation method of PUE (Yin et al., 2017). PUE is defined as the ratio of total energy consumption of data center to energy consumption of IT equipment, which can be calculated by the following formula:

$$PUE = \frac{P_{total}}{P_{IT}}$$

Where: P_{total} is the total energy consumption of the data center, including the energy consumption of IT equipment, air conditioning, power supply and distribution system and lighting; P_{IT} is the energy consumption of IT equipment.

It can be seen that the closer its value is to 1, the higher is the efficiency of energy utilization of the data center. Therefore, data centers take PUE as one of the evaluation indicators of whether to save energy, which laterally reflects the green energy saving level of data centers. In recent years, China has issued relevant policies and made requirements on data center PUE value for many times to regulate the energy consumption management of data centers.

As shown in **Fig.2**, from the requirements of policy documents issued by the China at different times, the PUE limit value changes from 1.5 in 2013 to 1.4 in 2017, and then to 1.3 in 2021. The change process of PUE limits reflects the China's high attention to energy saving and emission reduction, and the firm determination to build green data centers.

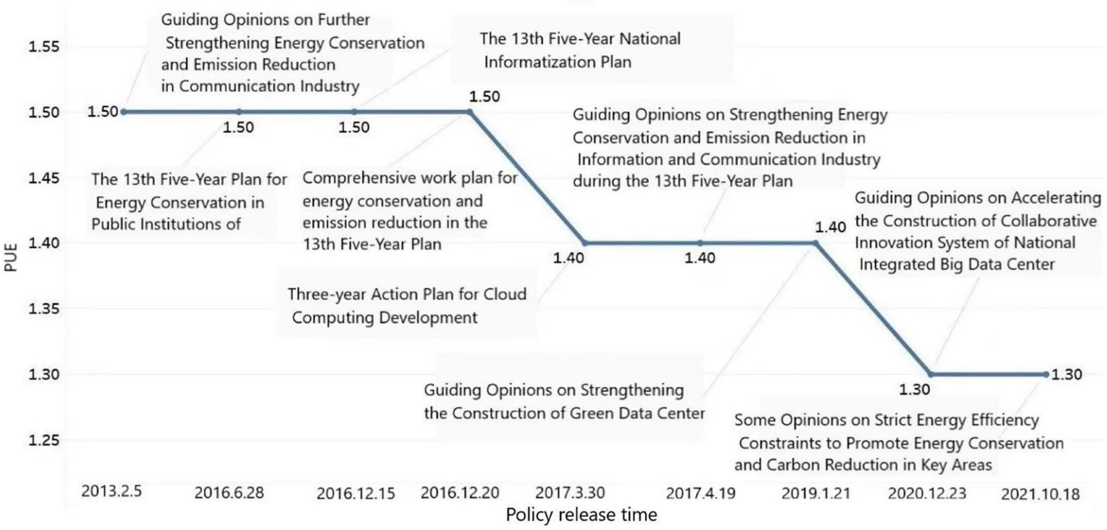

Fig.2. Point line diagram of changes of PUE limits in national policies

3.2 PUE status of data center projects

With the continuous development of green energy-saving technologies in China's data centers, the PUE values have decreased. **Fig.3** gives the distribution of PUE values of data centers in China in 2012, 2015 and 2019 (IDC Prospective Industry Research Institute, 2019). It can be seen that the proportion of data centers with PUE values greater than 2.0 decreased from 34.6% in 2012 to 2%, and the proportion of PUE values less than 1.5 increased from 3.70% to 12.90%, but most data centers still maintain PUE values between 1.5 and 2.0.

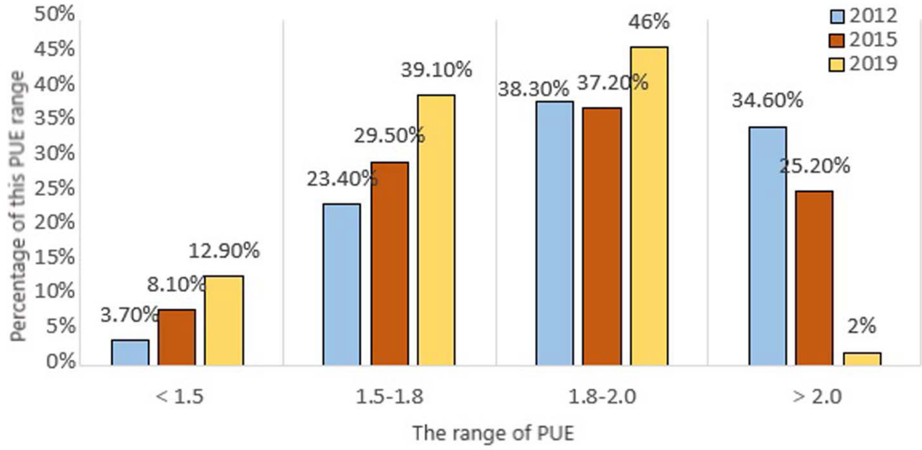

Fig.3. Distribution of PUE values in 2012, 2015 and 2019

In addition, according to the *statistics of PUE values of data centers* in 2017, 2018 and 2019 from the National Data Center Application Development Guidelines (Information and Communications Development Division, Ministry of Industry and Information Technology, 2018,2019,2020) (as shown in **Fig.4**), the PUE values of in-use super large and large data centers decreased in 2018 as compared with 2017, but increased again in 2019. The average PUE values of the two types of data centers in these three years are 1.60, 1.47, and 1.51, which are still far from the PUE value 1.4 required by the national policy in the same year.

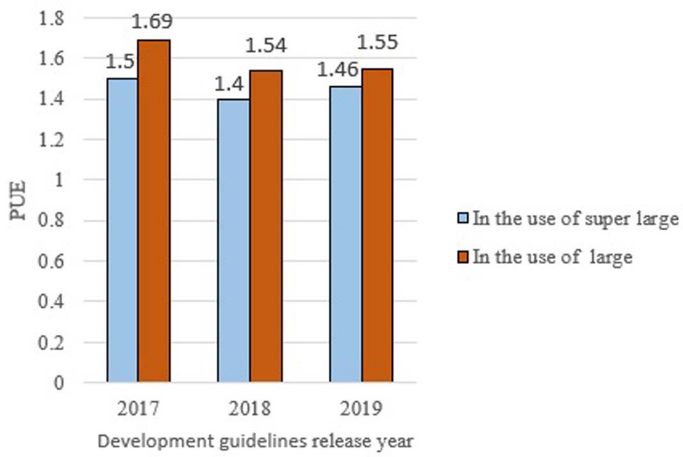

Fig.4. PUE values in 2017, 2018 and 2019

In addition to the statistics of PUE values of national data centers, there are statistics of PUE values of regional data centers in China (as shown in **Table 2**). The report (green peace organization,

2021) classifies the distribution of data centers in China, counts the PUE status of data centers in various regions in China in 2021, and calculates the average PUE value of each region. It can be seen that the average PUE value in most areas is between 1.4 and 1.7, which is higher than the PUE value required by the national policy.

Table 2

Regional distribution of data centers and average PUE

Region	Area	Average PUE
Beijing and surroundings	Beijing, Hebei, Tianjin, Inner Mongolia	1.43
Shanghai and surroundings	Shanghai, Zhejiang, Jiangsu	1.47
Guangdong and surroundings	Guangdong, Fujian, Hainan	1.58
Central Region	Anhui, Henan, Hubei, Hunan, Jiangxi, Shanxi, Shandong	1.62
Western Region	Guizhou, Gansu, Sichuan, Chongqing, Shaanxi, Yunnan, Qinghai, Xinjiang, Ningxia, Guangxi, Tibet	1.51
Northeast Region	Heilongjiang, Jilin, Liaoning	1.47

According to the above PUE statistics, the PUE value of most data centers in China is still maintained between 1.4-2.0. Since most of the projects are existing data centers at the time of statistics, the average PUE value of data centers is higher than the requirements in the policy. In general, there is still a gap between the PUE value of a large number of data centers and the PUE value required by the policy, and there is still a large space for energy saving in data centers.

4. Data center energy saving and carbon reduction technology path

4.1 Green low-carbon technology system

In order to actively promote green technology products for data centers and promote green and low-carbon development of data centers, the Ministry of Industry and Information Technology has been updating the *Green Data Center Advanced Applicable Technology Product Catalog* since 2016. The latest one is the *Green Data Center Advanced Applicable Technology Product Catalog* released in 2020(as shown in **Fig.5**), which involves 62 technical products in four fields, including energy and resource utilization efficiency improvement, renewable energy utilization, distributed energy supply and microgrid construction technology products, waste equipment recycling and treatment, restricted substance use control technology, green operation and maintenance management technology, etc, which includes the scope of application of each green technology product These include the scope of application of each green technology product, technical principles, application status and promotion prospects, application examples, etc, providing data center users with a referenceable green low-carbon technology path.

Fig.5. Green data center advanced applicable technology product catalog (2020)

4.2 IT equipment

IT equipment accounts for the largest proportion of total energy consumption in data centers, and common IT equipment includes servers, storage devices, and network devices (Zhou et al., 2021), among which servers account for up to 40% of energy consumption (Liao and Wu, 2014) and are the largest part of energy consumption in data centers. Therefore, reducing the energy consumption of servers can effectively reduce the energy consumption of the whole data center. The common server energy saving techniques are dynamic voltage frequency regulation (DVFS) technique, dynamic power management (DPM) technique, and virtual machine migration scheduling technique.

（1）DVFS Technology

DVFS technique is an effective strategy to reduce the energy consumption of servers (Hsu and Feng, 2005a,b) and is mainly used to control CPU power consumption. When the CPU is idle, the power consumption is adjusted by adjusting the CPU voltage and frequency to reduce energy consumption. Wang et al., 2010 developed an energy-saving scheduling algorithm that identifies the idle time when it is not the main task and adjusts its operating voltage and frequency, and the experimental results showed that such algorithm can achieve 44.3% energy saving effect. Huai, 2014 proposed a new performance model and power consumption model based on DVFS technology and conducted experiments using PTU algorithm, and the results showed that this method has better energy saving effect.

（2）DPM Technology

The basic principle of DPM technique is to turn off modules that are in idle state or put them in low energy state (Yang et al., 2013). Meisner et al., 2009 proposed to use sleep state (PowerNap) energy saving method to switch the system between high energy operation state and idle time. The results showed that server energy consumption reduces server energy consumption by 74%.Horvath et al., 2008 proposed an energy management strategy and applied it to a multi-tier server cluster. The results showed that this strategy can save 23% of energy consumption.

（3）Virtual Machine Migration Scheduling Technology

Virtual machine migration scheduling technology aims to transfer virtual machines from one host to another (Hu et al., 2021). Based on the energy consumption characteristics of DVFS technology, Wang, 2017 optimized server energy consumption by transforming high-load host into low-load host, and the results showed that such a strategy saves about 15.23% of energy consumption compared to DVFS technique. Reguri et al., 2016 proposed three efficient virtual machine migration energy consumption models on top of the original one, considering both migration volume and adoption of cluster space migration schemes, and the results showed that this model can save 23% of the total energy consumption.

4.3 Cooling System

Data center air conditioning system mainly has the following characteristics: large sensible heat, small latent heat, large air volume, small enthalpy difference, and annual cooling, etc. The most important characteristic is that data centers need annual cooling. The energy consumption of data center cooling system is second only to the energy consumption of IT equipment. Therefore, it is also a heavy task to reduce the energy consumption of cooling system by improving the cooling method.

（1）Make full use of natural cold sources

The common natural cooling methods for data centers are wind-side natural cooling and water-side natural cooling, of which wind-side natural cooling is mainly used in areas where the outdoor temperature is lower than the required temperature in the data center most of the time throughout the year. The water-side natural cooling method is mainly used in areas with rich water resources, making full use of water resources such as river, lake and seawater for cooling. Domestic and foreign data centers adopt wind-side and water-side natural cooling technologies with remarkable effects, and the PUE values are lower than 1.3, as shown in **Table 3.**

Table 3

Data centers with natural cooling technology

Data Center Name	Area	Types of natural cold sources	PUE
Facebook(Wang et al., 2021)	Luleo, Sweden	Air	1.15
Yahoo(Wang et al., 2021)	Lockport, New York	Air	1.08
Google(Communication world, 2012)	Belgium	River water	1.11
Alibaba(Lei, 2018)	Hangzhou,China	Lake water	1.18-1.3
Huawei Cloud(Wang et al., 2021)	Ulanqab,China	Air	1.15
Alibaba(Wang, 2021)	Heyuan,China	Lake water	1.25

（2）Adopt liquid cooling technology

As the scale of data centers gradually increases, the problem of high density and high heat dissipation that exists in them is becoming more and more serious, and the use of traditional air-cooling technology is restricted. In order to solve this problem, China's data centers are gradually introducing liquid cooling technology. There are three main types of liquid cooling technologies: immersion, cold plate, and spray (as shown in **Fig.6,7,8** (Xiao, 2022)). Among them, the immersion type and spray type are direct liquid cooling, in which the coolant is in direct contact with the cooling equipment; the cold plate type is indirect liquid cooling, in which the coolant is in indirect contact with the cooling equipment. The common liquid cooling technologies in data centers today are immersion type and cold plate type. Compared with the traditional air-cooling technology, liquid cooling technology has the characteristics of high cooling efficiency and low cooling energy consumption (Reguri et al., 2016). The data centers using liquid cooling technology are shown in **Table 4.**

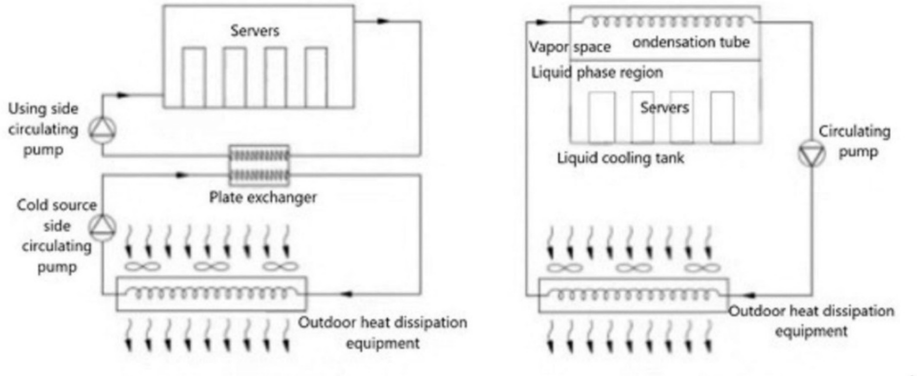

Fig.6. Single-phase submerged liquid cooling Two-phase submerged liquid cooling

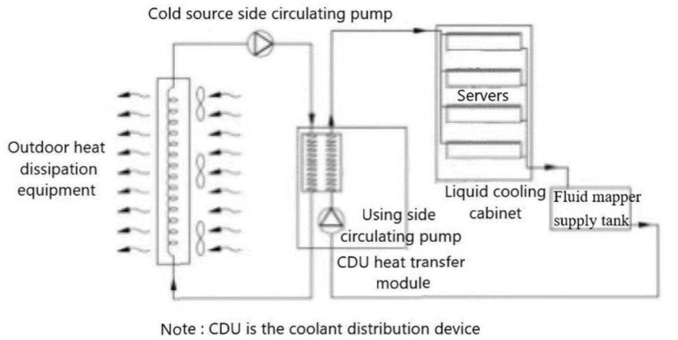

Fig.7. Spray liquid cooling schematic diagram

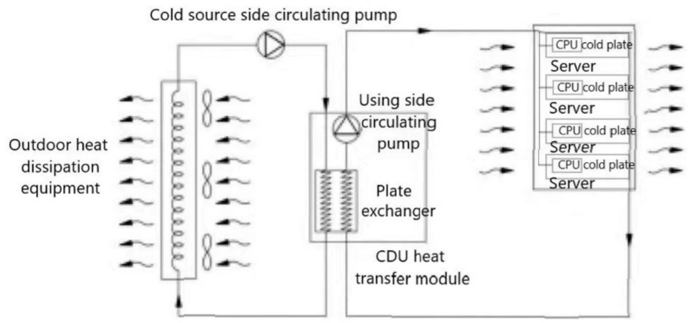

Fig.8. Cold plate liquid cooling schematic diagram

Table 4

Data centers with liquid cooling technology

Data center name	Area	Types of liquid cooling	PUE
China Mobile(Hou et al., 2019)	Huhhot,China	Cold plate type	1.05-1.09
A water-cooled supercomputing center(Xie and Zhao, 2019)	Beijing,China	Cold plate type	1.1
A cloud computing data center(Chen, 2019)	Beijing,China	Cold plate type	＜1.2
A data center(Zimmermann et al., 2012)	Switzerland	Cold plate type	1.15
Alibaba(Shanghai energy conservation, 2021)	Zhangbei,China	Immersion type	1.07
A data center(Chi et al., 2014)	British	Immersion type	1.14
A cloud rendering data center(Xie and Zhao, 2019)	Beijing,China	Immersion type	1.1

（3）Airflow organization optimization technology

Airflow organization is an important factor affecting the energy consumption of data center cooling systems, and unreasonable forms of airflow organization can cause problems such as local hot spots and low cooling capacity utilization (Chen and Zhang, 2014; Cheng and Liu, 2021). The research on airflow organization of data centers mainly includes two aspects, which are air supply form and closed channel. In terms of air supply forms, common air supply methods in data centers include under-floor air supply, air supply on the air cap, air supply on the duct, and air supply between columns (Yan, 2015). Zhang et al., 2019 used CFD software to simulate the upward air supply, downward air supply, and inter-column air supply, and the results showed that the inter-column air supply has a high energy utilization rate. Deymi-dashtebayaz et al., 2021 simulated two airflow organizations (floor air supply and top air supply) in a data center, and the results showed that the floor air supply can save 91.5 kWh of electricity per year and about 55.5 kg of CO_2 emissions. Liu et al., 2010 used fluent to simulate two types of airflow organization: top air supply and bottom air supply, and the simulation results showed that the bottom air supply can effectively reduce the temperature of the server, and at the same time, the measured data showed that the energy utilization of the bottom air supply reached 32.7%, which is higher than that of the top air supply.

In terms of closed channels, Liu and Wang, 2016 simulated a data center with air supply between columns in Tianjin, and proposed the method of using closed cold channels to optimize for the generated local hot spot problem, and the simulation results showed that the closed cold channels enabled effective cooling of servers and reduced the local hot spot phenomenon. Huang et al., 2019 optimized the airflow organization of a data center in Urumqi and proposed the method of using closed cold aisles, and the optimized results showed that the temperature of the server room was more uniform after the closed cold aisles, eliminating the local hot spot problem, and the cabinets got enough cooling capacity and the cooling efficiency became high. Schmidt et al., 2011 reduced the cooling energy consumption of the data center by 59% by using the closed cold aisles. Sun et al., 2019 adopted the closed hot aisle approach to improve the unit COP and extend the free cooling time. Feng et al., 2020 also used the closed hot aisle approach, and the PUE value of individual aisles was greatly reduced with significant energy savings.

4.4 Power supply and distribution system and lighting system

4.4.1 Power supply and distribution system

（1）Use of renewable energy for power supply

With the continuous maturity of renewable energy power supply technologies such as water, wind and solar energy, data centers at home and abroad are gradually considering the use of renewable energy for power supply, and according to statistics, for every unit of electricity saved, 0.997 kg of CO_2 is saved accordingly (Liu, 2015), which has a positive effect on reducing energy consumption and carbon emissions (Pierson et al, 2019). Google and Apple have achieved 100% renewable energy power supply (Xie, 2019;Hu and Liu, 2019); Green house data, built in Wyoming, USA, uses wind power; Facebook, built in Oregon, uses solar power (Song et al., 2018); Alibaba, built in Ulanqab, Inner Mongolia, uses wind and solar power on a large scale, and its PUE value is close to that of the Zhangbei data center (PUE=1.25).(Lei, 2018).

However, the intermittent nature of commonly used renewable energy sources is a major drawback of using them directly on-site, and how to effectively coordinate the intermittent renewable energy with the workload remains to be a major challenge. He et al, 2022 investigates the problem of workload scheduling for power cost minimization under the constraints of different

Service Level Agreements (SLAs) of delay tolerant workload and delay sensitive workload for green data centers in a smart grid, and the results show that the online delay-guaranteed workload scheduling saves about 5% average power cost compared to the baseline algorithms. In 2018, Grange et al presents an approach for scheduling batch jobs with due date constraints that takes into account the availability of the renewable energy to reduce the need of brown energy and therefore running costs. Caux et al, 2018 presents a model that considers the data center workload and the several moments where renewable energy could be engaged by the power side without the grid.

（2）Optimize power distribution

Uninterruptible power supply (UPS) is one of sources that can bring the biggest losses in the data center power distribution process, so an efficient conversion mode should be chosen. First, power conversion should be minimized (Oró et al., 2015), and for the conversion steps that must be performed, efficient transformers and power distribution units should be used (Sun and Xu, 2020).

4.4.2 Lighting system

Although the energy consumption of lighting system is a small percentage, it is not a negligible part. Wang et al., 2021 stated that the lighting system is divided into traditional lighting system, detective lighting system, and intelligent lighting system, analyzed the energy consumption of several lighting methods, and concluded that the intelligent lighting system consumes the least amount of electricity. Shi, 2016 stated that changing the IT module and air conditioner room lighting to LED lights can save about 100,000 kWh of electricity in a year. Liao and Wu, 2014 stated that energy-efficient power sources such as T8 or T5 series trichromatic straight tube fluorescent lamps and LEDs should be used in the server room, which can save 30% energy.

4.5 Intelligent Operations and Maintenance

As the number of data centers continues to increase and their scale becomes larger, their operation and maintenance management becomes difficult and complex. With the continuous development of digital and artificial intelligence technologies, combining them with the traditional operation and maintenance management system can provide real-time monitoring and intelligent adjustment of each equipment, reduce energy consumption and operation costs, and make the data center run safely and stably. Yu and Wang, 2022 implemented intelligent operation and maintenance management for cooling system, IT equipment, and lighting in a data center in Langfang, and the results showed that the PUE value was reduced by 1.2%, and 33.36 million kWh of electricity could be saved annually. Gao, 2022 claimed that the maintenance of the server room can reduce the total carbon emission by 36% by achieving 100% intelligent operation and maintenance through digitalization and electrification.

5. Policy impact and development suggestions

Nowadays, data centers use huge amount of energy, and the power consumption of data centers is increasing year by year, and the carbon emission is also increasing. In order to implement the goal of green and low-carbon data centers, policies on green development of data centers have been introduced since 2012, and data centers have gradually embarked on the path of green development since then.

A series of policies subsequently issued by the state have played an important role in guiding and promoting the rapid development of green data centers: (1) It has realized the standardized development of data centers. At present, China has a number of data center related standards and specifications, including standards for planning, design, construction, management, acceptance and rating, which provide a basis for carrying out various aspects in the whole life cycle of data centers and enable data centers to standardize and develop in a standardized manner. (2) The transformation from green development concept to actual green data center projects has been realized. With the landing of green data center projects, 153 data centers in China have been rated as green data centers according to the existing data center evaluation system, as a way to encourage more data centers to take the green path. (3) It has realized the improvement of green energy saving and emission reduction level of data centers. In order to guide data centers to actively adopt advanced green technology products and further promote the green construction of data centers, China has carried out the screening of advanced applicable technologies for green data centers and formed a catalog of advanced applicable technologies for green data centers, and some data centers have adopted some of these green technologies, which have remarkable energy-saving and emission reduction effects.

As an important infrastructure, data center will definitely usher in further development, which puts forward higher requirements for the green development of data center. Green data center is a continuous work involving many parties, and new concepts, technologies and models will be generated at different development stages While, new problems and challenges will be encountered. China's green data center has gone through many stages, such as concept proposal, policy promotion, industry discussion, technical research to the current stage of standardized development, and has accumulated certain experience in the process. The authors make suggestions for the development of green data center in light of China's green data center policy development and practical experience:

（1）Policy Planning. Determine the connotation of green development of data centers, combine the development reality, scientifically carry out the top level design of green data center development, systematically plan the development direction and development focus of green data centers, study and formulate the promotion policy and development route of green data centers.

（2）Technical standards. This paper analyzes the weak points of data center energy consumption, and then puts forward the technical requirements for improvement, thus forming the technical standard of green data center. Especially under the background of "double carbon", China data center still lacks guiding standards for carbon emission reduction, so we should actively formulate and improve standards for energy saving and carbon reduction, including data center carbon emission reduction design, evaluation, renovation, acceptance and other related standards.

（3）Engineering practice. By making full use of the policy advantages and green data center evaluation technology system, we start from the pilot green data center in the form of " promoting construction by evaluation ", continuously summarize the lessons learned in practice, timely adjust and improve the green data center policy, technical standards and evaluation system, and gradually form the scale development of green data center.

（4）Technology research and development. Constantly absorb new technologies and new ideas, focus on the innovation and research and development of green low-carbon technologies, and test the application of green low-carbon technologies in practice. At present, the green technology level of data centers in China is relatively backward. As the energy consumption of IT equipment accounts for the largest proportion of data center energy consumption, the research and application of virtualization, cloud computing and other technologies should be strengthened. The energy consumption of refrigeration is second only to that of IT equipment. With the increase of the number of data center cabinets, the application of traditional air-cooling technology has been restricted, and data center refrigeration should gradually develop to liquid cooling. In addition, the local climate and environmental conditions should be fully considered when selecting the location of the data center, and the natural cold source technology should be efficiently used to improve the green level of the data center.

CRediT authorship contribution statement

Guozhu Li: Methodolody, Writing-original draft, Formal analysis, Investigation. **Zixuan Sun:** Methodolody, Writing-original draft, Data reduction, Formal analysis, Investigation. **Qingqin Wang:** Formal analysis, Investigation. **Shuai Wang:** Formal analysis, Investigation. **Kailiang Huang:** Formal analysis, Investigation. **Naini Zhao:** Formal analysis, Investigation. **Yanqiang Di:** Formal analysis, Investigation. **Xudong Zhao:** Formal analysis, Investigation. **Zishang Zhu:** Formal analysis, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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