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CO_2 emission-mitigation pathways for China's data centers

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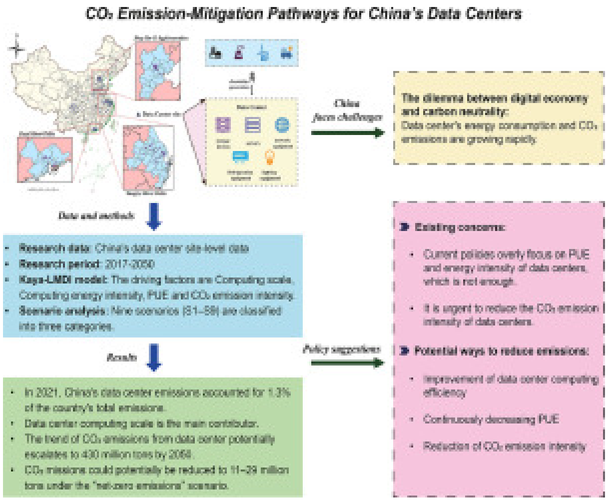
Highlights

- Combined macro-level CO_2 models with empirical data for a holistic carbon emissions view in China's data centers.
- Identified expansive computing scale as a primary driver for CO_2 emission surge across Chinese provinces (2017–2021).
- Projected tripling of data center CO_2 emissions by 2050, reaching 430 million tons if trends persist.
- Demonstrated 'net-zero emissions' strategy's potential to restrict 2050 CO_2 emissions between 11 and 29 million tons.

Abstract

Increased emissions related to China's burgeoning digital economy pose significant challenges. Using a Kaya–LMDI model, this study investigates the driving factors of data-center CO_2 emissions in China from 2017 to 2021, highlighting the roles of computing scale, energy intensity, power usage effectiveness, and emission intensity. We find a marked increase in emissions across various Chinese provinces, largely driven by computing scale. While projections suggest that data-center emissions could reach 430 million tons by 2050 (three times greater than 2021 levels), such emissions could potentially be reduced to 11–29 million tons under the “net-zero emissions” scenario. Highlighting the need to mitigate data-center emission intensity, our findings underscore the recalibrations in operational methods, technology, and energy sourcing needed to expedite the transition to net-zero emissions.

Graphical abstract



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Introduction

In an era characterized by rapid digitalization, data centers have significantly expanded, providing fundamental infrastructure for emerging technologies such as artificial intelligence and blockchain. The number of data center cabinets in China has experienced a substantial growth, from 1.08 million cabinets in 2015 to 3.6 million cabinets in 2021 (Brodie,2022). The proliferation of data center cabinets has resulted in a significant rise in power usage. Worldwide, the power demand of data centers has been estimated to be 205TWh, accounting for almost 1% of total global power consumption (Masanetetal., 2020). In certain nations, it is projected that the proportion of electricity consumption attributed to energy utilization may potentially increase to a range of 15–30% by the year 2030, despite the fact that it has remained relatively steady in recent years due to advancements in efficiency (Kvarnströmand Kamiya,2019). China's data center industry is among the world's largest and the electricity consumption by data centers has reached a staggering 168 billion kilowatt-hours, accounting for 2% of the nation's overall electricity consumption (Greenpeace,2019). The primary contributors to electricity power demand are IT equipment (Ahmedetal., 2021), cooling systems (Zhangetal., 2022), and power supply and distribution systems (Geetal., 2013). The growing energy consumption of data centers is accompanied by a corresponding rise in carbon emissions, so presenting a significant environmental concern. Global data centers contribute approximately 0.3% to the total carbon emissions (McLean,2020). In China, data centers generated a total of 99 million metric tons of CO_2 emissions in the year 2018

(Zaugg,2019). The escalating carbon emissions and energy consumption associated with data centers have emerged as a significant challenge in the context of climate change.

To help to achieve the goal of “carbon emission peak and carbon neutrality”, several Chinese organizations, including the National Development and Reform Commission, National Energy Administration, Office of the Central Cyberspace Affairs Commission, and Ministry of Industry and Information Technology (MIIT), collaborated to release an implementation plan. This plan aims to facilitate the advancement of environmentally friendly and high-standard development of new infrastructure, such as data centers and 5 G technology. In July 2021, the MIIT reiterated the importance of constructing environmentally friendly data centers in the "New Data Centre Development Three-year Action Plan (2021–2023)." The fundamental aim of data centers in China is to reduce primary energy consumption and improve energy efficiency. Moreover, Chinese government released “Implementing the Carbon Summit Carbon Neutral Target and Promote Green and High-Quality Development of Data Centers and 5G and Other New Infrastructure Implementation Plan” in October 2021. This plan mandates the adoption of innovative energy-saving technologies, optimization of energy-saving practices, and utilization of renewable energy sources. Its objective is to facilitate the environmentally friendly and low-carbon development of data centers, encouraging their active participation in carbon reduction efforts. Data infrastructure is becoming increasingly energy efficient, leading to a reduction in CO_2 emission (Jenneand Klein,2016; ChinaAcademy of Information and Communications Technology,2022; Guoetal., 2022). Over the past decade, data centers have witnessed notable advancements in the domains of sustainability and efficiency. Although data traffic grew 100% from 2015 to 2018, associated electricity consumption rose just 16%, and its share of total global consumption has remained unchanged (TheWorld Bank,2021). Huge gains in energy efficiency have made this possible. One reason is a shift from smaller data centers to more efficient larger ones, particularly observed among major industry participants in China, Japan, and the United States (Jones,2018; Shehabietal., 2018; Mytton,2020). The savings made by hyperscale centers are evident in their power usage efficiency (PUE), defined as the total energy needed for everything, including lights and cooling, divided by the energy used for computing (a PUE of 1.0 would be a perfect score) (Leiand Masanet,2020). Conventional data centers often exhibit a PUE of about 2.0, however hyperscale facilities have achieved a reduced PUE of around 1.2. One example of a company with a notable PUE is Google, which maintains an average PUE of 1.12 across all of its data centers. Based on China's strategic plan, it is projected that by 2025, the average PUE of newly constructed large and hyperscale data centers will decrease to below 1.3, in contrast to the current level of 1.6–1.7. Furthermore, alongside the decline in PUE, the modernization of telecommunication networks is also playing a significant role in the decrease of emissions. According to the International Energy Agency (IEA,2021), fiber-optic cable is 85% more energy efficient than vintage copper wires, while each successive generation of wireless technology conserves more energy than the previous one. However, those easy wins could end within a decade. The potential for further reduction in computing resource costs is contingent upon the ongoing impact of Moore's Law, which is presently confronted with various hurdles (Andrae,2020).

Despite rising electricity consumption, it is noteworthy that greenhouse gas (GHG) emissions originating from data infrastructure have remained constant since 2015, accounting for a mere 0.2% of the overall global emissions (TheWorld Bank,2021). This is due to the increasing proportion of renewable energy sources in the electricity composition utilized by data centers. For example, Equinix, one of the world's leading data center operators, increased its share of renewable energy from under one-third in 2014 to 92% in 2018, leading to a two-thirds reduction in GHG emissions (Equinix,2019). Moreover, the tech giants—Apple(2019), Google(2019), and Microsoft (Lucas,2021)—have switched to 100% renewable energy, while completely offsetting their GHG emissions. While China's digital infrastructure industry has made significant progress in terms of energy efficiency (Lietal., 2023), much less progress has been made on renewable energy use, which presents a potential avenue for the development of environmentally sustainable data centers in the future.

In summary, the carbon emissions stemming from data centers in China are experiencing a rapid increase, prompting the Chinese government to enact legislation aimed at the establishment and advancement of environmentally sustainable data centers. In order to effectively implement an efficient policy, it is imperative for policymakers to identify the primary factors that contribute to emissions from data centers. However, it is currently observed that there is a dearth of research in this area. While the aforementioned studies have examined particular energy management solutions for data centers, such as the optimization of IT equipment (Zhangetal., 2022), cooling technologies (Fleischer,2020), and content delivery networks (Geetal., 2013). However, they have failed to sufficiently address the increasing demand for digital services and the intricate relationship between market dynamics and policy interventions. This lack of investigation hinders the identification of the primary factors that impact emissions and presents challenges for policymakers.

Here, in this study, we first calculate the emissions of data centers from 2017 to 2021 using information gathered predominantly on-site, and project the growth of energy consumption and carbon emissions through 2050. Then, we conduct a comprehensive examination of the drivers that contribute to the generation of carbon dioxide emissions in data centers by employing a Kaya-based logarithmic mean Divisia index (LMDI) model. The LMDI model is a commonly employed method for conducting index decomposition analysis in the field of energy demand and supply (Angetal., 1998), air pollution emissions (Gengetal., 2021) and CO_2 emissions (Guanetal., 2018). This method is regarded as the most preferred index decomposition analysis method due to its theoretical foundation, adaptability and ease of use and result interpretation (Ang,2015). Our objective is to more comprehensively evaluate energy use and carbon emissions in data centers, encompassing both the current landscape and projections of future trends across various scenarios. Our proposed methodology has the potential to provide policymakers with a valuable decision-making instrument to improve sustainability within the data center business.

Section snippets

CO_2 emissions and related index calculations for data centers

To comprehensively estimate the overall energy use and CO_2 emissions from China's data centers, we consider various energy consumption metrics and infrastructural aspects of data center construction. Our initial calculations are based on the total rack count across all provinces, with data sourced from white papers by Greenpeace and other institutions (Greenpeace,2019, 2021; OpenData Center Committee,2022). However, given the significant regional variations in parameters such as computing …

CO_2 emissions of China's data centers

As shown in Fig.3, from 2017 to 2021, CO_2 emissions increased across China's provinces, underscoring the increasingly profound effects of data centers. This culminated in 135 million metric tons of CO_2 emissions in 2021, underscoring the environmental implications of the data center industry. The increase is largely linked to an exponential surge in data center demand, induced by the rapid expansion of China's digital economy. The Jing-Jin-Ji Agglomeration, Yangtze River Delta, and Pearl River …

Conclusions

We collected data from 590 data centers across China and linked them with macro-level indicators of Chinese data centers. First, we construct a Kaya-based data-center CO_2 emission estimation model, and then we decompose the driving factors of data-center CO_2 emissions using an extended LMDI decomposition model.

The results show that total emissions from Chinese data centers reached 135 million tons in 2021, accounting for 1.3% of the national total for that year. Since 2017, due to the strong …

CRediT authorship contribution statement

Wenli Ni: Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing. **Xiurong Hu:** Supervision, Visualization, Writing – original draft, Writing – review & editing. **Hongyang Du:** Data curation, Methodology. **Yulin Kang:** Writing – review & editing. **Yi Ju:** Writing – original draft, Writing – review & editing. **Qunwei Wang:** Writing – review & editing, Resources, Supervision, Writing – original draft. …

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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…Relying exclusively on decomposition analysis for crafting carbon reduction strategies may lack adaptability and foresight, overlooking the intricacies of the regional context. The dynamic shifts occurring in present and anticipated scenarios, which may vary significantly from historical patterns, could lead to inaccuracies in projecting the success of future carbon mitigation efforts (Luo et al., 2023; Ni et al., 2024; Wang et al., 2023). For instance, a province historically characterized by heavy industry and reliant on coal for energy.…

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