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OPERATIONAL CO_2 MITIGATION EVALUATION IN COMMERCIAL BUILDINGS OF THE TOP EMITTERS

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ABSTRACT

Building sector plays an important role in carbon neutral transition, and commercial buildings become key starting point in the building decarbonization. Taking China and the United States (US) as cases, this study is the first to assess carbon-dioxide (CO_2) mitigation in commercial building operations at different emission scales and investigate the carbon mitigation efficiency of the two countries in the past decades. The results show that: (1) Economic efficiency and energy intensity are key to reduce CO_2 emission intensity in commercial buildings in China and the US, respectively; (2) CO_2 mitigation efficiency in China was around 1.5 times that in the US, though CO_2 mitigation in China and the US was close; (3) the paths for energy efficiency improvement in commercial buildings in China and the US were mapped to explore the strategy that best decarbonizes buildings operation in the future. Overall, the evaluation model of CO_2 mitigation proposed in this study is able to be a guidance for other economies or regions to measure the effect of historical carbon mitigation in building operation.

Keywords: Commercial building, CO_2 mitigation, Mitigation efficiency, Index decomposition analysis.

NONMENCLATURE

Abbreviations	
CBEED	China Building Energy and Emission Database
CNY	Chinese Yuan
GDP	Gross domestic product
LMDI	Log-Mean Divisia Index
Mtce	Mega-tons of carbon
$MtCO_2$	Mega-tons of standard coal equivalent
USD	US dollar
Symbols	
C	CO_2 emission in commercial buildings
c	CO_2 emission intensity
E	Energy consumption in commercial buildings
e	Energy intensity
F	Floor space of commercial buildings
G	Gross domestic product (GDP)
G_S	Service industry value added
g	GDP per capita
i	Economic efficiency
K	Emission factor
P	Population
p	Population density
s	Industrial structure

1. INTRODUCTION

As the two largest carbon emitters in the world, carbon dioxide (CO_2) emissions in China and the United States (US) accounted for 43.3% of the global carbon emissions in 2019 [1]. In the US-China Joint Statement Addressing the Climate Crisis, China and the US emphasized taking enhanced climate actions on energy conservation and emission reduction in the building sector. Evidence shows that CO_2 emissions from the building sector accounted for 28% of global CO_2 emissions [2]. To promote CO_2 mitigation in the building sector, commercial buildings with higher CO_2 mitigation potential than residential buildings should be noted first

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[3]. Therefore, the research on CO_2 mitigation in commercial buildings in China and the US is of great significance to realize global carbon neutrality.

Studies on historical CO_2 emissions in the US are focused on building sectors [4], while those on historical CO_2 emissions in China go further to discuss emission level in the commercial building sector. **Thus there are still some gaps:** studies on carbon emissions in the US commercial buildings are insufficient [5]; the existing studies ignore the assessment of the CO_2 mitigation efficiency in China and the US ; there is a lack of comparison between the CO_2 mitigation in commercial building sectors in China and the US. **Therefore, this study focused on solving the following three problems.**

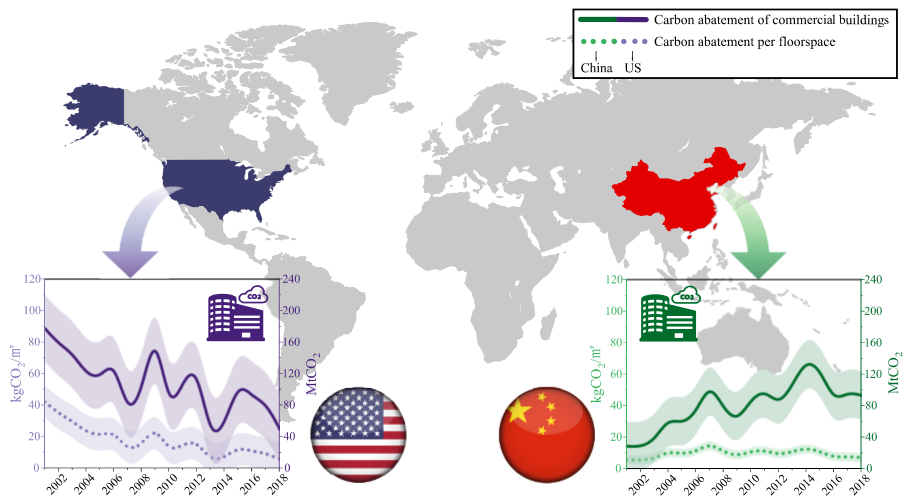

Fig 1 Graphical abstract. Historical carbon mitigation and carbon mitigation per floor space of commercial buildings in China and the US.

- What drivers the CO_2 mitigation and how to assess it in the commercial building operation?
- What is the efficiency gap of the emission mitigation between the two economies?
- How to decarbonize the building energy to hit the carbon neutral goal in the future?

To solve the above-mentioned problems, this study used Log-Mean Divisia Index (LMDI) to decompose the extended Kaya identity to perform a CO_2 mitigation assessment of commercial buildings. After exploring the emission factors, this study further analyzed their historical CO_2 mitigation features from 2000 to 2018. In addition, this study compared the efficiency of historical CO_2 mitigation of commercial buildings in China and the US, reviewed the historical CO_2 mitigation policies and energy efficiency improvement paths of China and the US, and proposed measures for achieving carbon neutrality.

Taking the top two emitters as an example, **the most important contribution of this study** is providing a useful and reliable model for assessing CO_2 mitigation in commercial buildings across different countries and regions. The popularity of slogans such as "carbon peak" and "carbon neutrality" highlights the need for a tool that can compare the CO_2 mitigation features of various countries. Such a comparison will help countries learn from each other's experience and jointly seek paths to energy decarbonization. Besides, this study is also the first to investigate the CO_2 mitigation features of commercial buildings in China and the US. Most previous studies focused on the two countries themselves or studied the relationship between the emissions and the economy, ignoring the two major emitters' building sector (especially the commercial buildings).

The rest of the study is divided into the following parts: Section 2 presents the materials and methods, including the assessment model, variables' definition and data collection. Section 3 shows the decomposing carbon intensity, historical CO_2 mitigation, mitigation efficiency and energy efficiency improvement paths of commercial buildings in China and the US. Section 4 presents core findings and further studies.

2. MATERIALS AND METHODS

2.1 Assessment model of CO_2 mitigation in commercial buildings

The assessment model of CO_2 mitigation in commercial buildings combines the extended Kaya identity, which is a widely used method in the field of studying CO_2 emission and CO_2 intensity factors [22, 23], with LMDI that is a kind of decomposition analysis method. The classical Kaya identity categorizes the factors of CO_2 emissions into three sorts, including

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population, affluence, and technology. As shown in Eq.(1), the three parts of factors in commercial building are presented in the form of these indicators: population (P), GDP per capita ($\frac{GDP}{P}$), and technical elements involving energy intensity ($\frac{E}{GDP}$) and emission factor ($\frac{CO_2}{E}$) [6].

$$CO_2 = P \cdot \frac{GDP}{P} \cdot \frac{E}{GDP} \cdot \frac{CO_2}{E} \qquad (1)$$

Kaya identity, usually as the first step of decomposition analysis, has the advantages of simple mathematical form, no residuals in decomposition, and strong explanatory power for the driving factors of CO_2 emission changes. In order to maintain the original advantages, and make the decomposition process more reasonable, it is wisely to extend the Kaya identity. After expanding, six factors of mitigating CO_2 intensity in commercial buildings can be specifically indicated, which are shown in Fig. 2.

The extended Kaya identity on CO_2 emission in commercial buildings is expressed as follows:

$$C = P \cdot \frac{G}{P} \cdot \frac{G_S}{G} \cdot \frac{F}{G_S} \cdot \frac{E}{F} \cdot K \qquad (2)$$

To facilitate research, CO_2 intensity is often used to replace totalCO_2 emission:

$$c = \frac{C}{F} = \frac{P}{F} \cdot \frac{G}{P} \cdot \frac{G_S}{G} \cdot \frac{F}{G_S} \cdot \frac{E}{F} \cdot K \qquad (3)$$

Let $c = \frac{C}{F}$, $p = \frac{P}{F}$, $g = \frac{G}{P}$, $\mathrm{s} = \frac{G_S}{G}$, $\mathrm{i} = \frac{F}{G_S}$, $\mathrm{e} = \frac{E}{F}$, then Eq.(3) converted to Eq.(4).

$$c = p \cdot g \cdot s \cdot i \cdot e \cdot K \qquad (4)$$

LMDI, as a branch of the index decomposition analysis, is especially suitable for those studies with few variables and involving time-series models. Therefore, the extended Kaya identity will be further decomposed through LMDI [7], to explore the contribution level of each influential factor on mitigatingCO_2 intensity and retrospective CO_2 mitigation from 2000 to 2018 (ΔT) in commercial buildings in China and US. The decomposition equation is showed as Eq.(5).

$$\Delta c|_{0\to T} = c|_T - c|_0 = \Delta c_p + \Delta c_g + \Delta c_s + \Delta c_i + \Delta c_e + \Delta c_K \qquad (5)$$

In Eq.(5), the right side parameters can be further expressed. Taking Δc_g as an example, the specific expression are showed as follows:

$$\Delta c_g = L(c|_T, c|_0) \cdot ln\left(\frac{g|_T}{g|_0}\right) = L(c|_T, c|_0) ln\left(\frac{G|_T \times P|_0}{G|_0 \times P|_T}\right) \qquad (6)$$

$$L(c|_T, c|_0) = \begin{cases} \frac{c|_T - c|_0}{\ln(c|_T) - \ln(c|_0)}, & c|_T \neq c|_0 \ (c|_T > 0, c|_0 > 0) \\ 0 \quad , & c|_T = c|_0 \ (c|_T > 0, c|_0 > 0) \end{cases} \qquad (7)$$

Therefore, CO_2 mitigation and the intensity can be expressed by the parameters which have negative influences on CO_2 emission.

$$\mathrm{CO_2\ mitigation\ intensity}|_{0\to T} = \sum|\Delta c_m|_{0\to T}| \qquad (8)$$

$$\mathrm{CO_2\ mitigation}|_{0\to T} = \mathrm{F}|_{0\to T} \times (\sum|\Delta c_m|_{0\to T}|) \qquad (9)$$

Where$\Delta c_m|_{0\to T} \in \{\Delta c_p, \Delta c_g, \Delta c_s, \Delta c_i, \Delta c_e \Delta c_K\}|_{0\to T}$, $\Delta c_m|_{0\to T} < 0$

2.2 Material and methods

The definitions of variables are shown in Table 1. The data that this study demands is divided into two categories: one part is from China and another part is from the US. Regarding the Chinese part, the data of commercial buildings is gathered from CBEED [1], including E, C, F and K. And the data on P, G and G_S are collected from National Bureau of Statistics of PR China. Regarding the part of the US, the data is from the Energy Information Administration.

3. RESULTS&DISCUSSION

3.1 Outputs of decomposing carbon intensity in commercial buildings

Fig. 3 shows the LMDI decomposition results for the changes in CO_2 emission intensity in commercial buildings in China and the US between 2000 and 2018 calculated by Eq. (5) to (7). The most significant positive factor in China is per capita of GDP and industrial structure (for example, $\Delta c_g + \Delta c_s|_{2000\to 2004} = 57.65\%$, $\Delta c_g + \Delta c_s|_{2004\to 2008} = 73.45\%$, $\Delta c_g + \Delta c_s|_{2008\to 2012} = 58.94\%$, and $\Delta c_g + \Delta c_s|_{2012\to 2018} = 54.72\%$), which plays the same role in the US (e.g.,$\Delta c_g + \Delta c_s|_{2000\to 2004} = 13.42\%$, $\Delta c_g + \Delta c_s|_{2004\to 2008} = 14.12\%$, $\Delta c_g + \Delta c_s|_{2008\to 2012} = 7.11\%$, and $\Delta c_g + \Delta c_s|_{2012\to 2018} = 18.84\%$), illustrated by the red and orange blocks in Fig. 2 a and b.

[1] https://www.researchgate.net/project/China-Building-Energy-and-Emission-Database-CBEED

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On the other hand, economic efficiency devotes the most in promoting CO_2 mitigation intensity in Chinese commercial buildings (e.g., $\Delta c_i|_{2000\rightarrow2004} = -35.4\%$, $\Delta c_i|_{2004\rightarrow2008} = -53.85\%$, $\Delta c_i|_{2008\rightarrow2012} = -35.18\%$, and $\Delta c_i|_{2012\rightarrow2018} = -25.04\%$), as revealed by the light-blue blocks in Fig.2 a. However in the US, energy intensity makes the greatest contribution to the growth of CO_2 mitigation intensity (e.g., $\Delta c_e|_{2000\rightarrow2004} = -23.92\%$, $\Delta c_e|_{2004\rightarrow2008} = -15.52\%$, $\Delta c_e|_{2008\rightarrow2012} = -18.36\%$, and $\Delta c_e|_{2012\rightarrow2018} = -10.37\%$), as revealed by the blue blocks in Fig. 2 b.

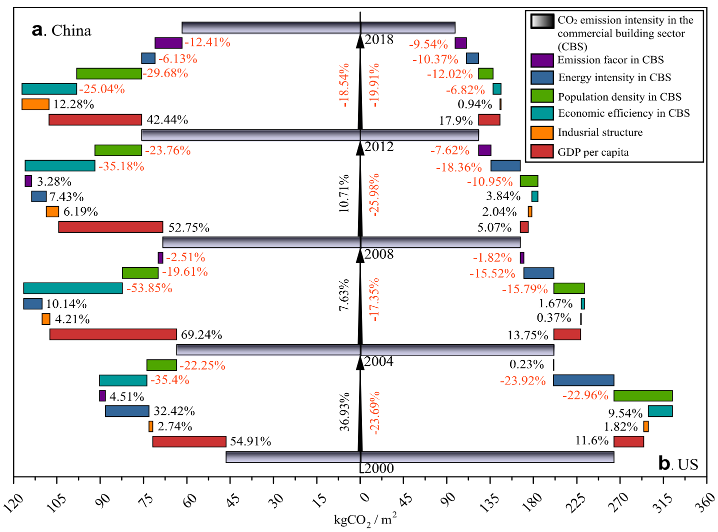

Fig 2 Intensity changes of carbon emissions in the commercial building operation in China and the US via a decomposition analysis (2000–2018).

After decomposing the contribution levels of the factors for CO_2 emission intensity changes of, this study explored the CO_2 mitigation effects of commercial buildings in China and the US from 2001 to 2018 using three scales (total CO_2 mitigation, CO_2 mitigation per capita, and per floor space), calculated by Eq.(8) to (9). Fig. 3 a presents the total CO_2 mitigation in commercial buildings from 2001–2018 in China (see the short dotted curve) and the US (see the solid curve):1451.89 ($\pm$549.05) and 1929.84 ($\pm$757.36) $MtCO_2$. The curves in Fig. 3 b and c illustrate the intensity values of CO_2 mitigation from commercial buildings of China and the US using two scales [i.e., average CO_2 mitigation per capita: 59.88 ($\pm$21.81) and 353.72 ($\pm$148.32) $kgCO_2$ per person; average CO_2 mitigation per floor space: 9.83 ($\pm$2.77) and 17.67 ($\pm$10.24) $kgCO_2/m^2$] during 2001–2018 in China and the US. Compared with Fig. 3 a and 3c, Fig. 3 b reveals that the difference of CO_2 mitigation per capita in the two countries is more significant than that in another two emission scales. The corresponding fit estimations of CO_2 mitigation intensity in commercial buildings at two scales are expressed on the right side of Fig. 3 b and 3c (China's results are represented by straight short, dotted lines and the US' by straight solid lines)

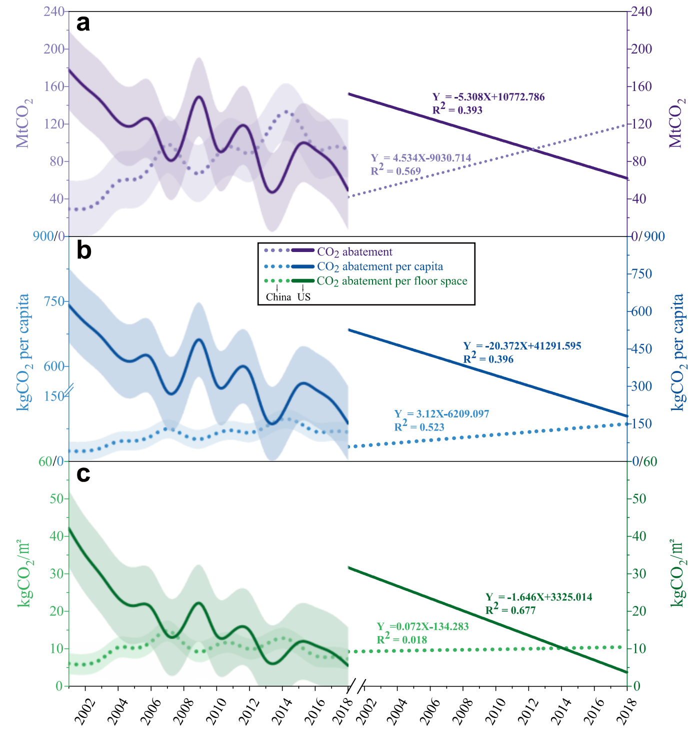

Fig 3 **a.** Total CO_2 mitigation; **b and c.** CO_2 mitigation intensity in commercial buildings in China and the US at two scales during 2001–2018 (CO_2 mitigation per capita and per floor space).

3.2 *Comparative analysis on CO_2 mitigation efficiency*

Section 3.2 proposes a comparative analysis of CO_2 mitigation efficiency of commercial buildings in China and the US in answer to the second research question.CO_2 mitigation efficiency is the ratio of CO_2 mitigation values to CO_2 emission values [8]. As shown in Fig. 4, from 2000 to 2018, the CO_2 mitigation efficiency of Chinese commercial buildings are lower than that of the US in 2000-2004 and has been higher than that of the US in the following 12 years. The CO_2 mitigation efficiencies on the total scale of China's commercial buildings in each period are: 2000-2004 (13.13%); 2004-2008: (17.99%); 2008-2012 (13.99%); 2012-2018 (14.75%). The corresponding CO_2 mitigation efficiencies in the US in each period are: 2000-2004 (14.51%); 2004-2008 (9.72%); 2008-2012 (12.45%); 2012-2018 (7.66%). At the same time, the performance of CO_2 mitigation

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efficiencies on the intensity scales (per floor space scale and per capita scale) is a little different from the results reflected by the total mitigation. This is due to changes in the number of people and the building floor space during the calculation periods in China and the US are relatively small. Therefore, the following specific analysis will be explained with the CO_2 mitigation efficiencies on the total scale.

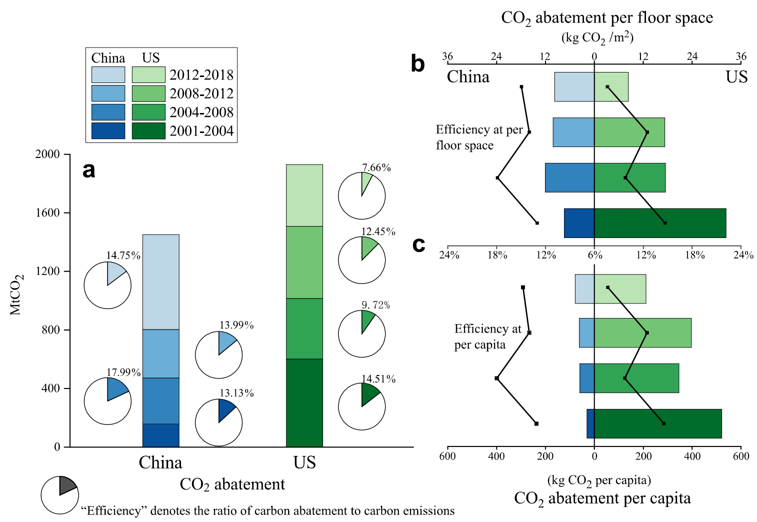

Fig 4 CO_2 mitigation efficiency of commercial buildings in China and the US at three emission scales.

Though China has a close absolute CO_2 mitigation volume to the US, the CO_2 mitigation efficiencies of China's commercial buildings are much higher than those of the US and even doubled those of the US in 2004-2008 and 2012-2018. Moreover, the CO_2 mitigation efficiency of commercial buildings in China is generally rising, while the CO_2 mitigation efficiency of commercial buildings in the US is generally declining. That is because old buildings with low energy efficiencies in the building stock in the US occupy a higher proportion, which leaves the CO_2 mitigation trapped in a carbon lock-in. However, Chinese commercial buildings are still trying to hit the carbon emission peak, and there is still some potential to mitigate CO_2 emission. Thus, CO_2 mitigation efficiency in China remains at a relatively high level.

3.3 Retrospection of energy efficiency improvement

CO_2 mitigation efficiency is highly related to the improvement of energy efficiency strategy. Taking China for example, CO_2 mitigation efficiency in China grew rapidly between 2004 to 2008 since the *Design Standard for Energy Efficiency of Commercial Buildings* was issued in 2005. During early 2000s, the Chinese government successively put forward a large number of policies and measures to reduce CO_2 emissions, including *Assessment Standard for Green Building* (GB/T 50378-2006) and *China Act on Energy Efficiency of Civil Buildings* (2008). In the GB/T 50378-2014 edition, there is a provision for CO_2 emission in the building sectors, showing that CO_2 emission in buildings is officially launched and included in the national standards. From 2018 to 2019, building low-energy buildings, near-zero energy buildings, and zero-energy buildings were gradually proposed.

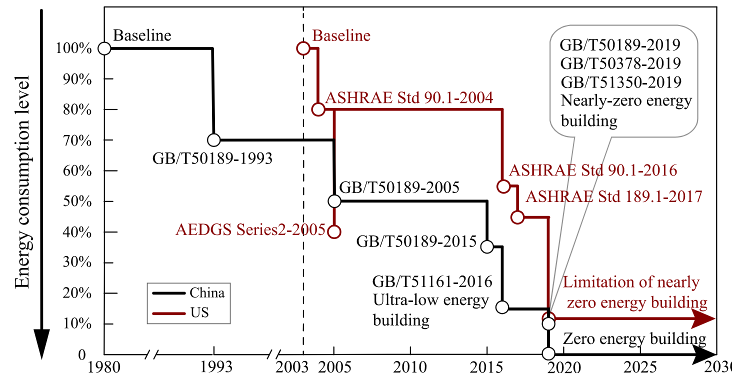

Fig 5 Roadmap of energy efficiency improvement on commercial building in China and the US (1980–2020).

Regarding energy decarbonization in the US, Department of Energy and American Society of Heating, Refrigerating and Air-Conditioning Engineers have formulated some energy efficiency improvement paths similar to China's. However, the standards vary from state to state in the US, determined by the state system. For example, California is a representative leading-edge state on CO_2 mitigation, which has implemented the *Building Energy Efficiency Standards-Title 24*. *Title 24* aims to conserve non-renewable resources and promote renewable resources, including reducing wasteful and unnecessary energy consumption in newly constructed and existing buildings. Thus, the number of off-site power plants were reduced. Moreover, *Title 24* is updated once every three years to ensure mitigation efficiency. The roadmap of the energy efficiency improvement on commercial buildings in China and the US is shown in Fig. 9.

Regarding energy supply, there is a need to advocate the use of renewable energy, to transform the energy industry from concentration to decentralization, and establish an appropriate energy transaction price. Regarding buildings' energy consumption, there is a need to provide suitable building heating schemes based on spatial techno-economic and environmental analysis, to conduct high-performance building envelopes, photovoltaic cell, lighting controls, heating, ventilation,

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air-conditioning controls; to study energy sensitivity and uncertainty; and to increase the coverage of nearly zero energy buildings. Furthermore, it's also useful for government to conduct fiscal decentralization and to formulate relevant energy poverty alleviation policies.

4. CONCLUSIONS

CO_2 mitigation efficiency in China is 1.1-1.9 times that in the US, although CO_2 mitigation from the commercial buildings in China and the US in 2001-2018 is close [China: 1451.89 (± 549.05) $MtCO_2$, US: 1929.84 (± 757.36) $MtCO_2$]. In other words, the total CO_2 mitigation from 2001 to 2018 in China is equivalent to 1.83 times the CO_2 emissions of China's commercial buildings in 2018. However, in the US, it's 2.18 times. Compared with the total emission mitigation, the CO_2 mitigation efficiencies of the two countries are quite different. Although CO_2 mitigation of commercial buildings in China is close to the US, the CO_2 mitigation efficiency of China's commercial buildings is much higher than that in the US. Specifically, the CO_2 mitigation efficiency of commercial buildings in China is maintained at 1.1-1.9 times that of the US.

Historical energy efficiency improvement paths have achieved remarkable results, and the policy guidance from various countries is the biggest driver of achieving global carbon neutrality. According to historical energy efficiency improvement paths in China and the US, policy guidance has led to a significant increase in the CO_2 mitigation of commercial buildings from 2000 to 2018. Therefore, on the road to achieving energy saving and emission reduction, China and the US should strengthen policy guidance, including building CO_2 emission supervision system in the construction industry chain, promulgating the promotion acts and clauses which integrate green finance and the full life cycle of buildings, establishing a fair and efficient subsidy policy, and upgrading the standard requirements for energy-saving buildings, etc. Furthermore, China and the US should cooperate with each other and share experience and technologies of emission reduction in the building sectors.

There are gaps in this study that should be filled through further research. First, the evaluation tool for the CO_2 mitigation potential of future building operations should be developed. Furthermore, the case area can be extended. Although this study assessed the historical CO_2 mitigation of commercial buildings in China and the US, the CO_2 mitigation effect in other countries is also worth investigation using the proposed method. The assessment can highlight cost-effective CO_2 mitigation potential in the global building sector. This effort will help buildings worldwide to achieve low carbon transition in the age of carbon neutrality.

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