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Decarbonizing data centers through regional bits migration: A comprehensive assessment of China's 'eastern data, Western computing' initiative and its global implications☆

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HIGHLIGHTS

- Energy, economic and carbon impacts of 'Eastern Data, Western Computing' are assessed.
- The national initiative shows significant energy-saving potential.
- 'Moving bits' is more energy efficient but doesn't always benefit decarbonization.
- The carbon emission benefits in different routes are significantly different.
- No economic benefit is observed when considering constructing duplicate data centers.

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ABSTRACT

As the world transitions towards a low-carbon economy, the data center industry is under increasing pressure to reduce its energy consumption and greenhouse gas emissions. To address this challenge, the Chinese government has launched an ambitious initiative, called 'Eastern Data, Western Computing', which aims to migrate computing workloads from electricity-deficient Eastern regions to renewable-rich Western regions. We therefore conduct a comprehensive assessment of its energy, economic and carbon impacts by analysing three major migration routes. We found that 'moving bits' is much more energy efficient than 'moving watts', but not necessarily beneficial for decarbonization. The national initiative shows significant energy-saving potential, 332–942 GWh (4.8–12.5 %) annually, attributed to reduced cooling energy and eliminated power-transmission loss. However, no economic benefit is observed if considering the high capital costs for constructing duplicated data centers in Western regions. The carbon emission benefits in different routes are significantly different. Shanghai-Sichuan route could reduce carbon emissions by up to 2803 $KtCO_2e$ (79.6 %) annually, whereas Beijing-Inner Mongolia route exhibits a notable increase (1164 $KtCO_2e$ (24.9 %)) in carbon emissions. Our findings has broader applicability beyond China, extending to other regions worldwide, and can inform the development of effective strategies for decarbonizing global data center industry.

1. Introduction

The rapid growth of the digital economy has led to an unprecedented surge in demand for computing capacity and data centers worldwide [1], resulting in significant energy consumption and greenhouse gas emissions [2]. As data centers become increasingly critical to the global economy, their environmental impact has become a pressing concern [3]. In 2021, data centers in China alone consumed over 200 TWh, accounting for approximately 2.7 % of total electricity consumption [4]. However, this trend is not unique to China; data centers in other countries, such as the United States and Europe, also face similar challenges in terms of energy consumption and carbon emissions [5].

The concentration of data centers in economically developed yet electricity-deficient regions, such as the Eastern regions in China, has led

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to power shortages [6] and increased reliance on long-distance power transmission [7]. However, power transmission lines are inevitably accompanied by power loss, averaging 5–6 % [8]. To address these challenges, the concept of “moving bits rather than moving watts” has emerged as a potential solution. By migrating computing workloads from data centers in electricity-deficient regions to data centers in renewable-rich regions, this approach can eliminate power losses incurred by long-distance transmission, reduce cooling energy use, and promote a more sustainable and efficient use of energy resources.

China’s national initiative, “Eastern Data, Western Computing” (EDWC) [9], is a pioneering example of this approach, launched in 2021, EDWC aims to migrate computing workloads from data centers in the East (electricity-deficient) to data centers in the West (renewable-rich) within China. Then, the abundant electricity in the Western regions can be utilized locally by the data centers, thereby eliminating the power losses incurred by long-distance transmission. Furthermore, the Western regions of China have favourable climates that could significantly reduce cooling energy use by more effective utilization of free cooling [10]. This could substantially reduce Power Usage Effectiveness (PUE) of data centers. Moreover, from the perspective of cost, the construction of fiber-optic networks is much cheaper, at $70-150 K per mile [11,12], compared to the construction of power transmission infrastructure, typically averaging $1.5–$2.0 million per mile [13,14].

Fiber-optic communication technology plays a key role in data transmission [15], which enables effective communication among geographically distributed data centers. Over the past four decades, significant progress has been made in this field [16,17], including the development of wavelength-division multiplexing [18] and space-division multiplexing [19]. Despite these advancements, network delay remains a challenge in long-distance data transmission [20,21]. In EDWC initiative, workloads that can tolerate delay, such as storage and backup, will be migrated. Whereas workloads requiring timely responses, such as web search and videoconferencing, will continue to be processed at local data centers in the East. It is noteworthy that data centers typically have a significant proportion of delay-tolerant workloads, more than 50 % of total workloads [22]. This provides substantial temporal and spatial flexibility for geographically distributed data centers [23]. Existing studies have shown an increasing interest in the flexible scheduling of workloads in geo-distributed data centers, with a focus on optimizing energy use and cost [24,25] and maximizing renewable utilization [21]. A study shows that up to 40 % of the operational cost can be reduced through load distribution and scheduling in geographically distributed data centers [26]. By migrating data center workloads from the fossil-fuel-heavy regions to the renewable-heavy regions, up to 239 $KtCO_2e$ can be reduced per year [27].

Despite the growing interest in computing workload migration, there is a knowledge gap in understanding the energy-saving potentials, economic benefits, and carbon emission reductions of such initiatives. Existing studies have primarily focused on the technical aspects of computing workload migration, with limited attention to the economic and environmental implications. Furthermore, the applicability of computing workload migration to other countries and regions remains unclear. This paper addresses this knowledge gap by presenting a comprehensive and quantitative assessment of the energy-saving potentials, economic benefits, and carbon emission reductions of EDWC. Our analysis focuses on three major routes, considering two scenarios for data transmission: on existing backbone networks and newly built dedicated fiber-optic lines. We develop a typical cooling system model and evaluate the power required for data transmission and power transmission losses for each route. By analysing three complex trade-offs on energy, economics, and carbon emissions for the implementation of the iniative, we provide a holistic understanding of the benefits and challenges of computing workload migration, and shed light on the potential for EDWC to serve as a model for similar initiatives in other countries and regions.

This study presents the first comprehensive and quantitative assessment of the energy-saving potentials, economic benefits, and carbon emission reductions of the national initiative EDWC, providing a valuable benchmark for similar initiatives in other countries. Our findings demonstrate the potential for computing workload migration to contribute significantly to global decarbonization efforts, particularly in regions with abundant renewable energy resources. These results serve as a crucial foundation for policy-makers, industry stakeholders, and researchers to make informed decisions and establish effective strategies to mitigate the challenges associated with computing workload migration and promoting a low-carbon data center industry. Moreover, these results have broader applicability beyond China, extending to other regions worldwide, and can inform the development of effective strategies for decarbonizing the global data centers.

2. Results

2.1. Energy performance of cooling systems and data-transmission energy

We collect the spatial distribution of the energy consumption of data centers across China in 2020 (Fig. 1A) [28]. Beijing-Tianjin-Hebei region, Yangtze River Delta Region, and Pearl River Delta Region show the highest energy consumption (see Table S1). These regions are also the destinations of power delivery in the ‘West-East Power Transmission (WEPT)’ project. Three existing major long-distance power transmission lines, Inner Mongolia to Beijing, Sichuan Province to Shanghai and Guizhou Province to Guangzhou Province are shown in Fig. 1B (bold blue lines). In this study, the three existing power transmission lines are considered as the baseline scenarios - power transmission scenarios. “Eastern Data, Western Computing (EDWC)” aims to migrate computing workloads from data centers in the East to data centers in the West for storage and processing, as shown in Fig. 1B (bold orange lines). It can eliminate the energy loss of long-distance power transmission and use cold weather in the Western regions for more energy-efficient cooling.

(A) Spatial distribution of the energy consumption of data centers across China [28].

(B) Cooling system COP in different locations.

(C) Cooling system COP as a function of wet-bulb temperature.

(D) Historical development of energy intensity of data transmission between 2004 and 2021.

In (D), y-axis is electricity intensity (kWh/GB). x-axis is the year of each estimate. Data points: (1) [29]; (2) [30]; (3) [31]; (4) [32]; (5) [33]; (6) [34]; (7) [35]; (8) [36]. (9) [37]; (10) [38]; (11) [39] (12) [40]; (13) [41]; (14) [42].

A basic cooling system model (Fig. S1) is developed based on fundamental principles and mathematical formulas combined with the test data of cooling equipment performance. Using the weather data in typical years, we simulated the cooling system under the three operation modes corresponding to outdoor conditions, and compared their coefficients of performance (COPs). The mode that satisfies the cooling load and consumes the lowest cooling energy is selected for each outdoor condition.

The cooling system COP in the wet-bulb temperatures range between −40 °C and 40 °C is shown in Fig. 1C. In both partial-free-cooling and mechanical-cooling modes (with chillers in operation), the cooling system COP is around 3–5, whereas in free-cooling mode the COP is around 11 (without chillers in operation). According to the annual wet-bulb temperature distribution of different cities and the cooling system COP as a function of wet-bulb temperature, the annual average COP of cooling systems in each city can be obtained. Fig. 1B shows the annual average COP of cooling systems in six major cities involved in three routes. The annual average COP of cooling systems is improved from 8.17 to 9.06 for Beijing – Inner Mongolia route, and from 5.75 to 7.08 for Guangzhou – Guizhou route, respectively. Whereas, it is reduced from 7.05 to 6.75 for Shanghai – Sichuan route.

Two scenarios for data transmission are considered in this study. One is data transmission on existing backbone networks, the other is on

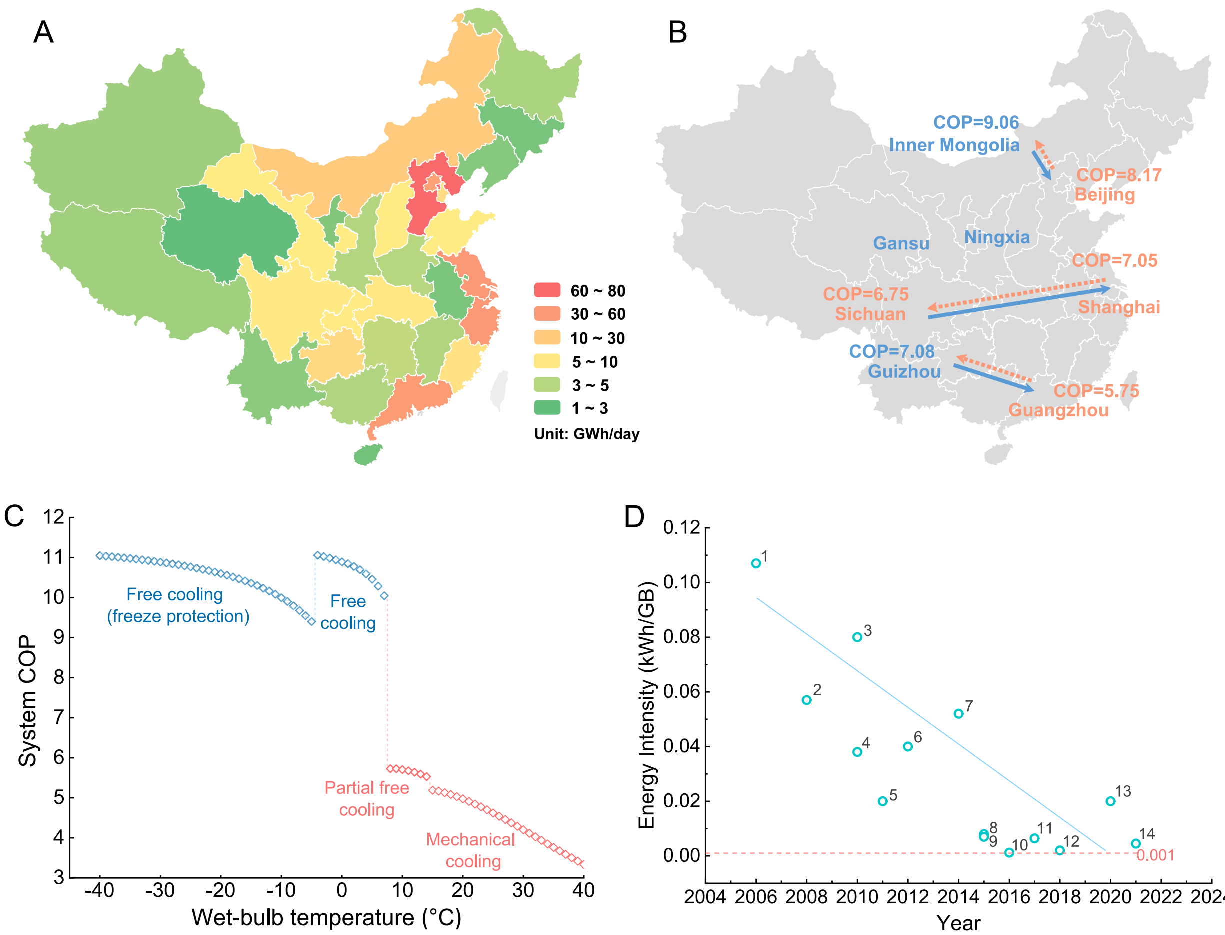

Fig. 1. Data center energy consumption, major migration routes, performance of cooling systems, and data-transmission energy intensity,

dedicated fiber-optic lines newly built. A commonly used metric, electricity intensity, representing the energy efficiency of Internet data transmission is adopted in this study. It is defined as the "electrical energy consumed per amount of data transmitted", and is measured as kilowatt hour per gigabyte of data transferred (kWh/GB) [43]. The historical evolution of the energy intensity (EI) of data transmission on the backbone networks from 2004 to 2021 is summarized in Fig. 1D. There is a consistent downward trend in data-transmission EI over this period. In 2021, data-transmission EI on the backbone networks is estimated as 0.001 kWh/GB at an average distance of 700 km [42]. We also calculate the data-transmission EI on newly-built dedicated fiber-optic lines for three routes based on the power model developed by Heddeghem et al. [44,45], given by Eq. 12–17. Furthermore, we consider the improvement in energy efficiency of equipment due to technological updates according to Moore's law. The data-transmission EI on newly built dedicated fiber-optic lines is estimated as 0.00003 kWh/GB in 2021.

2.2. Impacts on energy, economy and carbon emissions

2.2.1. Data transmission on the existing backbone networks

All migration routes show significant energy-saving potential, indicating that 'moving bits' is much more energy efficient than 'moving watts' (Fig. 2A). Both Beijing-Inner Mongolia and Guangzhou-Guizhou routes show substantial energy savings, i.e., 695 GWh (9.8 %) and 942 GWh (12.5 %) annually respectively. For these two routes, the energy benefits can be primarily attributed to the cooling energy saving and eliminated power transmission loss. Both routes transfer a portion of the cooling load of data centers to regions where cooling systems are more energy efficient.

Unlike the above two routes, the Shanghai-Sichuan route shows a notable increase in cooling energy consumption. This is due to the fact that this route transfers a portion of the cooling load of data centers to the region where cooling systems are less energy efficient. However, this route still shows high energy saving, i.e., 320 GWh (4.8 %) annually, primarily due to the elimination of long-distance power transmission loss. Similarly, the energy consumption associated with 'moving bits' is considerably lower than the eliminated power loss. Moreover, all these three routes show that more computing workload migration results in more overall energy saving (Fig. 2B).

However, no economic benefit is observed for all migration routes if considering the high capital costs for constructing duplicated data centers in the Western regions (Fig. 3C). The energy cost savings associated with reduced cooling energy and eliminated power transmission loss are quite low, compared with the capital cost of constructing new data centers. Furthermore, we assess the impact of government subsidies on overall economic benefits, and the results are shown in Fig. 3D. The government subsidies refer to incentives offered by certain regions to encourage companies to build and operate data centers in their regions. These subsidies are mainly discounted electricity rates for data center operations. Some regions offer significantly reduced electricity costs, with discounts of up to 50 % or more (see Table S2). Currently, the local governments of Ulanqab in Inner Mongolia Province, Ya'an in Sichuan Province, and Guiyang in Guizhou Province provide substantial subsidies on their electricity bills for data centers to encourage the development of data centers in the Western regions. Nevertheless, the three routes still do not yield economic benefits although a certain amount of capital costs are offset by government subsidies.

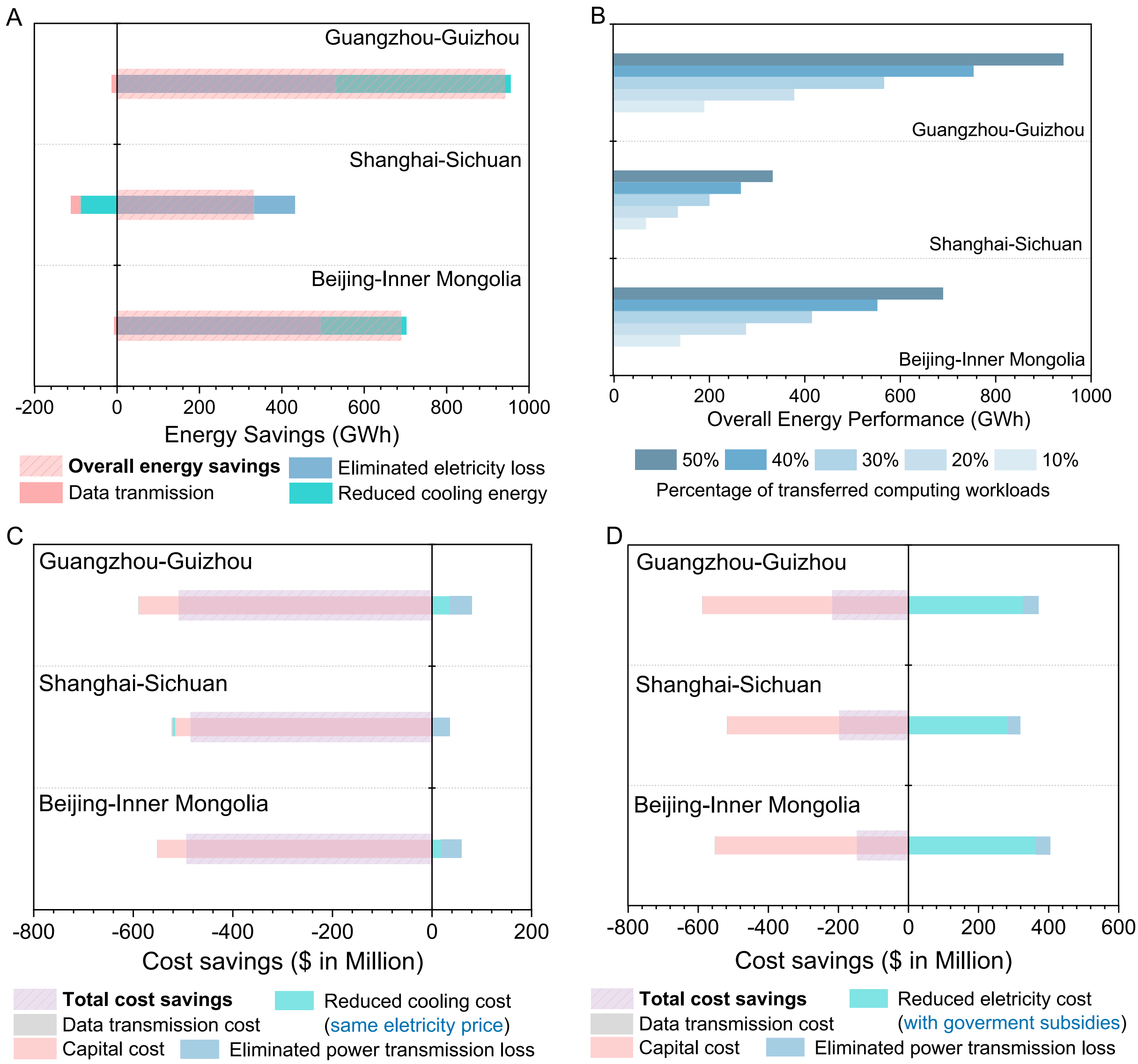

Fig. 2. Energy and economic benefits when data transmission on the existing backbone networks.

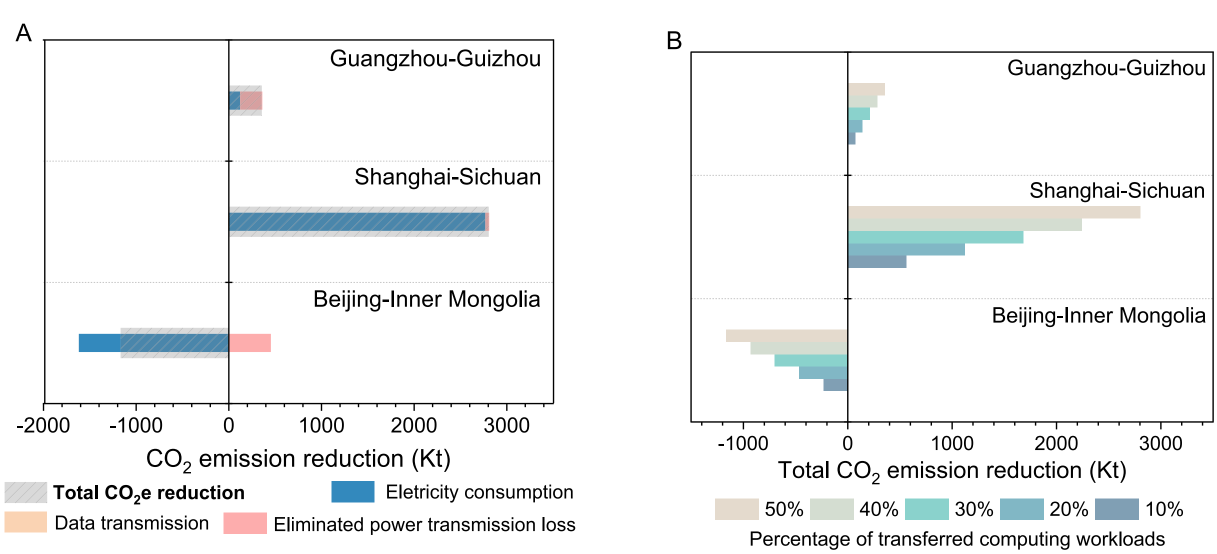

Fig. 3. Carbon emission reductions when data transmission on the existing backbone networks.

The high capital costs of constructing new dedicated data centers reduce its economic feasibility. However, several potential cost-offset strategies can be explored to enhance economic viability. One promising approach is modular data center design, which can substantially reduce capital costs. Additionally, colocation models, shared infrastructure, leasing or renting data center space, and phased construction are also viable solutions that can help mitigate upfront costs. By adopting one or more of these strategies, the initiative can potentially reduce its capital expenditures, improve its return on investment, and ultimately enhance its economic feasibility.

(A) Overall energy savings and the detailed breakdown with 50 % workload migration.

(B) Overall energy performance with 10 %–50 % workload migration.

(C) Total cost savings and detailed breakdown with 50 % workload migration.

(D) Total cost savings considering government subsidies with 50 % workload migration.

The benefits of carbon emission reduction in different routes are significantly different (Fig. 3A). Both Shanghai-Sichuan and Guangzhou-Guizhou routes show a reduction in total carbon emissions, i.e., 2803 $KtCO_2e$ (79.6 %) and 356 $KtCO_2e$ (10.7 %) respectively. However, the Beijing-Inner Mongolia route shows an increase in total carbon emissions, i.e., 1164 $KtCO_2e$ (24.9 %). Although there are different causes for the carbon emissions changes in the three routes, there are still some similar observations. The eliminated transmission power loss contributes to total carbon reduction for all three routes but it is not the major reason. In addition, the energy consumption of data transmission is extremely low, thereby having a negligible influence on the overall magnitude of total carbon emissions for all three routes.

For the route unfavourable to carbon reduction (Beijing-Inner Mongolia), the increase in CO_2 emissions is primarily attributed to the difference in the CO_2 emission associated with electricity consumption at the departure city (Beijing) and destination city (Inner Mongolia). As reported by a published comprehensive study of regional CO_2 emissions in China, summarized in Table S3, the CO_2e factor in Inner Mongolia (917 g/kWh, where thermal power dominates local power generation nowadays) is much higher than that in Beijing (661 g/kWh). There is an increase in carbon emission by 1612 $KtCO_2e$ as the Beijing-Inner Mongolia route transfers a total electricity consumption of 7064.71 GWh computing workloads from Beijing to Inner Mongolia (the total electricity consumption of these computing workloads in Inner Mongolia is 6856.52 GWh, due to the cooling energy savings). In addition, the increase in carbon emission incurred by 'moving bits' is extremely low, only 6 $KtCO_2e$. In contrast, there is a reduction in carbon emissions of 454 $KtCO_2e$ due to eliminated power transmission loss.

For the route favourable to carbon reduction (Shanghai-Sichuan), the reduction in CO_2 emissions is also primarily attributed to the difference in the CO_2 emission associated with electricity consumption at the departure city (Shanghai) and destination city (Sichuan). The CO_2e factor in Sichuan Province (112 g/kWh, a large proportion of hydropower [46])) is much lower than that in Shanghai (532 g/kWh). There is a reduction in carbon emission by 2769 $KtCO_2e$ as the Shanghai-Sichuan route transfers a total electricity consumption of 6610.15 GWh computing workloads from Shanghai to Sichuan (the total electricity consumption of these computing workloads in Sichuan is 6698.85 GWh, due to an increase in cooling energy). Furthermore, there is a reduction in carbon emissions of 42 $KtCO_2e$ due to eliminated power transmission loss.

For another route favourable to carbon reduction (Guangzhou-Guizhou), the reason is significantly different from the above two routes. In this route, the CO_2e factors at the departure city (Guangzhou) and destination city (Guizhou) are similar. The reduction in CO_2 emissions in this route is primarily attributed to energy-saving benefits, i.e., eliminated power transmission loss and reduced cooling energy. There is a reduction in CO_2 emissions of 240 $KtCO_2e$ and 122 $KtCO_2e$ for eliminated power transmission loss and the reduced cooling energy, respectively. In addition, both Guangzhou-Guizhou and Shanghai-Sichuan routes show that more computing workload migration results in more carbon emission reductions (Fig. 3B), whereas Beijing-Inner Mongolia shows the opposite results.

It can be concluded that migrating computing workloads to regions with high renewable energy penetration holds great promise for reducing carbon emissions from data centers. Policymakers can leverage this insight to develop targeted strategies that encourage the development of data centers in regions with abundant renewable energy resources. For instance, governments can offer incentives, such as tax breaks or subsidies, to data center operators that locate their facilities in areas with high renewable energy penetration. Additionally, policymakers can expedite the transition towards low-carbon power generation in fossil-fuel-heavy regions by increasing investments in renewable energy infrastructure, such as wind farms and solar panels. By implementing these policies, governments can help reduce the carbon footprint of the digital economy and contribute to a more sustainable future for the data center industry.

(A) Total carbon emission reductions and detailed breakdown with 50 % workload migration.

(B) Total carbon emission reductions with 10 %–50 % workload migration.

2.2.2. Data transmission on newly built dedicated fiber-optic lines

Currently, the bandwidth on existing backbone networks connecting the Eastern and Western regions is insufficient for the implementation of EDWC. A low network latency and higher network capacity are required for the timely transmission of batch computing workloads without data loss. Therefore, establishing new dedicated fiber-optic communication lines with higher bandwidth is needed for the implementation of EDWC.

Furthermore, it is worth discussing the feasibility of implementing dedicated fiber-optic communication lines for the EDWC initiative. The implementation of dedicated fiber-optic communication lines requires careful consideration of several factors, including significant investments in infrastructure development and the development of new protocols and standards for data transmission. Despite these challenges, the implementation of these technologies is still feasible and necessary for the success of the initiative. Firstly, recent advancements in fiber-optic technology have made it more efficient and cost-effective to deploy high-capacity networks, reducing the barriers to implementation. Secondly, while there is certain initial investment, the long-term benefits of increased data transmission speed and reliability can outweigh the costs. Additionally, the scalability of fiber-optic networks allows for future upgrades and expansions, ensuring that the infrastructure can adapt to growing data demands and technological advancements, making it a sustainable long-term solution for the EDWC initiative.

Fig. 4A-4D shows the overall energy savings, economic benefits, and carbon emission reductions of the national project EDWC in the scenario of 'data transmission on newly built dedicated lines'. The energy consumption of data transmission on newly built dedicated lines is lower than that on the existing backbone networks, and can even be ignored (Fig. 4A). The amortized capital cost of constructing fiber-optic lines is relatively low, compared with that of newly built data centers. *All three representative routes show higher energy-saving potential, compared with data transmission on the existing backbone networks, ranging from 344 GWh to 955 GWh.* Similarly, all routes are not economically beneficial if involving high capital costs for constructing new data centers for two scenarios, without considering government subsidies (Fig. 4B) and considering government subsidies (Fig. 4C). Regarding the benefit of carbon emission reduction (Fig. 4D), both Shanghai-Sichuan and Guangzhou-Guizhou routes show a notable reduction in carbon emissions, i.e., 2810 $KtCO_2e$ and 362 $KtCO_2e$ respectively. While the Beijing-Inner Mongolia route shows an increase in carbon emissions, i.e., 1158 $KtCO_2e$. The results are also similar to the scenario 'data transmission on

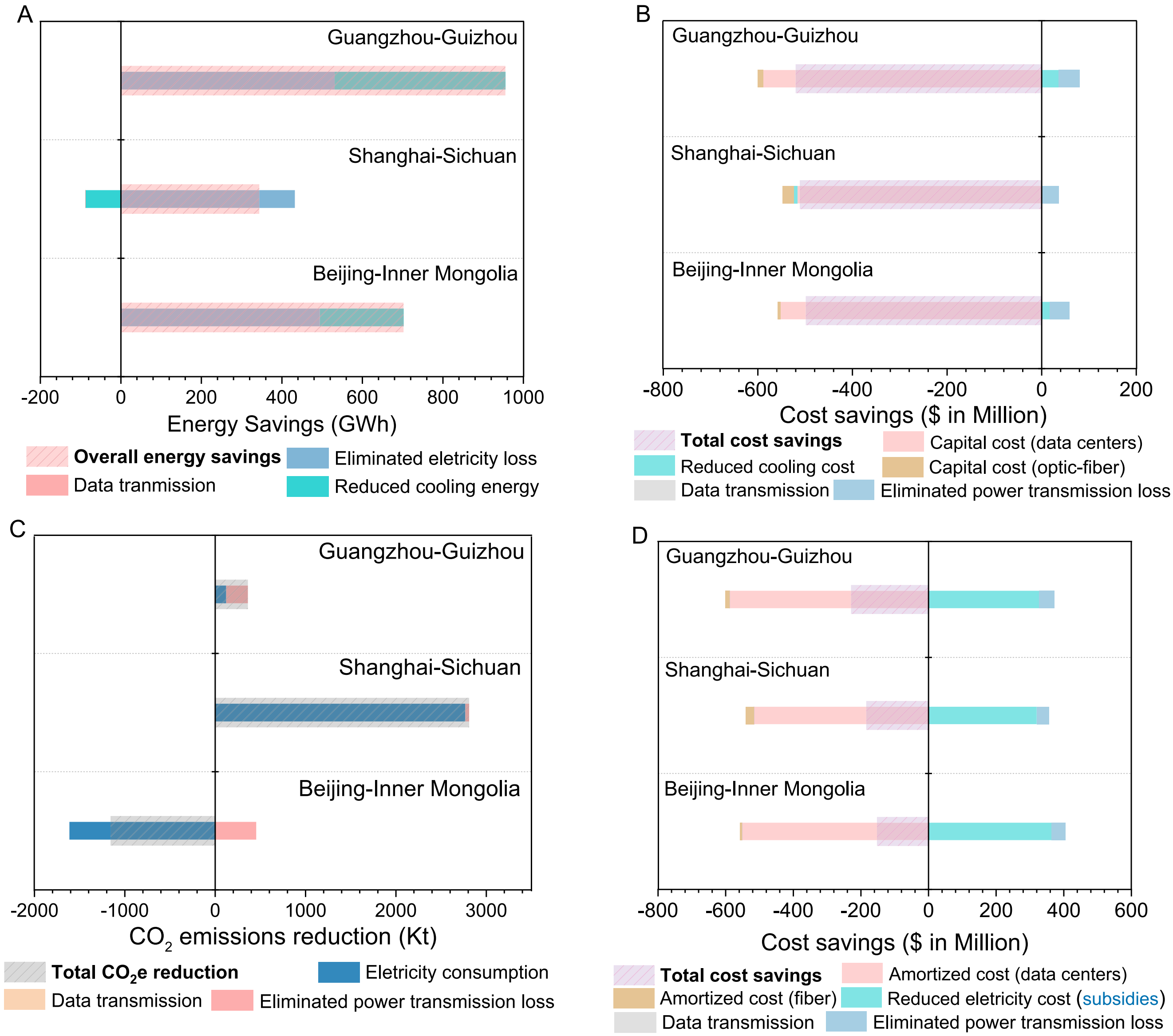

Fig. 4. Energy, economic and carbon benefits when data transmission on dedicated lines.

existing backbone networks'.

(A) Overall energy savings and the detailed breakdown with 50 % workload migration.

(B) Total cost savings and detailed breakdown with 50 % workload migration.

(C) Total carbon emission reductions and detailed breakdown with 50 % workload migration.

(D) Total cost savings considering government subsidies with 50 % workload migration.

2.3. *Future perspectives on carbon emission reduction and abatement cost*

Figs. 5A-5C show the total carbon emission reductions considering future potential changes and uncertainties, an increase or a decrease in the difference in CO_2e factor of power consumption between the two locations involved in a route.

Currently, the Beijing-Inner Mongolia route exhibits a notable increase in total carbon emissions. However, once the CO_2e factor difference between Inner Mongolia and Beijing is reduced to 85 gCO_2/kWh (the current difference is 255 gCO_2/kWh), the route could yield carbon emission reductions (Fig. 5A). For the Shanghai-Sichuan route, the current difference in the CO_2e factors is −420 gCO_2/kWh (Fig. 5B). If we consider the potential decrease in the difference in CO_2e factor in Shanghai (532 g/kWh) and Sichuan (112 g/kWh), the carbon emission reductions of this route will decrease. For the Guangzhou-Guizhou route, the current difference in the CO_2e factors is −9 gCO_2/kWh, and the total carbon emission of this route is reduced (Fig. 5C). However, the CO_2e difference may increase or decrease in the future, primarily due to the penetration of renewable energy in these two regions involved.

In addition, it is worth noting that the Shanghai-Sichuan route shows more carbon emission reductions when more workloads are transferred (Fig. 5B). Whereas, the other two routes show significantly different trends when CO_2e factor differences are on either side of a critical value. For example, in the Beijing-Inner Mongolia route, when more workloads are transferred, carbon emission reductions increase when the CO_2e difference is greater than 85 gCO_2/kWh, and decrease when the CO_2e difference is less than 85 gCO_2/kWh (Fig. 5A). Similarly, the critical value for the Guangzhou-Guizhou route is 56 gCO_2/kWh (the current difference is −9 gCO_2/kWh) (Fig. 5C).

Fig. 6A-6B shows the net carbon abatement costs considering future potential changes and uncertainties in the CO_2e factors in the two locations involved in each route. Currently, the net carbon abatement

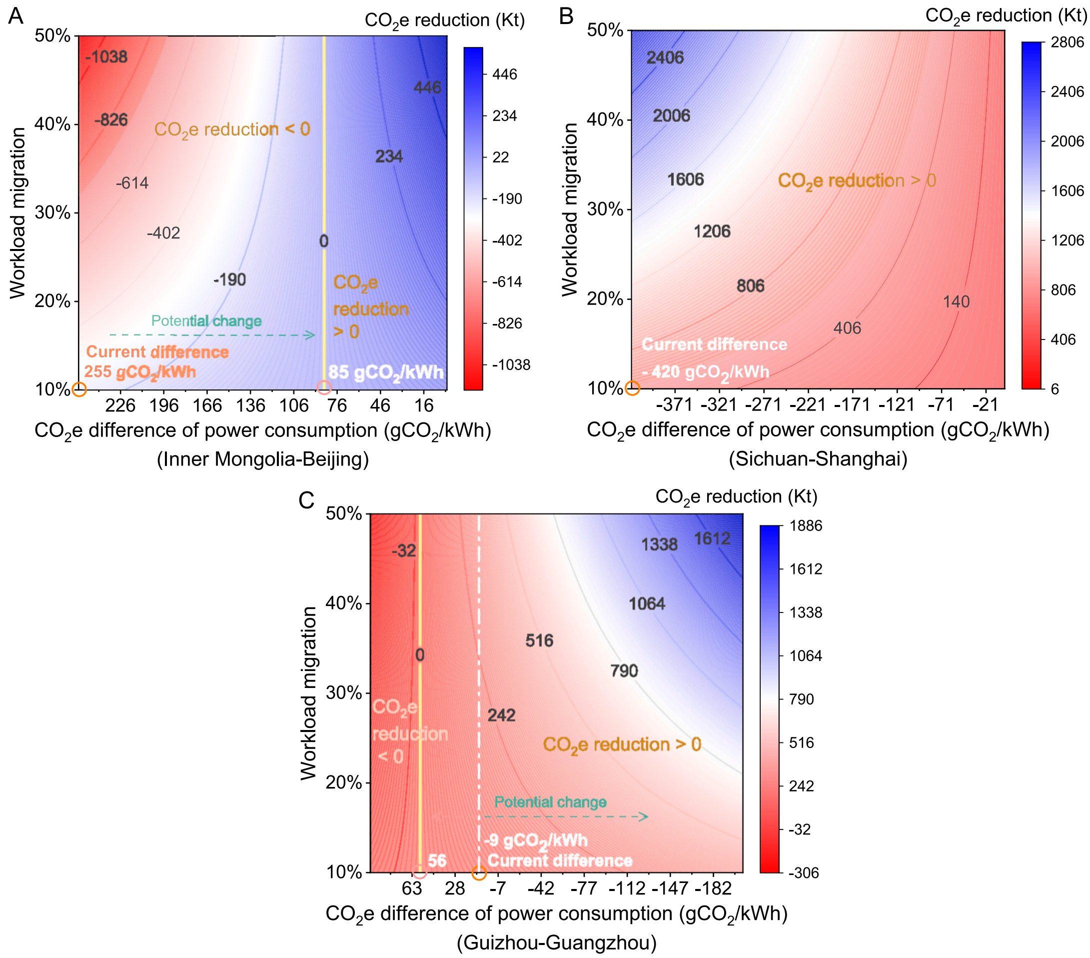

Fig. 5. Quantitative carbon emission reductions considering potential increases or decreases in the difference in CO2e factor between the two locations involved in a route. (A) Beijing-Inner Mongolia route (B) Shanghai-Sichuan route (C) Guangzhou-Guizhou route.

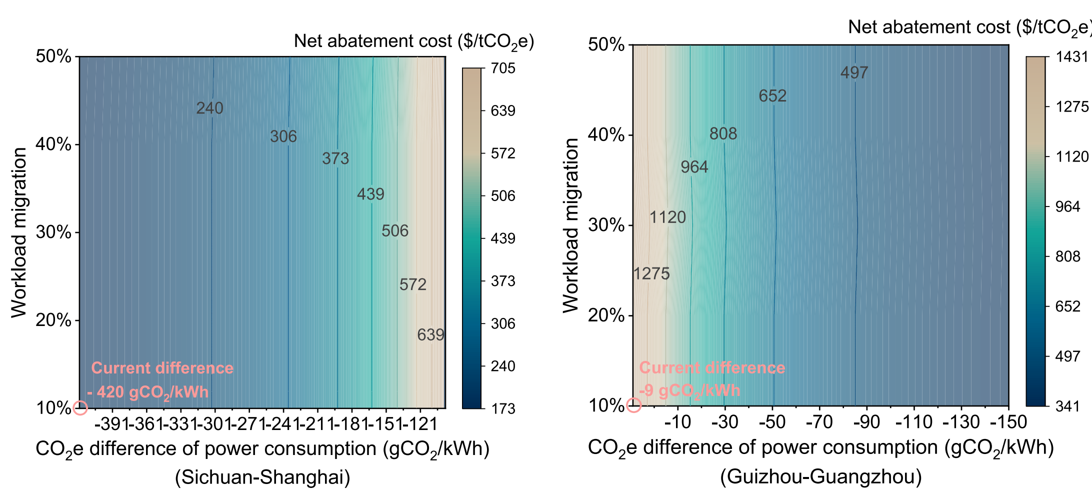

Fig. 6. Net carbon abatement cost considering future potential changes in CO2e factor difference of power consumption.

costs for Shanghai-Sichuan and Guangzhou-Guizhou are 174 \$/tCO_2e and 1431 \$/tCO_2e, respectively. In the Shanghai-Sichuan route, the net carbon abatement cost will increase if the CO_2e factor difference decreases in the future. For the Guangzhou-Guizhou route, the net carbon abatement cost will decrease if the CO_2e factor difference increases.

(A) Net carbon abatement cost for Shanghai-Sichuan route.

(B) Net carbon abatement cost for Guangzhou-Guizhou route.

3. Discussion and policy implications

The above sections provide a comprehensive analysis of the energy, economic, and carbon impacts of EDWC, summarizing key conclusions that have far-reaching implications. Notably, these findings are not only relevant to this national project but also applicable to global cases, as the demand for cloud services continues to grow worldwide. From the perspective of energy savings, 'moving bits' is much more energy efficient than 'moving watts', which is suitable for all cases globally. From an economic perspective, while the initial investment in constructing data centers may be high, the long-term returns and benefits are substantial. The development of AI technology, in particular, is likely to drive local economic growth and yield multifaceted benefits. Furthermore, from a decarbonization standpoint, migrating computing workloads to regions with high renewable energy penetration holds great promise for reducing carbon emissions from data centers. *There are some other challenges and concerns faced for the successful implementation of the EDWC project, such as data confidentiality and security, efficient workload scheduling and timely transmission of workloads.* A combination of policy formulation, technological investment, and strategic planning is essential for addressing these challenges to ensure the successful implementation of the EDWC project.

Firstly, ensuring the confidentiality of sensitive data is a major challenge when transferring batch computing workloads across geographically distributed data centers. Addressing data confidentiality necessitates the formulation of stringent data encryption policies. This involves mandating the use of cutting-edge encryption technologies for both data at rest and in transit, such as homomorphic encryption [47]. In addition, aggregation protocols, advanced encryption technology and financial incentives could potentially address confidentiality-related concerns [27].

Secondly, the challenge of efficient workload scheduling in geo-distributed data centers calls for the development and implementation of dynamic scheduling algorithms. These algorithms must be capable of adapting to changing network conditions and workload demands, optimizing for both cost and latency. Policies prioritizing resource allocation based on the criticality and latency-sensitivity of workloads are needed to ensure that high-priority tasks are completed first. Additionally, a framework for conducting cost-benefit analysis is needed to make informed decisions when balancing the trade-offs between cost, performance, and latency.

Thirdly, current technologies are still far from reaching the level of timely transmission of batch computing workloads without data loss. To fulfill the need for timely transmission of batch computing workloads without data loss, significant investment in high-speed network infrastructure is required. Exploring data transfer optimization techniques, such as data compression and deduplication, can minimize the volume of data needing transmission.

Furthermore, the inconvenience and higher cost of employing IT experts locally is another practical issue of concern. Establishing training and development programs to upskill local IT staff will reduce reliance on external experts. Investing in remote collaboration and support tools would enable remote experts in the East to effectively assist local teams.

4. Conclusions

This paper presents a comprehensive assessment of the impact of China's national initiative 'Eastern Data, Western Computing' on energy, economic, and carbon emission aspects. By analysing the three major migration routes, we found that *'moving bits' is much more energy efficient than 'moving watts', but not necessarily beneficial in decarbonization.* The results provide valuable insights into the potential environmental and economic implications of this national initiative.

All migration routes show significant energy-saving potential, ranging from 332 GWh to 942 GWh per year. The energy consumption associated with data transmission in both scenarios is significantly lower than the energy savings due to the reduction of cooling energy and the elimination of power transmission losses. Particularly, when dedicated data transmission lines are built, the energy consumption of data transmission can be even ignored.

The benefits of carbon emission reduction in different routes are significantly different. Both Shanghai-Sichuan and Guangzhou-Guizhou routes show a sharp decline in total carbon emissions, up to 2803 $KtCO_2e$ and 356 $KtCO_2e$ respectively. However, the Beijing-Inner Mongolia route shows a significant increase in total carbon emissions, 1164 $KtCO_2e$. Furthermore, we find that, if the CO_2e factor difference between Inner Mongolia and Beijing is reduced to 85 gCO_2/kWh, this route could also achieve carbon emission reduction. In addition, the net carbon abatement costs for Shanghai-Sichuan and Guangzhou-Guizhou routes are 174 $\$/tCO_2e$ and 1431 $\$/tCO_2e$ respectively, when considering extra capital cost for building duplicated data centers in Western regions.

The routes migrating computing workloads to renewable-heavy regions have great potential to reduce carbon emissions, whereas the routes migrating workloads to fossil-fuel-heavy regions show negative impacts. One recommendation for the governments in making policies is to expedite the transition towards low-carbon power generation in these fossil-fuel-heavy regions. Another alternative is to establish new migration routes in which computing workloads are transferred to regions with low carbon emission factors, such as Yunnan province.

Currently, *no economic benefit is observed if considering the high capital costs for constructing duplicated data centers in the Western regions unless new data centers need to be built anyway.* However, other potential economic benefits are visible in the near future. For example, the development of the data industry could attract other industries and businesses to these regions, thereby boosting overall economic development. Additionally, zero-carbon data centers [27] adopting containers and co-locating at renewable generation sites directly could be a promising alternative for building new data centers. They are more cost-effective and highly customizable compared to traditional data centers.

Our findings imply that the major plans of the national initiative 'EDWC' offer significant opportunities for reducing carbon emissions in the data center industry, whereas the others do not. These results serve as a crucial foundation for policy-makers, industry stakeholders, and researchers to make informed decisions and establish effective strategies for the successful implementation of the EDWC projects. Moreover, our research has broader applicability beyond China, extending to other regions worldwide. As the need for cloud services continues to expand globally, there is substantial potential for reducing carbon emissions through 'moving bits'. The quantitative results offer a promising direction for the global decarbonization of the data center industry.

5. Methods

5.1. Modeling approach

5.1.1. Cooling system model

In this study, a cooling system commonly deployed in practice is selected to simulate the coefficient of performance (COP) of the cooling system under varying climatic conditions. The cooling system consists of chillers, heat exchangers, cooling towers, chilled water pumps, cooling water pumps and computer room air handlers, shown in Fig. S1. The cooling load of the cooling system unit is assumed to be 4000 kW. The specification of the cooling system is shown in Table S4.

Chiller modeling and the assumption for heat exchangers.

Braun's method is used to model the power consumption of chillers [48], shown in Eqs. 1–3. Two variables are used, i.e., the load and the temperature difference between the leaving condenser and chilled water flows. Eq. 1 is the correlation of the chiller power and variables. In addition, the testing data of the chiller used in this study is from a major manufacturer (Trane).

$$\frac{P_{ch}}{P_{des}} = a_0 + a_1X + a_2X^2 + a_3Y + a_4Y^2 + a_5XY \tag{1}$$

$$X = \frac{\dot{Q}_e}{\dot{Q}_{des}} \tag{2}$$

$$Y = \frac{(T_{cwr} - T_{chws})}{\Delta T_{des}} \tag{3}$$

where, X is the ratio of the chiller load to the design load. Y is the leaving water temperature difference divided by a design value. P_{ch} is the chiller power consumption and P_{des} is the power consumption at the design condition. The empirical coefficients in Eq. 1 (a_0, a_1, a_2, a_3, a_4 *and* a_5) are determined using linear least-squares curve fitting based on the chiller performance data from the manufacturer. Detailed empirical coefficients and parameters of the chiller model can be found in Table S5. In addition, a 1.5 °C temperature approach for heat exchangers is assumed [49,50].

5.1.1.1. Cooling tower modeling. In the cooling system, heat rejection equipment includes open cooling towers and dry coolers [51]. The cooling water loop will switch to dry coolers when the ambient wet-bulb temperature is lower than −5 °C according to engineering practice, to avoid freeze problems.

Open cooling towers involve sensible and latent heat transfer. In this study, the ε-NTU method is used to model open cooling towers [52]. For a counterflow cooling tower, it is described as Eq. 4–6.

$$\varepsilon_a = \frac{1 - \exp(-NTU(1 - m^*))}{1 - m^* exp(-NTU(1 - m^*))} \tag{4}$$

where,

$$\mathrm{NTU} = \frac{h_D A_v V_{cell}}{m_a} \tag{5}$$

$$m^* = \frac{m_a C_s}{m_{w,i} C_{pw}} \tag{6}$$

The saturation-specific heat, C_s, is defined as the average slope of the saturation enthalpy with respect to the temperature curve. It can be determined with the water inlet and outlet conditions and psychometric data using Eq. 7.

$$C_s = \frac{h_{s,w,i} - h_{s,w,o}}{T_{w,i} - T_{w,o}} \tag{7}$$

The wet-bulb temperature is used as a primary input of the open cooling tower model because the enthalpy can be approximated as a formula related to wet-bulb temperature [53], at a given atmospheric pressure. For dry coolers, the ε-NTU method is also used to obtain the performance of the dry cooler at different conditions. Dry-bulb temperature is one of the main input parameters for the dry cooler model. Detailed mathematical references of these two models can be found in TRNSYS 18 component mathematical manual [52].

According to the desired cooling capacity for cooling towers and outdoor conditions, the airflow rate can be determined. The fan power is in cubic growth of the rotational speed ideally, (k = 3) as shown in Eq. 8 [54]. In this study, k is selected as 1.5 based on practical in-situ operation data. Cooling towers cannot achieve the ideal performance (k = 3) in practical operations [54].

$$\frac{W_{ct}}{W_{ct,design}} = \left(\frac{Q_{ct}}{Q_{ct,design}}\right)^k \tag{8}$$

where, W_{ct} is the energy consumption of cooling towers. $W_{ct,design}$ is the energy consumption of cooling towers at the design condition. Q_{ct} is the air flow rate, and $Q_{ct,design}$ is the air flow rate at the design condition.

In the free cooling mode, the speed of the cooling tower fans is controlled to make the outlet water temperature of the heat exchangers reach the desired chilled water supply temperatures. In both partial free cooling and mechanical cooling modes, the chilled water supply temperature is controlled by the chiller itself, and the speed of cooling tower fans is modulated to maintain the cooling tower water outlet temperature at a setpoint given by Eq. 9. Where, $T_{ct,out}$ is the outlet cooling water temperature, T_{wet} is the wet bulb temperature, and $T_{min,cd}$ is the minimum condenser water entering the temperature setpoint.

$$T_{ct,out} = \max\left(T_{wet} + 5^{\circ}\mathrm{C}, T_{\min,\mathrm{cd}}\right) \tag{9}$$

5.1.1.2. Pump modeling. The cooling water pumps are usually constant-speed pumps and they are assumed to work at rated power. The chilled water pumps are variable-speed pumps. The energy consumption of chilled water pumps depends on the pressure drop, the water flow rate and pump efficiency, as shown in Eq. 10. Where, W_{cwp} is the energy consumption of pumps, Δp_{cwp} is the pressure head of pumps, m_w is the water flow rate, and η_{cwp} is the efficiency of pumps [10]. The pressure head of pumps (equal to the pressure drop of the chilled water loop) is set to be linear to the water flow rate in operation [54].

$$W_{cwp} = \frac{\Delta p_{cwp} \times m_w}{\eta_{cwp}} \tag{10}$$

5.1.1.3. Computer room air handlers. The difference between supply and return air temperatures of the computer rooms is assumed a constant of 10 K [55].

5.1.1.4. Energy efficiency of cooling systems. The coefficient of cooling system performance (COP) is used to analyze the energy performance and efficiency of data center cooling systems, given by Eq. 11.

$$COP = \frac{L_{cooling}}{W_{system}} \tag{11}$$

where $L_{cooling}$ is the cooling load and W_{system} is the total energy consumption of the cooling system.

5.1.2. Data transmission model

5.1.2.1. Data transmission on the existing backbone networks. The historical trends of the energy intensity (EI) of data transmission on the existing backbone networks from 2006 to 2021 are shown in Fig. 1D and Table S6. In 2021, data-transmission EI on the backbone network is estimated as 0.001 kWh/GB at an average distance of 700 km [42]. The power consumption of the backbone network is the sum of the energy consumption of network equipment (i.e., routers, amplifiers, etc.) [56]. Notably, it is assumed that the data-transmission EIs are proportional to the distance between the two regions involved.

5.1.2.2. Data transmission on newly built dedicated fiber-optic lines. In the scenario ‘dedicated data-transmission lines’, we use the power consumption model developed by Heddeghem et al. [44,45], given by Eqs. 12–13.

$$P_{BACKBONE} = P_{IP} + P_{WDM} \tag{12}$$

$$P_{WDM} = P_{OXC} + P_{TXP} + P_{OLA} \tag{13}$$

The power consumption of each network equipment is further given as Eq. 14–17 [44,45].

$$P_{IP} = \eta_{eo} \bullet \frac{\eta_{pr}}{2} \bullet \eta_{op} \bullet T \bullet (H+1) \bullet \left(\frac{P_{ip}}{C_{ip}} \bullet 2\right) \tag{14}$$

$$P_{OXC} = \eta_{eo} \bullet \eta_{pr} \bullet \eta_{op} \bullet T \bullet H \bullet \left(\frac{P_{oxc}}{C_{oxc}} \bullet 2\right) \tag{15}$$

$$P_{TXP} = \eta_{eo} \bullet \eta_{pr} \bullet \eta_{op} \bullet T \bullet H \bullet \left(\frac{P_{txp}}{C_{txp}} \bullet 2\right) \tag{16}$$

$$P_{OLA} = \frac{\eta_{eo}}{2} \bullet \frac{\eta_{pr}}{2} \bullet \eta_{op} \bullet T \bullet H \bullet \left(\frac{P_{ola}}{C_{ola}} \bullet \frac{\text{link length}}{80\ \text{km}}\right) \tag{17}$$

where P_x is the power consumption of network equipment *x,* Internet protocol (IP), Wavelength division multiplexing (WDM), Optical cross-connects (OXC), Transponder (TXP) and Optical cross-connects (OLA) (W); η_{eo} is the external overhead factor; η_{pr} is the protection factor; η_{op} is the overprovisioning factor; T is the total traffic in the network (Gbps); H is the average hop count in the respective network layer; $\frac{P_x}{C_x}$ expresses the average power per capacity (in W/Gbps) for a given equipment x. Note that telecommunication equipment becomes more power efficient each year largely driven by Moore's law. In this study, we assume there is an 11 % per year reduction in energy-per-bit [44,57]. The analytical parameters (Table S7) are all based on the latest-generation equipment in this study.

5.2. Analysis on energy, economy and carbon emissions

5.2.1. Energy-saving potential

The potential energy benefits can be achieved by *i.* the reduction in cooling energy due to the different climate conditions in two regions involved in each route and *ii.* the eliminated power transmission loss involved in long-distance power transmission.

5.2.1.1. Difference in cooling energy consumption of data centers in the East and West. It is assumed that the electricity used by data centers in the East is transmitted from Western regions. The power transmission losses of these power transmission lines are summarized in Table S8. A 10 MW typical data center is used as the fundamental unit for analysis [27], which has a total peak power of 21 MW and consumes approximately 114 GWh of electricity annually [27]. The detailed specifications and characteristics of the typical data center are given in Table S9. The energy consumption breakdown in a typical data center is summarized in Table S10. In addition, it is assumed that the energy consumption of IT equipment is proportional to computing workloads [58]. The cooling energy of processing the same computing workloads in the West is calculated by Eq. 18. The energy consumption of the same computing workloads in the East and West is given by Eq. 19–20.

$$Ele_{coolwest} = \frac{Ele_{cooleast} \times COP_{West}}{COP_{East}} \tag{18}$$

$$TotEle_{Eest} = Ele_{IT} + Ele_{cooleast} + Ele_{others} \tag{19}$$

$$TotEle_{West} = Ele_{IT} + Ele_{coolwest} + Ele_{others} \tag{20}$$

5.2.1.2. Energy Consumption of Data Transmission vs Power Transmission Loss. The amount of data in China's data centers is estimated by [59,60], shown in Table S11. It is assumed that data volume is proportional to the computing workloads from the perspective of overall trends and general patterns. The energy consumption of data transmission is calculated by Eq. 21.

$$Ele_{Datatrans} = EI_{Datatrans} \times V_{Datatrans} \tag{21}$$

Three existing typical lines in the WEPT project are selected as baseline scenarios. The energy loss of power transmission is calculated by Eq. 22.

$$Ele_{Ploss} = \lambda_{Ptrans} \times Ele_{Ptrans} \tag{22}$$

5.2.2. Carbon emission reduction

The carbon emission reductions are achieved by *i.* the difference in carbon emissions of power consumption between Eastern regions and Western regions. *ii.* the difference in carbon emissions of data transmission and power transmission losses.

Cross-regional electricity trade entails the transfer of carbon emissions, thereby resulting in unequal CO_2 emission factors associated with power generation and power consumption in specific provinces and cities. The carbon emission factors associated with power generation and power consumption of different provinces and cities are summarized in Table S3. In addition, carbon emissions factors associated with raw material and production of data transmission and power transmission are summarized in Table S12. The equations for calculating total carbon emission reductions are presented in Eqs. 23–27.

$$\Delta CE_{Total} = \Delta CE_{Elecons} + \Delta CE_{Other} \tag{23}$$

$$\Delta CE_{Elecons} = f_{Westcons} \times TotEle_{West} - f_{Eastcons} \times TotEle_{East} \tag{24}$$

$$\Delta CE_{Other} = CE_{Datatrans} - CE_{Ploss} \tag{25}$$

$$CE_{Datatrans} = \beta_{Datatrans} \times V_{Datatrans} + f_{Avecons} \times Ele_{Datatrans} \tag{26}$$

$$CE_{Ploss} = \beta_{Ptrans} \times Ele_{Ploss} + f_{Westgene} \times Ele_{Ploss} \tag{27}$$

5.2.3. Economic analysis

In the economic analysis, we consider several key factors. *i*, capital investment required for building duplicated data centers in the Western regions (and building dedicated fiber-optic lines). *ii*, the difference in electricity prices between Eastern regions and Western regions. *Iii*, the difference in the energy costs of data transmission and eliminated power transmission loss.

In the data-transmission scenario, the amortized cost of traditional data centers is \$1.56/W per year (at an interest rate of 8 % and depreciating data centers over 12 years) [61]. Therefore, a 10 MW traditional data center has an amortized facility cost of \$15.6 million. The amortized capital cost for newly built fiber-optic lines is estimated according to the literature [62,63], shown in Table S13. The electricity cost in different regions involved in this study is summarized in Table S2. The economic analysis is calculated by Eqs. 28–32. Nomenclature for Eqs. 18–32 is shown in Table S14.

$$\Delta Cost_{Total} = \Delta Cost_{DC} + \Delta Cost_{Ele} + \Delta Cost_{Other} + (\Delta Cost_{DL}) \tag{28}$$

$$\Delta Cost_{Ele} = Eprice_{West} \times TotEle_{West} - Eprice_{East} \times TotEle_{East} \tag{29}$$

$$\Delta Cost_{Other} = Cost_{Datatrans} - Cost_{Ploss} \tag{30}$$

$$Cost_{Datatrans} = AveEprice \times Ele_{Datatrans} \tag{31}$$

$$Cost_{Ploss} = AveEprice \times Ele_{Ploss} \tag{32}$$

CRediT authorship contribution statement

Yingbo Zhang: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft. **Hangxin Li:** Writing – review & editing. **Shengwei Wang:** Funding acquisition, Writing – review & editing.

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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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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