ARTICLE

Greening China's digital economy: exploring the contribution of the East–West Computing Resources Transmission Project to CO$_2$ reduction

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China's East–West Computing Resources Transmission Project (EWCRT Project) is a unique and innovative path toward developing China's green digital economy. The EWCRT Project consists of building transregional digital infrastructure, including eight data center hubs and 10 data center clusters across China. Our estimations indicate that the EWCRT Project could result in a reduction of 2125 metric tons (Mt) of CO$_2$ between 2020 and 2050. Combined with other improvement measures, such as an increase in power usage effectiveness (PUE) and a boost in the use of green electricity in these data centers, the project could result in a reduction of 9500 Mt of carbon emissions over the next three decades. Recognizing the heterogeneous makeup of data centers in general, it is crucial to identify diverse strategies that can transform each into "green engines" for the digital economy. Therefore, in this study, we use fuzzy-set qualitative comparative analysis (fsQCA) to characterize the complex conditions of different data center configurations. By doing so, we highlight differentiated strategies for data centers to support the greening of the digital economy.

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Introduction

The data-driven digital economy has become increasingly significant to the global economy, with major implications for achieving sustainable development goals (SDGs). Although it is difficult to measure the exact scale of digital data, it is clear that the creation and use of digital data is growing exponentially. For example, global Internet protocol traffic in 2022 was projected to exceed all Internet traffic up to and including 2016 combined (UNCTAD 2022). It is important to understand that both digital data and digital technologies have direct and indirect effects on energy consumption and greenhouse gas (GHG) emissions. According to the International Energy Agency (IEA), data centers and data transmission networks—the two types of critical infrastructure supporting the digital economy—were responsible for 300 metric tons (Mt) of CO_2 in 2020, accounting for nearly 1% of energy-related GHG emissions (Masanet et al. 2020; IEA 2022). To align with the worldwide goal of net-zero GHG emissions, it will be necessary to halve the emissions generated by data centers globally by 2030 (IEA 2022). Achieving this target is a daunting task, however, especially for emerging economies.

One particular emerging economy, China, stands out within the digital economy, as it contains a number of the world's hyperscale data centers. China's digital economy has nearly doubled since 2016, growing from CNY 22.6 trillion in 2016 to CNY 45.5 trillion in 2021 (CAC 2022). Correspondingly, the number of racks that provide the calculating power for the country's digital industry has quadrupled from 1.24 million in 2016 to 5.9 million in 2022 (CAICT 2022; Xinhua News Agency 2022), and this level of growth is expected to continue. According to China's latest three-year action plan for new data centers—enacted in July 2021—China will maintain an average annual growth rate of 20% for the scale of racks over the 2021–2023 period (MIIT, 2021). While this is considered an overall positive for the country, the rapid development of China's digital economy has unfortunately also resulted in a sharp increase in carbon emissions from its national data centers. In 2020, the electricity consumption of China's data centers equaled 150.7 billion kilowatt hours (KWH), accounting for 2.01% of the country's total electricity consumption (Greenpeace 2021). Over 80% of the electricity used in these data centers was generated from fossil fuels (NEA 2021; Guo et al. 2022), resulting in over 94.85 million Mt of carbon dioxide emissions (Greenpeace 2021). A recent report predicted that China's total data center energy consumption would reach 380 billion KWH by 2030, with carbon emissions expected to increase by more than 300% (ODCC 2022). The rapid development and increasing growth of China's digital economy have highlighted the urgent need to reduce energy consumption and carbon emissions from the country's data centers. Therefore, the Chinese government has implemented a range of policies to promote a greener digital economy (see Table 1).

Recent research has underscored the importance of measuring the environmental impacts caused by data centers dotted around the world. These studies analyzed data center energy estimates published between 2007 and 2021 and identified two main areas of focus in this published research: (1) data center energy consumption and reduction, and (2) measures that could be used to mitigate the environmental impact of GHG emissions, particularly by transitioning to cleaner energy sources for power generation (Mytton and Ashtine 2022; Zhao and Zhou 2022). Researchers have proposed various strategies to reduce carbon emissions from data centers, such as improving their power usage effectiveness (PUE) and managing the data centers via new algorithms (Deymi-Dashtebayaz et al. 2019; Lei and Masanet 2020; Aliyu et al. 2021). Additionally, authors have discussed how carbon emissions reductions could be accomplished by shifting from fossil-based energy to renewable energy sources (Zhao and Zhou 2022; Shen et al. 2023). For example, one study analyzed data from data centers located in California, Pennsylvania, New Jersey, and Maryland in the United States and demonstrated that migrating data center workloads from fossil-fuel-heavy sources to renewable energy sources could absorb up to 62% of total curtailment while incurring negative abatement costs, thereby reducing emissions overall (Zheng et al. 2020).

However, the existing research has paid limited attention to the long-term trend of powering green digitization in China, with the exception of a couple of studies that focused on China's digital infrastructure, such as its 5 G network infrastructure (Greenpeace 2021; Guo et al. 2022). Although some researchers have examined the relationship between the digital economy and carbon emissions by using panel data at the region and city levels (Ma et al. 2013; Li et al. 2021; Zhang et al. 2022b), there is still a lack of direct evidence regarding various carbon emissions reduction paths that could be taken by China's data centers to help make the country's digital economy greener.

In this study, we focused on the EWCRT Project and its potential for contributing to the greening of China's digital economy, estimating the impact of the EWCRT Project on China's emissions reductions between 2020 and 2050 by establishing three main scenarios and five sub-scenarios. Our results showed that the EWCRT Project could significantly reduce China's carbon emissions while the country pursues the expansion of its digital economy. The results also demonstrated that improving China's PUE and adopting green electricity could minimize carbon emissions from the country's data centers. Furthermore, we employed fuzzy-set qualitative comparative analysis (fsQCA) to explore various configurations that have the potential to reduce the carbon emissions intensity of the digital economy at the regional level for the nation's 10 data center clusters.

Table 1 China's actions and policies regarding strategies for big data and net-zero carbon emissions.

Date	Policy
2020.9	China announces its goal to achieve a carbon dioxide peak prior to 2030 and carbon neutrality prior to 2060.[a]
2021.7	China officially implements its three-year action plan for new data center development (2021–2023).[b]
2022.1	China announces its latest five-year plan for digital economic development, including digital industrialization and digital synergetic governance mechanisms.[c]
2022.2	China officially implements its East–West Computing Resources Transmission Project to transport data from the country's eastern regions to its western regions for more energy-efficient storage and processing.[d]

[a]Xinhua News Agency.
[b]The Ministry of Industry and Information Technology of the People's Republic of China.
[c]The State Council of the People's Republic of China.
[d]The National Development and Reform Commission of the People's Republic of China.

Literature review and project background

Digital infrastructure and carbon emissions. Digital infrastructure is defined as "shared, unbounded, heterogeneous, open, and evolving sociotechnical systems comprising an installed base of diverse information technology capabilities and their user, operations, and design communities" (Tilson et al. 2010, p. 748). Over the past two decades, there has been sharp growth in easy-to-use digital infrastructure involving computers, mobile devices, broadband network connections, and advanced application platforms, which has enabled transformations in various industries and affected the natural environment (Fichman et al. 2014; Zhang et al. 2024b). As the underlying element of this digital convergence, the role of digital infrastructure in reducing carbon emissions has become increasingly prominent (Tang and Yang 2023; Tilson et al. 2010).

A number of studies have assessed carbon emissions produced by digital infrastructure at the regional level (Ahmed and Le 2021) or industrial level (Zhang et al. 2023b), as well as at the city (Wang et al. 2023) and household (Xu et al. 2024; Zhang et al. 2024a) levels. However, most overlooked the fundamental role of data centers, which provide computing resources for nearly every device. Incorporating detailed data on the data centers would allow researchers to estimate carbon emissions at their source (IEA 2022). Moreover, there is little research that has presented methods for modeling data center energy use at both global and regional scales (Gui et al. 2023; Lei and Masanet 2020; Zhang et al. 2023a), and the literature that does exist is inadequate for understanding future energy use and carbon emissions trends of data centers at the national level (Lei and Masanet 2020). The wide range of estimates, coupled with challenging-to-validate calculations, makes it difficult to rely on study estimates for assessing data center carbon emissions (Masanet et al. 2020; Mytton and Ashtine 2022). Hence, the lack of clear methodologies and data provenance remain major constraints for assessing carbon emission reductions of data centers (Mytton and Ashtine 2022). Accurately estimating data centers' carbon emissions on a national scale over the long term, especially in emerging economies, is clearly a challenging task (Mytton and Ashtine 2022).

Furthermore, recent studies on this subject have continued to lack direct estimation for data center carbon emission reductions in China. Instead, the existing research has more attention to discussing the emission effects and economic impacts of digital infrastructure in the Chinese context (Zhang et al. 2024a; Zhang et al. 2022a). Most have utilized particular digital policies, such as the e-commerce pilot policy (Wang et al. 2023) or the "Broadband China" strategy (Feng et al. 2023; Tang and Yang 2023), as quasi-natural experiments to examine indirect evidence on carbon emissions caused by digital infrastructure. Due to China's unbalanced economic development and energy distribution, the impacts of digital infrastructure on carbon emission reductions would naturally vary across regions: while the decarbonization of the digital economy would be more significant in the nation's eastern regions, it would not be as significant in the central and western regions (Wang et al. 2022; Zhang et al. 2022a). After all, disparities in resource endowments, economic structures, and energy sources yield distinct carbon emissions in China's data centers across regions (Dai et al. 2024). Yet, research on this subject has paid insufficient attention to data center carbon emission reductions regionally despite the clear, significant regional differences in China.

Project background. In February 2022, China initiated the East–West Computing Resources Transmission Project (EWCRT Project), a national digital project meant to address imbalances in the distribution of data and power resources in the country. Currently, China's data resources are largely concentrated in its eastern regions, which have dense populations and well-developed digital infrastructure, while the nation's western regions have more abundant energy resources, including solar, wind, and water. Under the EWCRT Project, the country's eastern regions would continue to provide computing resources to core private and public sectors, such as the financial industry, industrial Internet, and disaster warning systems, but data processing activities would shift to the nation's western regions, where an ample supply of green electricity would support activities like disaster backup and offline analysis. The EWCRT Project provides an excellent opportunity to explore the carbon emissions of digital infrastructure over the long run in the unique context of China.

As Fig. 1 shows, the EWCRT Project was formulated to facilitate the distribution of data through eight new data center hubs and 10 new data center mega-clusters across China (NDRC 2022). Additionally, the EWCRT Project will implement measures to promote the greening of China's digital economy by improving PUE and increasing the use of clean energy in data centers (NDRC 2022). This is China's fourth national-level, hyper-scale resource allocation project; it follows the implementation of the South–North Water Diversion Project, the West–East Electricity Transmission Project, and the West–East Natural Gas Transmission Project (Ma et al. 2013; Li et al. 2016; Zhu et al. 2020). Despite the significance of the EWCRT Project, to date, no studies have been conducted to analyze its implications in terms of carbon emissions in China.

Methodology

We employed both a scenarios approach and fsQCA to estimate the impact of digital infrastructure on carbon emissions in China. While the scenarios approach involves a comprehensive exploration of key factors (e.g., PUE, green electricity, etc.) that influence carbon emissions across the entire EWCRT Project, the fsQCA focuses on the configurational relationships of these key factors by undertaking a review of 10 data center clusters as cases. By integrating these two methods, we aim to provide a more comprehensive understanding of how different conditions, such as the amount of green energy and the number of racks, would coexist in different scenarios within China's EWCRT Project, as well as how the different conditions would lead to distinct carbon emission reduction outcomes.

Scenarios approach. We used the scenarios approach to estimate the carbon emissions using the low emissions analysis platform (LEAP) software (version 2020.1.0.64), as proposed by Heaps (2022). The data generated by our analysis can be found in supplemental material (see Data S1–S8).

Step 1: The bottom-up method. Following prior studies (Ziegler et al. 2019; Saunois et al. 2020; Greenpeace 2021), we adopted a bottom-up method to estimate the carbon emissions levels from the data centers required for each scenario using the following equations:

$$E_i = \sum_{i=1}^{n} N_i \times P_i \times L_i \times U_i \times t \quad (1)$$

$$Carbon\ emissions = \sum_{i=1}^{n} E_i \times G_i \times F_i \quad (2)$$

where E_i denotes the total electricity consumption of the data centers; N_i is the number of racks; P_i is the purposely designed power of a single rack; L_i is the average IT load utilization rate (i.e., the ratio of the actual load of the IT equipment to the purposely designed full load of the IT equipment); U_i is the

Fig. 1 China's EWCRT Project. This figure shows the eight national-level data center hubs and their 10 data center mega-clusters to be developed under the EWCRT Project, with the data center hubs in the east (shown in green) providing data resources, and the data center hubs in the west (shown in yellow) providing computing power. The red arrows indicate the direction of the data and computing resource flows, and the blue dotted arrows represent the backflow of data.

average PUE (determined by dividing the total energy consumption of a data center by the total energy consumption of its IT devices); t is the working hours; G_i is the proportion of green electricity; and F_i denotes the emissions factors (based on those of the local or national grids where the data centers are located). For further details, see Data S3, S6, and S8.

We analyzed the eight national-level data center hubs included in the EWCRT Project. The four data center hubs in China's western region are the *Inner Mongolia Hub* (including the *Helingel Cluster*), *Gansu Hub* (including the *Qingyang Cluster*), *Ningxia Hub* (including the *Zhongwei Cluster*), and *Guizhou Hub* (including the *Guian Cluster*). The four data center hubs in China's eastern region are the *Beijing-Tianjin-Hebei Hub* (including the *Zhangjiakou Cluster*), *Yangtze River Delta Hub* (including the *Wuhu Cluster* and *Demonstration Zone of the Yangtze River Delta Cluster*), *Greater Bay Hub* (including the *Shaoguan Cluster*), and *Chengdu-Chongqing Hub* (including the *Tianfu Cluster* and *Chongqing Cluster*). According to policy requirements, the *Chengdu-Chongqing Hub* is considered one of the four hubs in the east despite its actual geographical location, which is in the western part of the country.

Step 2: Scenarios and data sources. To explore the EWCRT Project's contribution to the greening of China's digital economy, we established three scenarios: a business as usual (BAU) scenario, an EWCRT Project (PRO) scenario, and an advanced improvements (ADV) scenario with additional greening measures. Using

available data, we assumed each parameter of the BAU and PRO scenario. The data sources are found in Table 2.

Data center hub managers often consider a mix of actions to reduce CO_2 emissions, such as simultaneously improving PUE and increasing the proportion of green electricity. We assumed that the data center hubs could combine PUE improvement with green electricity use in the ADV scenario: (i) PUE for all data center hubs would fall to 1.1 after 2030 because a PUE value close to 1.1 would be the ultimate improvement, demonstrating true technological progress (Masanet et al. 2020). (ii) The proportion of green electricity in China's eastern and western hubs would gradually increase to 100% (up from 20% initially) by 2040. Based on China's net-zero carbon emissions policy, all digital infrastructure is to be fully powered by clean energy in the future (NEA 2021; Qiu et al. 2021); moreover, some data center hubs in China have committed to increasing their use of green electricity to 100% by 2030. Otherwise, the values of all of the other parameters (i.e., the number and distribution of racks, the purposely designed power of a single rack, the average IT load utilization rate, the working hours per rack/year, and the average CO_2 emissions factor) are the same as those in the PRO scenario (see Table 3).

Step 3: Calculation of CO_2 reductions in the different scenarios. Following previous studies (Liang et al. 2019; Ouedraogo 2017), we used the LEAP model to explore the optimum decarbonization path for China's data centers under the EWCRT Project

Table 2 Parameters of the BAU and PRO scenarios.

Parameters	BAU Scenario	Identifier	PRO Scenario	Identifier
Number and distribution of racks	(1) Number of racks: • 2020–2030: The number of racks will increase by 20% per year. • 2030–2040: The annual growth rate of racks will decrease from 20% to 5% year by year. • 2040–2050: The number of new racks will increase by 5% per year, while the old racks added from 2020 will be eliminated. (2) Distribution of racks: The ratio of racks in the eastern region compared to the western region of China is 8:2.	(1) Number of racks: • The *Three-Year Action Plan for New Data Center Development* requires that the total number of racks in the country's data centers grows by 20% per year on average over the 2021–2023 period.[a] • It is estimated in China's *Development Plan for Digital Economy* that the digital economy in China will enter a period of comprehensive expansion in 2025 and will mature around the year 2035.[b] • In the late period of the development of the digital economy in China, there will be a significant correlation between rack growth and GDP growth.[c] According to economist Yifu Lin, China's GDP growth rate in 2040–2050 will be nearly 5%; thus, the rack growth rate for the 2040–2050 period will be nearly 5%. (2) Distribution of racks: report from Greenpeace.[c]	(1) Number of racks: The number of racks is based on the BAU scenario. (2) Distribution of racks: The ratio of racks in China's eastern region compared to its western region will shift from 8:2 to 4:6.	The EWCRT Project will make the distribution of the data centers more balanced between China's eastern and western regions by the year 2025.[d]
Average PUE	1.43–1.58	Averaged data from the provincial data centers, as measured by Greenpeace.[c]	PUE <1.25 (1.2) in China's eastern (western) data center hubs.	The EWCRT Project requires that the data center hubs in the east (west) have their PUE below 1.25 (1.2).[b,d,e]
Average single rack power	5–7 KWH per rack	Averaged data from the provincial data centers, as measured by Greenpeace.[c]	6 KWH per rack (standard value)	Other requirements include the stipulation that each rack needs to meet the standard power of 6 KWH.[d]
Average IT load utilization rate	38%–64%	Averaged data from the provincial data centers, as measured by Greenpeace.[c]	>65%	The EWCRT Project also requires that all data center hubs maintain their loading rates above 65%.[d]
Working hours per rack/year	8760 h	Averaged data from the provincial data centers, as measured by Greenpeace.[c]	8760 h	8760 h

Table 2 (continued)

Parameters	BAU Scenario	Identifier	PRO Scenario	Identifier
Proportion of green electricity	The proportion of green electricity consumed by the data centers in China's eastern region will increase to 30% by 2030 (up from 20% initially); in China's western hubs, this could be achieved 5 years earlier.	• Presently, there is little digital infrastructure that uses renewable electricity; additionally, the type of energy depends on the local grids (Guo et al. 2022). Hence, the proportion of current data centers adopting green electricity is in line with the *proportion of green electricity consumption* in their respective provinces; the average value is nearly 20%. • China has announced plans to increase the proportion of clean energy consumption to 25% by 2030.[f] Based on the *proportion of green electricity consumption* of each province in the country's 14th *Five-Year Plan*, the maximum proportion is to be 30% in 2025; thus, by 2025, China's western hubs will be able to increase their green electricity to 30%, and this same level will be achieved in the country's eastern hubs by 2030.	The initial proportion of green electricity in China's eastern and western data center hubs will be 20%. It is anticipated that green electricity in the eastern data center hubs will rise to 50% by 2040, while it is anticipated that those in the west will meet the 50% goal by 2035.	• The EWCRT Project will also encourage the data center hubs to adopt more clean energy.[d] • Based on the *proportion of installed capacity* of each province from renewable energy or clean energy in China's 14th *Five-Year Plan*, the maximum proportion is 50%. Thus, in 2030, the western hubs can increase their green electricity to 50%, and those in the eastern hubs can do so in 2040.
Average CO_2 emissions factor	0.071–0.992 tCO_2/MWh	Averaged data from the provincial data centers, as measured by Greenpeace.[c]	Green electricity grid: 0.071 tCO_2/MWh; national electricity grid: 0.581 tCO_2/MWh.	

As the sizes of the racks vary, we use a standard industry rack size with a power of 6 KWH to measure the scale of the data centers.
[a]The Ministry of Industry and Information Technology of the People's Republic of China.
[b]The State Council of the People's Republic of China.
[c]Greenpeace (2021).
[d]The National Development and Reform Commission the People's Republic of China.
[e]China Academy of Information and Communications Technology.
[f]The Ministry of Science and Technology of the People's Republic of China.

Table 3 Parameters of the Three Main Scenarios.

Parameter	BAU	EWCRT Project	Advanced Improvements
Number and distribution of racks	Number: (i) 2020–2030: 20% annual growth. (ii) 2030–2040: The growth rate will decrease from 20% to 5% year by year. (iii) 2040–2050: New racks will increase by 5% per year while the existing racks will be phased out according to their standard 20-year service life. Distribution: The ratio of racks in China's eastern region compared to its western region is 8:2.	Number: The number of racks is based on the BAU scenario. Distribution: The ratio of racks in China's eastern region compared to its western region shifts from 8:2 to 4:6.	Same as the PRO scenario.
Average power usage efficiency (PUE)	1.43~1.58	PUE < 1.25 in China's eastern data center hubs. PUE < 1.2 in China's western data center hubs.	PUE for all data center hubs will fall to 1.1 after 2030.
Purposely designed power of a single rack	5~7 KWH per rack	6 KWH per rack (standard value)	Same as the PRO scenario.
Average IT load utilization rate	38%~64%	>65%	Same as the PRO scenario.
Working hours per rack/year	8760 h	8760 h	8760 h
Proportion of green electricity	The proportion of green electricity consumed by the data centers in China's eastern hubs will increase to 30% by 2030 (up from 20% initially); this 30% could be achieved 5 years earlier in China's western hubs.	The initial proportion of green electricity in China's eastern and western data center hubs will be 20%. In the eastern hubs, this percentage will rise to 50% by 2040, while in the western hubs, it will rise to 50% by 2035.	The proportion of green electricity in China's eastern and western hubs will gradually increase to 100% by 2040 (up from 20% initially).
Average CO_2 emissions factor	0.071~0.992 tCO_2/MWh	Green electricity grid: 0.071 tCO_2/MWh. National electricity grid: 0.581 tCO_2/MWh.	Same as the PRO scenario.

(Heaps 2022), as well as to generate the predictive values of the number of racks in the BAU and PRO scenarios (see Data S2 and S3). Then, by taking 2020 as the baseline year, we predicted the parameters of the other scenarios (i.e., the P1 scenario, P2 scenario, G1 scenario, G2 scenario, M1 scenario, and ADV scenario) and calculated their respective carbon emissions between the years 2020 and 2050.

fsQCA. We used both fsQCA and an empirical method based on Boolean algebra to analyze our cases, as such methods allow researchers to analyze combinations of several features, and because they also allow one to theorize the configuration of patterns between cases by identifying similarities and differences (Ragin 2006; Xie and Wang 2020). For example, in previous work, one QCA study used 10 cases from Africa, Asia, and Latin America to find crucial preconditions for community forest management performance and to provide a theoretical lens different from most community forest management research (Arts and de Koning 2017). The scenario analysis focused on the trend of the data centers' carbon emissions over the long run, while the fsQCA results provided details on the low-carbon configurations in different data centers that have been overlooked in previous analyses. We thus adopted the fsQCA methodology to analyze the configuration of patterns between the 10 data center clusters included in the EWCRT Project. This framework comprised an outcome variable and five conditions, as discussed below.

Outcome. We used two sub-variables to measure the carbon emissions intensity of the digital economy at the regional level. The present variable (*Carbon Emissions Intensity*) means that the digital economy produces more carbon dioxide per unit; otherwise, the absent variable (~*Carbon Emissions Intensity*) means that the digital economy produces less carbon dioxide per unit.

Conditions. Prior studies related to digital infrastructure, the digital economy, and low-carbon development have discussed various financial, institutional, digital, and energy conditions (Fedorowicz et al. 2018; Manny et al. 2021). Following this literature, we selected five representative conditions to capture the antecedents of a low-carbon digital economy, as follows. (1) The amount of public green investment at the regional level (*Green Investment*) is an important factor for strengthening pollution control and improving the environmental effects of the digital economy (Ding et al. 2023). (2) The number of racks in data centers at the regional level (*Racks*) is a key underlying parameter in prevailing data center energy models and is used for estimating carbon emissions (Lei and Masanet 2020). (3) The proportion of green electricity consumption at the regional level (*Green Energy*) can reduce data centers' energy costs, as well as their carbon emissions (Masanet et al. 2020; Ziegler et al. 2019). (4) The regional government's attention to the environment (*Green Attention*) influences the low-carbon transition of most industries, including data centers and related enterprises (Tang et al. 2023). (5) The digitalization index score at the city level (*Digital Level*) reflects the quality of digital infrastructure in a given city (e.g., the pilot cities of the "Broadband China" strategy have better digital infrastructure than non-pilot cities) (Feng et al. 2023). Table 4 shows the measurement of all variables. Based on the theoretical framework, our fsQCA procedure involved three key steps.

Step 1: Calibration: Following prior literature (Howell et al. 2022; Jia et al. 2023), we employed the direct calibration method to transform the continuous quantitative data to fuzzy-set memberships based on three qualitative thresholds: "fully in" (i.e., more than the 75th percentile), "crossover point" (i.e., the 50th percentile), and "fully out" (i.e., less than the 25th percentile). For example, we coded a data center cluster with green investment in

Table 4 Measurements.

Variable	Measure	Source	Data source
Carbon emissions intensity	Carbon emissions per unit of output in the digital economy at the city level. (Calculation: Carbon emissions ÷ digital economy output value of the region where the data center cluster is located.)	Shao et al. (2022); Cheng et al. (2023).	Carbon emissions: report from Greenpeace. Digital output: China Urban Digital Economy Index from H3C Group (H3C 2021).
Green investment	Environmental governance investment expenses at the regional level.	Fedorowicz et al. (2018); Zhao et al. (2022).	National Bureau of Statistics of China.
Racks	Number of racks at the regional level.	Cheng and Wang (2022); Wang et al. (2022).	Report from Greenpeace.
Green energy	Proportion of green electricity consumption at the regional level.	Shen et al. (2023).	The 14th *Five-Year Plan* report at the regional level.
Green attention	Proportion of environment-related words to total words in the government's annual reports at the regional level.	Qi et al. (2020); Bao and Liu (2022).	WinGo Textual Analytics Database.
Digital level	Digitalization index score at the city level. (Calculation: four first-level indicators, 12 second-level indicators, and 46 third-level indicators).	Zoppelletto and Orlandi (2022).	China Urban Digital Economy Index from H3C Group (H3C 2021)

The values of all variables are at their 2020 levels (base year: 2020).

Table 5 Fuzzy-set membership calibrations and descriptive statistics.

Variable	Fuzzy-set calibration			Description of sampling		
	Fully in	Crossover	Fully out	Mean (SD)	Max	Min
Carbon emissions intensity	0.072	0.023	0.011	0.050 (0.062)	0.188	0.001
Green investment	126,552.500	63,837.500	35,370.250	118,398.200 (158,743.765)	554,985.000	27,068.000
Racks	0.428	0.187	0.118	0.303 (0.308)	1.089	0.033
Green energy	0.272	0.193	0.114	0.217 (0.134)	0.545	0.070
Green attention	0.020	0.018	0.014	0.017 (0.004)	0.023	0.011
Digital level	79.350	66.700	55.100	66.640 (14.395)	90.100	42.400

$N = 10$.

the upper quartile (the biggest scale) of all cases as "fully in" the set of high green investment. As shown in Table 5, we use those three thresholds to calibrate each condition and outcome.

Step 2: Analysis of necessary conditions: In fsQCA, an outcome does not exist without a necessary condition, and the value of the necessary condition must be higher than 0.9 (Rihoux and Ragin 2008). Our results indicated that there was no necessary condition—that is, none of the five conditions could fully produce a non-green outcome (i.e., *Carbon Emissions Intensity*) or an expected green outcome (i.e., *~Carbon Emissions Intensity*). Table 6 shows the results of the necessary condition analyses.

Step 3: Configuration analysis: The results of this step are provided in Table 7. Either the present outcome (i.e., *Carbon Emissions Intensity*) or absent outcome (i.e., *~Carbon Emissions Intensity*) has three different configurations; hence, we attained Eqs. (3) and (4):

$$\text{Carbon Emissions Intensity} = \sim GI \sim R * \sim GE * GA + \sim GI * R * \sim GE * \\ \sim GA * DL + GI * R * \sim GE * GA * \sim DL \quad (3)$$

$$\sim \text{Carbon Emissions Intensity} = GI * R * \sim GA * \sim DL + \sim GI * \sim R * GE * GA \\ + GI * \sim R * GE * \sim GA * DL \quad (4)$$

where * represents Boolean AND (i.e., intersection), and~represents Boolean NOT (i.e., non-membership). The conditions of each configuration are as follows: Configuration 1

Table 6 Necessary analyses.

Condition	Carbon emissions intensity	~Carbon emissions intensity
Green investment (GI)	0.4000	0.596226
~Green investment (~GI)	0.651064	0.449057
Racks (R)	0.521277	0.483019
~Racks (~R)	0.551064	0.581122
Green energy (GE)	0.317021	0.852830
~Green energy (~GE)	0.885106	0.326415
Green attention (GA)	0.72766	0.422641
~Green attention (~GA)	0.393617	0.683906
Digital level (DL)	0.565957	0.537736
~Digital level (~DL)	0.544681	0.562814

Abbreviations are in parentheses. - represents Boolean negation (i.e., non-membership).

(GI*R*~GA*~DL), Configuration 2 (~GI*~R*GE*GA), and Configuration 3 (GI*~R*GE*~GA*DL) are the low-carbon configurations; and Configuration 4 (~GI*~R*~GE*GA), Configuration 5 (~GI*R*~GE*~GA*DL), and Configuration 6 (GI*R*~GE*GA*~DL) are the high-carbon configurations.

Although this study was focused on how to reduce the carbon emissions intensity of the digital economy in China, we also analyzed the conditions for the unexpected outcome of high-carbon emissions intensity: Configuration 4 indicates that the government's green attention should be present, while public green investment, the number of racks in data centers, and regional green energy should be absent in order to contribute to the high-carbon

Table 7 Configurations analysis (full results).

Condition	Outcome: ~carbon emissions intensity			Outcome: carbon emissions intensity		
	C1	C2	C3	C4	C5	C6
Green investment	●	⊗	●	⊗	⊗	●
Racks	●	⊗	⊗	⊗	●	●
Green energy		⬤	⬤	⊗	⊗	⊗
Green attention	⊗	●	⊗	⬤	⊗	⬤
Digital level	⊗		●		●	⊗
Example cases	Case (W), Case (S)	Case (Q), Case (C)	Case (T)	Case (H), Case (Z1)	Case (G)	Case (Z2)
Consistency	0.974194	0.972826	0.989796	0.939655	0.986486	1
Raw coverage	0.284906	0.337736	0.183019	0.46383	0.155319	0.244681
Unique coverage	0.226415	0.284906	0.109434	0.37234	0.108511	0.174468
Solution coverage	0.703774					
Solution consistency	0.959016			0.979003		

Core conditions are represented by ● (presence) and ⊗ (absence); contributing conditions are represented by ● (presence) and ⊗ (absence).
C1 indicates Configuration 1, C2 indicates Configuration 2, etc.; Case (W) denotes the Wuhu Cluster, Case (S) denotes the Shaoguan Cluster, Case (Q) denotes the Qingyang Cluster, Case (C) denotes the Chongqing Cluster, Case (T) denotes the Tianfu Cluster, Case (H) denotes the Helingel Cluster, Case (Z1) denotes the Zhongwei Cluster, Case (G) denotes the Guian Cluster, and Case (Z2) denotes the Zhangjiakou Cluster.
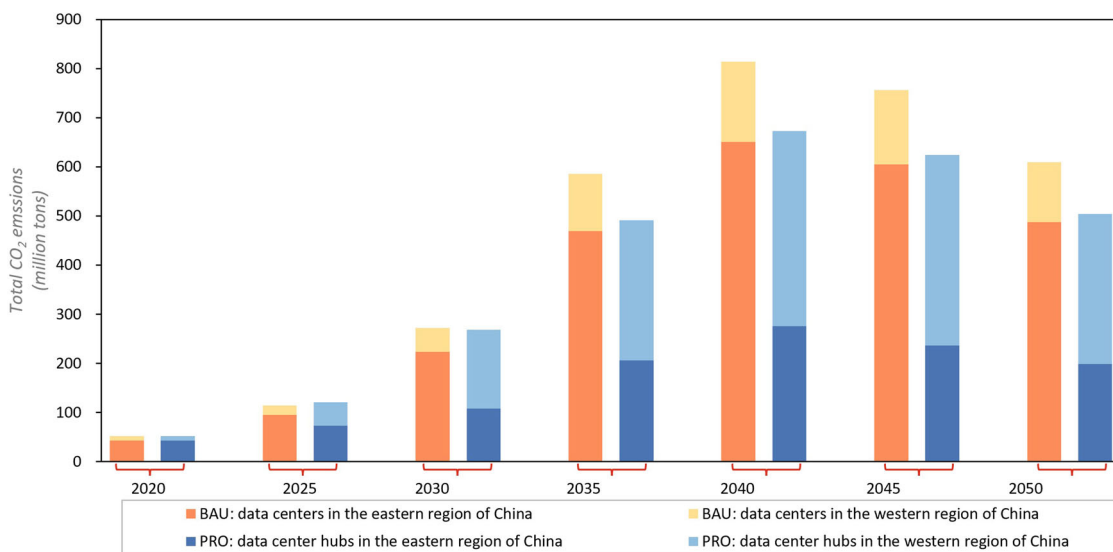

Fig. 2 Carbon emissions trends among national-level data center hubs in Eastern and Western China under the EWCRT Project, 2020–2050. The data sources and calculation methods used for computing these estimates can be found in Data S2, S3, and S4.

emissions intensity (~GI*~R*~GE*GA). This configuration is exemplified by the Helingel Cluster and Zhongwei Cluster, both of which are located in China's western region. Configuration 5 suggests that the racks and the digital activity at the city level should be present, while green investment, green energy, and the government's green attention should be absent in order to increase the carbon emissions intensity (~GI*R*~GE*~GA*DL). The example case for Configuration 5 is the Guian Cluster, located in China's western region. Configuration 6 shows that green investment, the number of racks, and the government's green attention should be present, while the regional green energy and the city's digital level should be absent (GI*R*~GE*GA*~DL). The example case for Configuration 6 is the Zhangjiakou Cluster, located in China's eastern region.

Results
CO_2 reduction from data center hubs under the EWCRT Project. Our estimation of carbon emissions from China's data centers was based on the amount of electricity consumed by racks. The estimation indicated that the total electricity

consumption in the regions where the eight national data center hubs will ultimately be located would be approximately 102.7 billion KWH, generating 51.58 Mt CO_2. This would account for almost half of the total carbon emissions from China's data centers in 2020 (Greenpeace 2021). Moreover, we illustrated the distribution of carbon emissions in the first year after the project's official launch, showing that the data center hubs in China's eastern regions contributed to nearly 73% of carbon emissions in 2022 (52.77 Mt), while the four hubs in the western regions contributed to 27% (19.58 Mt) that same year (Fig. 2). This disparity is due to the uneven distribution of electricity and computing resources across China. Additionally, the data centers in China's eastern regions utilize more power and have a higher load rate than the country's western regions (Greenpeace 2021), contributing to more carbon emissions.

Given that the digital economy powered by the data centers is expected to be central to China's growth over the next three decades, we formulated three main scenarios to predict the reduction of CO_2 emissions from China's data centers between 2020 and 2050. As discussed earlier, the first scenario is the *business as usual* (BAU) scenario, which assumes conventional
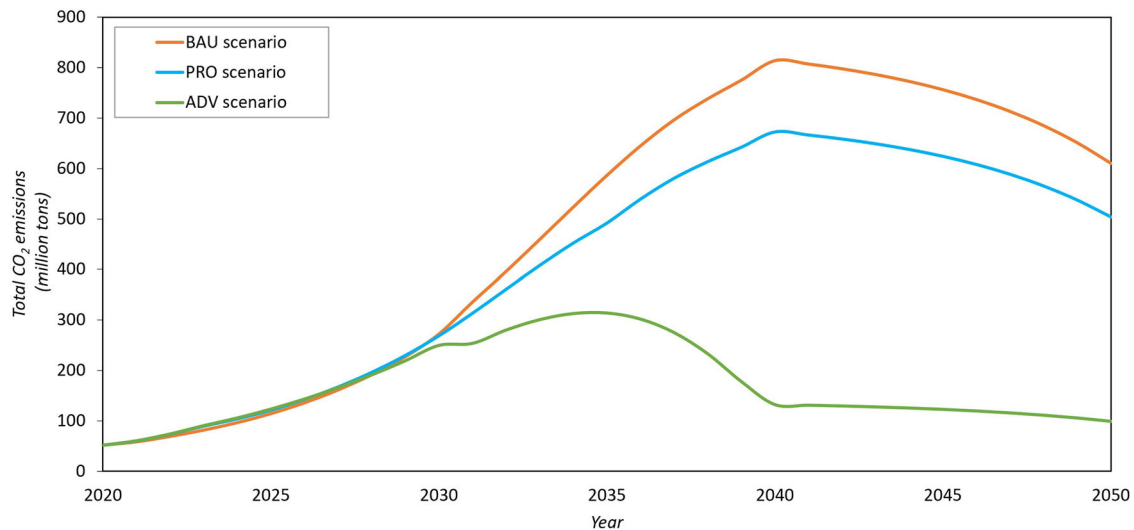
Fig. 3 Total estimated carbon emissions from national-level data center hubs under China's EWCRT Project, 2020–2050. This figure shows three scenarios: the business as usual (BAU) scenario, the EWCRT Project (PRO) scenario, and the advanced improvements (ADV) scenario. The sources and calculation methods for computing this data can be found in Data S3 and S5.

growth of the data centers and reflects the development of China's digital economy (see the Methodology section and Data S2 for a more detailed description of this scenario and for an explanation of its underlying assumptions, including the number of racks). The second scenario is the *EWCRT Project* (PRO) scenario, which builds on the BAU scenario and takes into account the policies and regulations associated with the construction of the eight national-level data center hubs and 10 data center clusters. Lastly, the third scenario is the *advanced improvements* (ADV) scenario, in which each national-level data center hub undergoes significant technical efficiency improvements and reduces its energy consumption.

In the BAU scenario, the number of racks used by the data centers shows rapid growth, which is in accordance with recent government policy requiring a 20% average annual increase in the total number of racks in the country's data centers from 2021 to 2023. Moreover, in discussing its digital economy, China's 14th *Five-Year Plan* states that the country will enter a period of comprehensive expansion in 2025, with maturity expected around 2035. However, the government is also concerned about the rapid growth of carbon emissions and has announced plans to increase the proportion of clean energy consumption to an average of 25% nationally by 2030 (MOST 2022). Figure 3 provides a trend comparison between the BAU scenario and the PRO scenario. Compared to the BAU scenario, the PRO scenario is projected to result in a reduction of 2125 Mt CO_2 emissions between 2020 and 2050. The main reasons for this level of reduction are that the PRO scenario has a lower PUE value and adopts more green energy; however, the PRO scenario must also keep the standard rack power and loading rates at higher levels in order to maintain the agglomerative advantages of the data center hubs (see Data S3). PUE is determined by the ratio of the total energy consumption of a data center to the total energy consumption of its IT devices; a PUE value close to 1 indicates the IT devices are efficient. Because the EWCRT Project will result in a more balanced distribution of data centers between the eastern and western parts of China by 2025 (NDRC 2022; Economic Observer 2022), we assume the ratio of the racks in the eastern hubs to those in the western hubs to be 4:6, which can be compared to the respective ratio of 8:2 in the BAU scenario (see the Methodology section and Data S3 for the assumptions and justifications). Furthermore, it is expected that the EWCRT

Project will encourage the adoption and use of more clean energy in the data center hubs (NDRC 2022), although no further specifications are available. Currently, more than half of the green electricity on the nation's grid is transported from western to eastern China (ODCC 2022). Based on the 14th *Five-Year Plan*, which discusses clean energy in the provinces in which the new hubs will be located, we assumed that the share of green electricity used by China's eastern hubs would rise to 50% before 2040, while this 50% level might be achieved 10 years earlier in the country's western hubs.

The *ADV* scenario encompasses several additional measures to mitigate emissions, such as improving the PUE, adopting a greater portion of green electricity, or both. In line with China's net-zero carbon emissions policy, some researchers have suggested that China's digital infrastructure should transition to using only clean energy and reduce its PUE in the near future (MIIT 2021; Qiu et al. 2021; Guo et al. 2022). Notably, certain data center hubs in China have already committed to achieving 100% green electricity usage by 2030. Based on this information, in this study, we assumed that all national data hubs could increase their proportion of green electricity to 100% by 2040 while also significantly improving their PUE to 1.1, which would align with the "practical minimum value" recommended by Masanet et al. (2020). Our findings revealed that the EWCRT Project, when combined with advanced improvements in the ADV scenario, could reduce carbon emissions by nearly 64% (equivalent to 9500 Mt CO_2) between 2020 and 2050 compared to not implementing the EWCRT Project. Therefore, we concluded that this combination of improvements would be the most effective of the three scenarios discussed here (see Fig. 3).

The leveraging effect of the EWCRT Project in different scenarios. Because China's data centers could improve their PUE and adopt clean energy to reduce their carbon emissions regardless of the implementation of the EWCRT Project, we formulated an additional six sub-scenarios to further investigate potential improvements, including improving the PUE (see Fig. 4B), adopting a greater portion of green electricity (see Fig. 4C), and taking mixed actions (see Fig. 4D). Our results showed that the hyper-scale data center hubs under the EWCRT Project have a clear advantage in producing the green infrastructure needed to
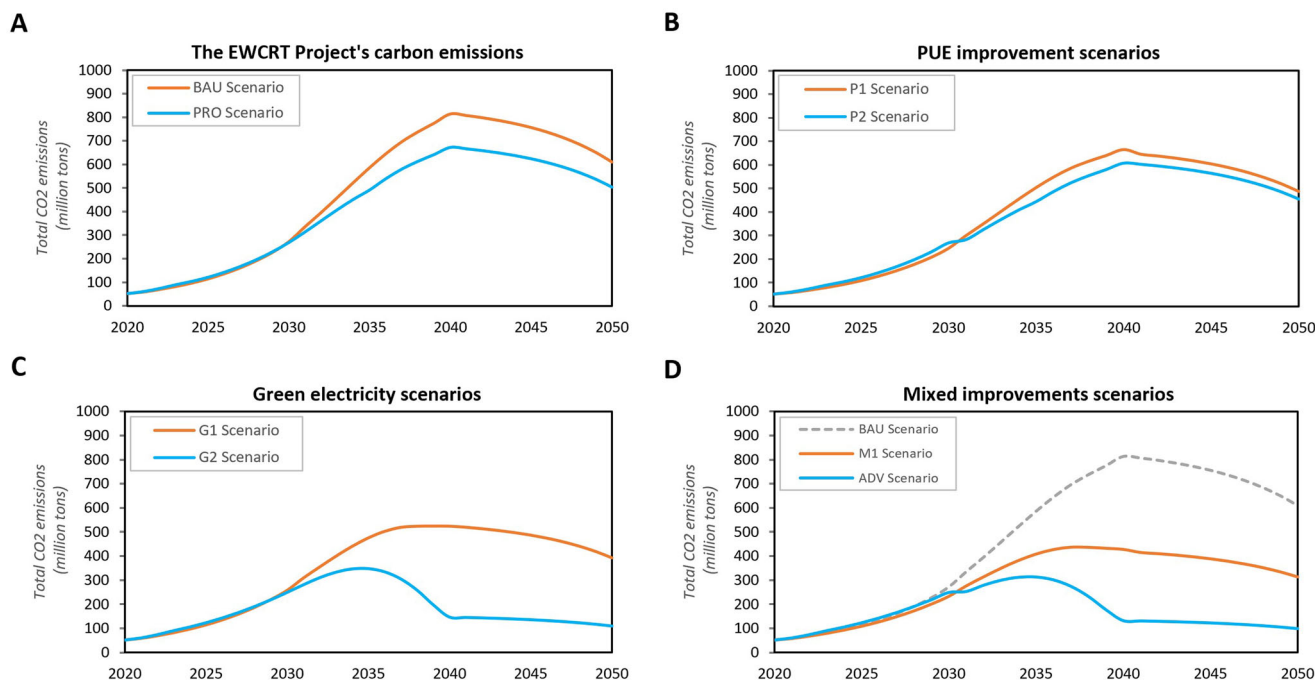
Fig. 4 Total estimated carbon emissions from national-level data center hubs under China's EWCRT Project, 2020–2050. Trends in carbon emissions between 2020 and 2050: **A** in BAU and PRO scenarios; **B** in P1 and P2 scenarios; **C** in G1 and G2 scenarios; **D** in BAU, M1, and ADV scenarios. The sources and calculation methods for computing this data can be found in Data S6 and S7.

keep their carbon emissions low compared to using traditional, smaller data centers (Masanet et al. 2020).

First, we established a new scenario that takes into account the improved PUE under the EWCRT Project. According to the related policy, new and larger data centers in China's temperate regions must achieve a PUE below 1.3, and those in the colder regions of the country must achieve a PUE below 1.25 (MIIT 2021; NEA 2021). To examine the carbon emissions reduction potential of improving the PUE, we assumed that technological progress could yield high PUE improvement: in the BAU with PUE improvement scenario (P1), we found that the data centers could improve their PUE by 1% per year until reaching 1.2; and in the EWCRT Project with PUE improvement scenario (P2), the data center hubs could improve their PUE to 1.1 after 2030. Figure 4B shows that the data center hubs with improved PUE could reduce their carbon emissions by at least 6% (equivalent to nearly 759 Mt CO_2) compared to taking no action (see Data S7).

Second, we established a scenario based on differentiated levels of green electricity usage in China's data centers in the eastern and western regions of the country. Currently, the distribution of clean energy in China is unbalanced, with more than half of the green electricity on the nation's grid conveyed from the west to the east (Guo et al. 2022). It is projected that the proportion of green electricity sent through the future cross-regional, ultra-high-voltage direct current (UHVDC) lines will be over 50% (MOST 2022). Therefore, we assumed that in the BAU with green electricity scenario (G1), the eastern and western data centers' green electricity consumption could increase to 50% and 100%, respectively, by 2040. However, based on China's net-zero carbon emissions policy, the country's digital infrastructure is expected to be fully powered by clean energy in the future (Qiu et al. 2021; Guo et al. 2022); moreover, some data center hubs in China have committed to increasing their use of green electricity to 100% by 2030. Therefore, we assumed that all national data hubs could increase their proportion of green electricity to 100% by 2040 under the EWCRT Project with the green electricity scenario (G2). Figure 4C shows that compared to the G1 scenario, the

G2 scenario could more significantly reduce carbon emissions, in the amount of 5043 Mt between 2020 and 2050, by increasing the proportion of green electricity use (see Data S7).

Third, we assumed that the data center hubs could combine the PUE improvement with greater green electricity use. In terms of reducing overall carbon emissions, Fig. 4D shows that compared to the BAU with mixed improvements scenario (M1), the EWCRT Project with mixed improvements (the ADV scenario) could reduce carbon emissions by 94, 296, 266, and 215 Mt in 2035, 2040, 2045, and 2050, respectively. Furthermore, our results showed that the EWCRT Project with mixed improvements could reduce carbon emissions by nearly 42% over the next three decades compared to not implementing the EWCRT Project (see Data S7). Therefore, we found that the combination of improvements in the ADV scenario would be the most effective approach among all the scenarios discussed in this paper.

Opportunities created by data centers for greening the digital economy. To investigate the factors that could significantly influence the carbon emissions intensity of the regional digital economy, we employed fsQCA to explore various configurations using a sample of 10 national-level data center clusters from the EWCRT Project proposal. Here, we examined five important conditions: regional green investment, number of racks, proportion of regional green energy consumption, government's green attention, and digital activity at the city level. The fsQCA results revealed three configurations associated with relatively low-carbon emissions intensity and three configurations associated with high-carbon emissions intensity. Although there is no necessary condition for these six configurations (i.e., all necessary condition values equal <0.9), our results still identified necessary but not sufficient conditions.

Table 8 highlights the complex conditions for the three low-carbon configurations. Configuration 1 indicates that the green investment and racks should be present, although this configuration does not emphasize the presence of the government's green attention or the digital activity at the city level

Table 8 Configurations analysis.

Condition	Outcome: ~carbon emissions intensity		
	C1	C2	C3
Green investment	●	⊗	●
Racks	●	⊗	⊗
Green energy		⬤	⬤
Green attention	⊗	●	⊗
Digital level	⊗		●
Example cases	Case (W), Case (S)	Case (Q), Case (C)	Case (T)
Consistency	0.974194	0.972826	0.989796
Raw coverage	0.284906	0.337736	0.183019
Unique coverage	0.226415	0.284906	0.109434
Solution coverage	0.703774		
Solution consistency	0.979003		

Core conditions are represented by ⬤ (presence) and ⊗ (absence); contributing conditions are represented by ● (presence) and ⊗ (absence).
C1 indicates Configuration 1, C2 indicates Configuration 2, and C3 indicates Configuration 3; Case (W) denotes the Wuhu Cluster, Case (S) denotes the Shaoguan Cluster, Case (Q) denotes the Qingyang Cluster, Case (C) denotes the Chongqing Cluster, and Case (T) denotes the Tianfu Cluster.

(GI*R*~GA*~DL). This configuration includes two typical cases, namely, the Wuhu Cluster and the Shaoguan Cluster, both located in China's eastern region. These two data center clusters highlight the priority of green investment and racks, rather than relying solely on the government's green attention or the digital activity at the city level. Hence, our investigation of Configuration 1 revealed that even a large number of racks could coexist with China's anticipated low-carbon digital economy. It also supported our simulation results, which indicated that the EWCRT Project could significantly reduce carbon emissions with a large increase in the number of racks. Configuration 2 requires the absence of racks and green investment but the presence of green energy and the government's green attention (~GI*~R*GE*GA). Examples of cases with this configuration include the Qingyang Cluster, which has abundant natural resources for green energy, and the Chongqing Cluster, which has already announced radical clean energy improvements. Configuration 3 requires green investment, green energy, and digital activity at the city level to be present, while the racks and government's green attention should be absent (GI*~R*GE*~GA*DL). An example of this configuration is the Tianfu Cluster, which has abundant resources for hydroelectric power. To reduce the carbon emissions intensity of the digital economy, our findings indicated that green energy is the main antecedent for data center clusters located in regions with abundant renewable energy resources. Therefore, our fsQCA results aligned with our simulation results based on the scenarios approach, which emphasizes the advantage of using mixed research strategies when undertaking studies on green energy for the greening of the digital economy.

Conclusions

Discussion. The modeling of potential futures can be achieved through both qualitative and quantitative scenarios (de-Ruiter and van Loon 2022). In this study, we employed both the scenarios approach and fsQCA to investigate the path of "big data goes green" for China's data centers (Savage 2018). According to the simulation results of the PRO scenario, although the project would produce more carbon dioxide in the first decade compared with the BAU scenario, it would reduce carbon emissions by 2125 Mt over the next three decades. When combined with other measures, such as improved PUE and green electricity adoption, it is clear that implementing the EWCRT Project in China would

significantly reduce carbon emissions from the nation's data centers. Our results showed that compared with not implementing the EWCRT Project, the EWCRT Project with PUE improvement, green electricity, or a combination of the two would reduce carbon emissions by nearly 6%, 47%, or 42%, respectively, over the next 30 years. Therefore, simultaneously increasing China's digital infrastructure and pursuing a green digital economy is possible.

Furthermore, our fsQCA results showed that if green energy is used, having a large number of racks does not necessarily lead to high-carbon emissions intensity. Even in regions where green energy is relatively limited, data center clusters (e.g., the Wuhu Cluster) could achieve low-carbon configurations when more investment is made in green technologies/devices, which also mitigate the carbon emissions resulting from the increased number of racks. For those data center clusters that have access to abundant green electricity (e.g., the Tianfu Cluster), our findings suggest that both local governments' green attention and cities' digital levels play important parts in carbon emission reduction efforts. Hence, our findings support prior research discussing the need for China to enhance the development of its digital infrastructure (Feng et al. 2023; Tang and Yang 2023; Zhang et al. 2022a). Consequently, digital infrastructure—as represented by data center clusters—can empower the green development of China's digital economy (Wang et al. 2021).

Theoretical implications. This study enriches current research on how best to estimate carbon emissions from digital infrastructure. First, compared to recent studies that used digital development or digital policy as a proxy variable for digital infrastructure (Feng et al. 2023; Wang et al. 2022), our work directly estimated the EWCRT Project's carbon emissions over the next three decades by considering various scenarios. Our findings revealing the nonlinear curve of the EWCRT Project's carbon emissions extend prior research that held the complex relationship between digital infrastructure development and its carbon emissions at the national level (Ahmed and Le 2021). Second, this study presented a framework for measuring the reduction of digital infrastructure carbon emissions and exploring detailed configurations over the long term. The assessed reduction of carbon emissions after implementing China's EWCRT Project demonstrates that big data deployment across the country's regions is a viable path for developing the nation's green digital economy. By combining the scenarios approach with fsQCA, our findings contribute to a deeper understanding of both long-term trends in data center carbon emissions and their diverse low-carbon configurations. Third, we highlight the positive effect of carbon emissions reduction on digital infrastructure in the context of an emerging economy. Compared to developed countries, most emerging economies may lack advantages in driving sustainable digitalization transformation (Hou et al. 2024). Hence, implementing the EWCRT Project would offer a valuable model to other emerging economies and regions that face the same challenge of making big data computing centers move in greener directions, thereby assisting these emerging economies and regions in bridging significant digital divides (UNCTAD 2022).

Practical implications. The results of our combined study approach provide policymakers with a nuanced understanding of how different policies in the EWCRT Project may lead to specific outcomes. First, the national-level data center hubs, including the new large data centers currently under construction, should improve their PUE by strengthening their network infrastructure and computing technology. Policymakers should also encourage the data centers to improve their efficiency by providing green data center certification, strengthening efficiency standards, and/or offering subsidies for energy-saving renovation projects (Masanet

et al. 2020). Data centers could achieve lower PUE through more energy-efficient and sustainable technologies including liquid cooling, waste heat recovery, passive cooling systems, and energy storage (Isazadeh et al. 2023; Lei and Masanet 2020). Second, policymakers should encourage data centers and digital industries to use green electricity instead of conventional power. They can provide green subsidies or credits to data centers and related firms, assisting them in switching to green energy (Xie et al. 2022). Considering the unbalanced distribution of green energy in most countries like China, both central and local governments should coordinate the construction of UHVDC lines across regions to avoid challenges like those faced by particular cities where the electricity infrastructure cannot keep up with the rapid growth of the digital infrastructure (Masanet et al. 2020; NEA 2021). Third, a successful global green digital economy network will require multilateral coordination and collaboration worldwide. Heeding the call to pursue climate financing and climate collaboration, as put forward at the 27th Conference of the Parties (COP27) of the UNFCCC in Egypt in 2022, the United Nations needs to create, replicate, and rapidly scale all types of climate-friendly solutions so that these solutions can be implemented in developing countries. Moreover, in 2023, the COP28 agreement signaled the "beginning of the end" of the fossil-fuel era and called for action to turn nations' pledges into real-economy outcomes without delay. Hence, the United Nations should encourage multinational green project collaborations between developed and developing economies based on big data infrastructure strategies, such as transnational fiber-optic networks and data center hubs.

Limitations. This study had several limitations. First, exact data on the racks in each national-level data center hub are unavailable since Chinese authorities have not disclosed detailed data center information at the province level. Future studies could enhance the accuracy of our model by incorporating more precise panel data at the province and city levels. Second, our estimates did not account for other potential environmental benefits from the EWCRT Project, such as the potential economic and environmental advantages of building fiber-optic networks for data transmission compared to having large-scale power transmission infrastructure that produces more carbon dioxide (Zheng et al. 2020). Third, our model was based on the assumption that the EWCRT Project would be completed without major technical issues over the next three decades. However, similar to concerns raised in previous research (Ziegler et al. 2019; Shao et al. 2022), the transition toward carbon neutrality in China's digital economy will likely face a variety of challenges, one of which will be the need for deep decarbonization of electricity production. The EWCRT Project also faces other potential challenges, such as inefficiencies in long-distance data transmission, high initial investment, and lengthy return times, as well as insufficient support systems for digital infrastructure, digital technology, and clean industries.

Data availability
This research analyzed existing, publicly available data. The data generated by our analysis can be found in the supplementary spreadsheets (Data S1–S8). Supplemental information will be found online at the official website of *HSSC*. The code used for the analysis and for the carbon emissions data generated by our analysis is available from the lead contact upon request. Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

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Acknowledgements

Author contributions

XX: conceptualization, writing—review & editing, project administration, funding acquisition, and supervision. YH: conceptualization, methodology, and writing—original draft. HT: conceptualization, writing—review & editing, project administration.

Competing interests

The authors declare no competing interests.

Ethical approval

Ethical approval was not required as the study does not involve human participants.

Informed consent

This article does not contain any studies with human participants performed by any of the authors.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1057/s41599-024-02963-0.

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