Applied Energy Symposium 2020: Low carbon cities and urban energy systems
October 10-17, 2020
Paper ID: CUE2020-D-110

Towards low carbon pathway of the commercial building sector for 2070: Lessons from China

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ABSTRACT

This study is the first to assess the historical carbon mitigation and simulate the energy and emission peaks of China’s commercial building sector using a dynamic emission scenario. It shows that the emission mitigation of the commercial building sector during 2000–2016 is 1221.50 (± 486.89) million tons of carbon dioxide ($MtCO_2$), and the scenario simulation demonstrates that the commercial building sector will achieve its carbon emission peak in year 2039 (± 8) with a peak value of 1154.88 (± 191.05) $MtCO_2$. The sensitivity analysis reveals that the impacts of emission factor and GDP per capita are the most significant for the uncertainty of emission peaks. A strict energy demand benchmark of the commercial building sector suggests a control at 465.99 million tons of standard coal equivalent (Mtce), and its peaking year is estimated for 2035, which is 13 years ahead of the business-as-usual scenario, with energy savings of 112.90 Mtce. For the earliest peaking time, if the commercial building sector aims to achieve its emission peak before 2030, the emission peak should be controlled at 958.03 $MtCO_2$. Overall, this paper can assist the government in more accurate and feasible building emission mitigation strategies. Moreover, the results provide a more powerful decision-making reference in issuing targeted and feasible strategies for future commercial building emission mitigation.

Keywords: Commercial building; Emission mitigation; Energy and emission peaks; Decomposition analysis; Dynamic scenario analysis.

NONMENCLATURE

Abbreviations	
BAU	Business as usual
LMDI	Log-Mean Divisia Index
Mtce	Million tons of standard coal equivalent
$MtCO_2$	Million tons of carbon dioxide

Symbols	
C	Carbon emissions released by commercial buildings
CM	Carbon mitigation of commercial buildings
E	Energy demand of commercial buildings
e	Energy intensity of commercial buildings
F	Commercial building stocks
G	Gross Domestic Product (GDP)
g	GDP per capita
G_s	Output value of the service industry
I	Industrial efficiency of the service industry
K	Energy-related carbon intensity of commercial buildings (i.e., the emission factor)
P	Population size
S	Industrial structure
Greek letters	
ω	Random value
σ	Standard deviation

1. INTRODUCTION

25th Conference of the Parties announced that the global building sector and construction industry account for nearly 40% of the total carbon emissions and 36% of the end-use energy [1]. Growing population size as well as rapid development of service industry in emerging economies and developing countries lead to an energy demand in buildings that could increase by 60% in 2070 [2]. Besides, building stock is expected to double by 2050, contributing to the continuous increase of global construction emissions [3]. As the largest developing economy, China is facing a fast-growing energy demand pressured by the service industry, which requires massive fossil energy use and further increases the emissions of carbon dioxide (CO_2) [4]. Carbon emissions driven by the commercial buildings have increased significantly at a 6.83% yearly rate over the past decade, and the total emissions in 2017 were 767.86 million tons of CO_2 ($MtCO_2$) [5].

Selection and peer-review under responsibility of the scientific committee of CUE2020

On the other hand, the building sector provides the largest cost-effective emission mitigation potential [6], with possible net cost savings and economic gains via existing technologies and policies [7]. Lawrence Berkeley National Laboratory [8] developed a bottom-up scenario analysis via long-range energy alternatives planning model to illustrate the prospective emission roadmaps of China's building sector for 2050. The most positive emission mitigation scenario showed that the commercial building would achieve the goal in 2032, with a total primary energy consumption of 580 million tons of standard coal equivalent (Mtce). **However**, the above studies conducted the emission peak analyses through static scenario models, and the impact of uncertainty on the emission peaks was rarely considered. Therefore, the above peak schemes may discourage the government to accurately and feasibly conduct the emission mitigation goals. **Here, three issues should be addressed for the Chinese commercial building sector as follows:**

- How is the carbon mitigation potential of commercial buildings over the last decades?
- What are the prospective building emission pathways considering the uncertainty impacts?
- How to reinvent the future commercial building and achieve its emission peak goals the earliest?

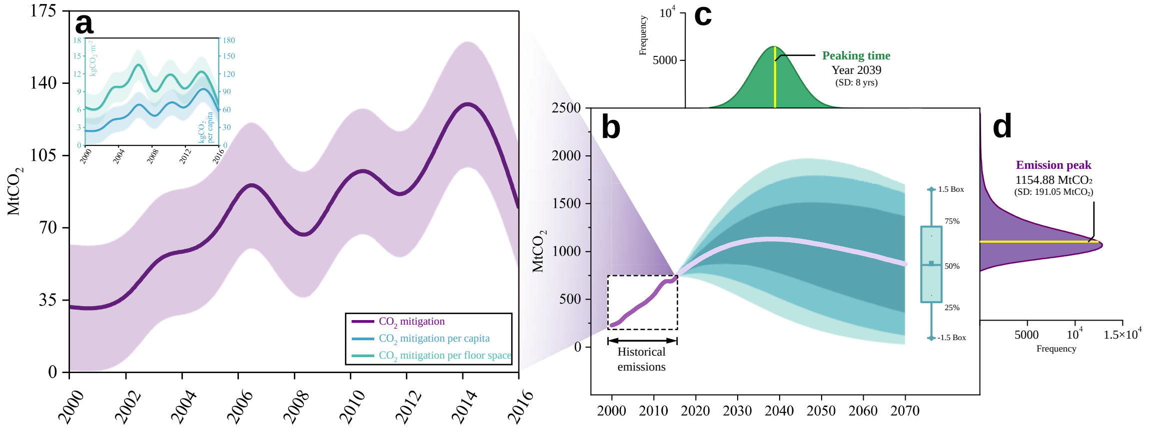

Fig 1 Flowchart of this study: (a) historical carbon emission mitigation assessment since 2000, (b) dynamic scenario simulations of the prospective emission peak up to 2070, and (c-d) distributions of the emission peak and its peaking time of the commercial building sector.

To address these issues, this study is, to the best of our knowledge, the first to propose a historical carbon mitigation assessment, develop a dynamic emission scenario analysis, and identify low carbon pathways of the commercial building sector in China over the period of 2000–2070. Specifically, this work establishes the emission model by Kaya identity, assesses the carbon mitigation during 2000–2016, and analyzes the prospective energy and emission scenarios up to 2070 via Monte Carlo simulation. Thereafter, the strict schemes of the energy demand of the commercial building sector are proposed by applying the uncertainty measured by the scenario analysis. Furthermore, the emission benchmarks for the future commercial building sector were discussed to achieve its earliest emission target.

The most significant contribution of this study is the simulation of energy and emission peaks of the commercial building sector considering the impact of uncertainty. Currently, there are few studies on such topic. To the best of our knowledge, the existing studies only performed the emission peak analysis using a static scenario model, and the uncertainty of the emission peaks caused by the model parameter changes was not considered. Therefore, the proposed peak scheme may not be adequate to accurately and feasibly implement emission mitigation goals, which will be further explained in the literature review.

In this paper, Section 2 focuses on the materials and methods, including the emission model, historical carbon mitigation assessment, static scenario design, and dynamic scenario simulation. In addition, dataset is also introduced. Section 3 shows the historical carbon mitigation trend, and illustrates the prospective carbon emission pathways in the commercial building sector. Section 4 summarizes the core findings and proposes upcoming studies.

2. MATERIALS AND METHODS

2.1 *Emission mitigation model*

To assess the historical carbon mitigation of commercial buildings and establish different carbon emission scenarios of the future commercial building sector, this study considered a series of impact factors to set the building emission model via the Kaya identity, as expressed and refined in Eqs. 1 and 2, respectively.

$$C = P \cdot \frac{G}{P} \cdot \frac{G_S}{G} \cdot \frac{F}{G_S} \cdot \frac{E}{F} \cdot K \tag{1}$$

$$C = P \cdot g \cdot S \cdot I \cdot e \cdot K \tag{2}$$

Due to the space limitation, all the parameters in Eqs. 1 and 2 are explained in the NONMENCLATURE. After establishing the building emission model, the Log-Mean Divisia Index (LMDI) decomposition was applied to analyze the contribution of each factor to the carbon emissions of commercial buildings. Furthermore, the carbon mitigation of the commercial building sector was estimated based on the decomposition result. LMDI is a typical approach to estimate the contribution of each factor to the carbon emissions [9]. Combined with the Kaya identity, the change of carbon emissions of commercial buildings in Period ΔT ($\Delta C|_{0\to T}$) is decomposed as:

$$\Delta C|_{0\to T} = C|_T - C|_0 = (\Delta C_P + \Delta C_g + \Delta C_S + \Delta C_I + \Delta C_e + \Delta C_K)|_{0\to T} \tag{3}$$

Where $\Delta C_K = \frac{C|_T - C|_0}{lnC|_T - lnC|_0} \cdot ln\left(\frac{K|_T}{K|_0}\right)$ (4)

Based on Eq. 3, the carbon mitigation of the commercial building sector (*CM*) is expressed as:

$$CM|_{0\to T} = -\sum \Delta C_x|_{0\to T} \tag{5}$$

Where

$$\Delta C_x|_{0\to T} \in (\Delta C_P,\ \Delta C_g,\ \Delta C_S,\ \Delta C_I,\ \Delta C_e,\ \Delta C_K),\ \Delta C_x|_{0\to T} < 0 \tag{6}$$

2.2 Emission scenario analysis

Scenario analysis is a typical approach to illustrate the prospective roadmap of carbon emissions, and it has been widely applied for different emission sectors. The key to design different emission scenarios is to obtain a set of parameters that affect the carbon emissions (i.e., impact factors). The final carbon emissions should produce a significant feedback based on changes of key parameters. Moreover, the essence of scenario analysis is not to reliably simulate the prospective emissions following the hypothetical socioeconomic and technological levels, but to reveal how will the emission develop upon different strategies and then identify the emission mitigation pathway for the future.

In this section, the static emission scenario at the business-as-usual (BAU) level was developed. For that, the BAU level of emission trend and socioeconomic progress was considered over the period of 2000–2070. The BAU scenario is the most likely to occur, and its emission trend and socioeconomic progress follow the existing background. Furthermore, the potential change degrees of all parameters (see Eq. 2) in this scenario are at the BAU level, which is the benchmark for designing the other emission scenarios.

After setting the static emission scenarios for the commercial building sector over the period of 2000–2070, the dynamic BAU scenario was modeled via Monte Carlo simulation. This model covered the uncertainties caused by parameter changes in the emission model. The simulation illustrates the possible ranges of prospective energy demand and carbon emissions with different probabilities. Monte Carlo simulation is a useful tool to project risk analysis, and it has been recommended to model prospective carbon emission roadmaps considering various uncertainties [10]. This study presented the dynamic scenario simulation in three steps. First, taking Eq. 2 as the emission model, random values (ω) following different distributions were set to express the potential range of factors change affecting the carbon emissions in the commercial building sector. Then, the static BAU scenario changed into the dynamic BAU scenario based on the uncertainties (see Eq. 7). Second, various times of simulations were deployed to model the dynamic BAU scenario by randomly sampling the parameters following the probability distributions defined in Step 1. A total number of 100,000 Monte Carlo simulations were applied to ensure the simulation obtained reliable results. Finally, the simulation results (i.e., frequency distributions) of the potential carbon emission peak and respective peaking time were fitted via the suitable distributions. Then, the emission peak and peaking time were identified.

$$C^{Dynamic} = C^{Static} \cdot \left(1 + \omega \cdot \frac{T-2016}{2070-2016}\right),\quad \omega \sim N(0,\sigma) \tag{7}$$

Using Monte Carlo simulation, this study drew the possible ranges of carbon emission peak and peaking time of the future commercial building sector at different probabilities. Therefore, the results can support the government to conduct emission mitigation strategies more accurately and feasibly for the commercial building sector. Moreover, a more powerful decision-making reference is provided for targeted and feasible strategies to mitigate building emissions in the future.

2.3 Dataset

This study collected historical data (2000–2016) of energy, emissions, stocks, and economy of the Chinese commercial building sector from https://www.researchgate.net/project/China-Building-Energy-and-Emission-Database-CBEED. Historical data on population size were accessed from https://population.un.org/wpp/. For the data in the period of 2016–2070, this study referred to predictions issued by the UN World Population Prospects and CBEED.

3. RESULTS & DISCUSSION

3.1 *Historical carbon mitigation of commercial buildings*

Fig. 2 shows the carbon emission mitigation of the commercial building sector over the period of 2000–2016, which was assessed via Eqs. 5 and 6. Regarding the uncertainty of the emission mitigation result, the error bars at different levels should be considered. For the total CO_2 mitigation, CO_2 mitigation per capita, and per floor space (i.e., CO_2 mitigation intensity), the uncertainty values are: ± 30.43 $MtCO_2$ per year, ± 21.80 $kgCO_2$ per capita, and ± 2.52 $kgce{\cdot}m^{-2}$, respectively.

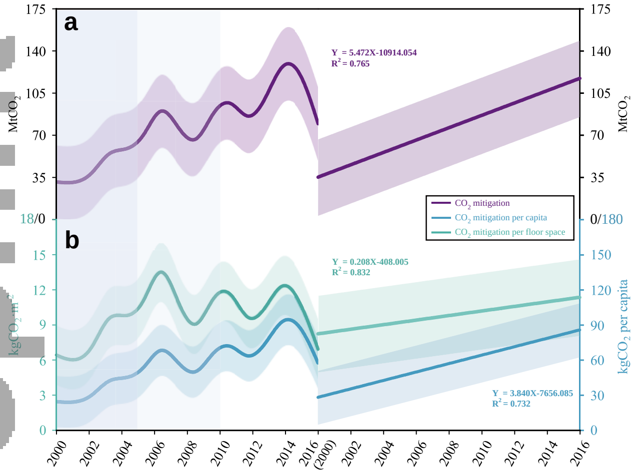

Fig 2 Historical carbon emission mitigation of commercial buildings at the scales of (a) total CO_2 mitigation and (b) CO_2 mitigation per capita and per floor space.

In general, the total carbon mitigation of the commercial building sector in 2000–2016 is 1221.50 (± 486.89) $MtCO_2$ (see Fig. 2 a). Specifically, the total emission mitigation values during the following three periods are: 211.13 (± 152.15, 2000–2005), 391.40 (± 152.15, 2006–2010), and 618.97 (± 182.58, 2011–2016) $MtCO_2$, respectively. Furthermore, the intensity of CO_2 mitigation during the above three periods is: 7.69 (± 2.52), 11.18 (± 2.52), and 10.41 (± 2.52) $kgce{\cdot}m^{-2}{\cdot}yr$, respectively (see Fig 2 b). As the historical emission mitigation trends in Fig. 2 a and b follow the W-shaped curves, the mitigation trend is not monotonic. After fitting the mitigation results, it can be observed that the continuous increase of carbon mitigation at three different scales is significant. Let the total emission mitigation be an example, the accumulative mitigation value in 2000–2016 increased consistently, at a 74.01 $MtCO_2$ yearly level.

3.2 *Emission paths of the future commercial buildings*

Fig. 3 a illustrates the static scenario at the BAU level of the carbon emissions in the commercial building sector and the potential ranges of the dynamic scenario simulations with different probabilities. Following different levels of emission trend and socioeconomic progress, the static and dynamic emission scenarios show the pathways of carbon emission development up to 2070. It was observed that the emission trend of the commercial building sector in the static scenario would follow the inversed U-shaped curve. Specifically, commercial buildings would achieve their emission peak in 2038 (emission peak: 1128.95 $MtCO_2$).

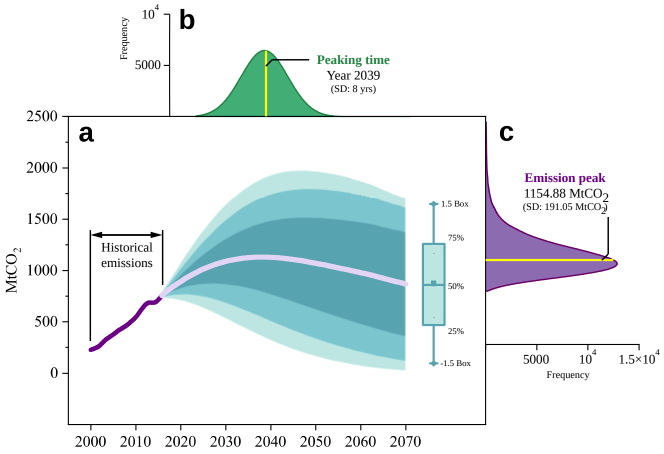

Fig 3 Dataset of (a) static scenarios of carbon emissions in the commercial building sector and (b-c) potential ranges of dynamic scenario simulations with different probabilities in 2000–2070.

Fig. 3 b and c briefly shows the results of the BAU scenario analysis of emissions in the commercial building sector based on 100,000 Monte Carlo simulation runs. The commercial building sector would achieve the emission peak in 2039 in all probability. Regarding the uncertainty of the simulation result, one standard deviation value of 8 years for the peaking time should be considered. Here, the interval of peaking year was expressed as 2039 (± 8). As for the peak value of carbon emissions of the commercial building sector, it would be 1154.88 (± 191.05) $MtCO_2$. It was observed that the results of static scenario analysis (see Fig. 3 a) were basically consistent with the ones of dynamic scenario simulation (see Fig. 3 b and c).

Regarding the peak and peaking year of the energy demand of the commercial building sector, Fig 4 a illustrates that commercial buildings would achieve the peak in year 2048 (± 13) with the value of 578.89 (± 112.90) Mtce. To analyze the difference between energy and emission peaks, the distributions of emission peak with its peaking year were illustrated in Fig 4 b, it reflects that the peaking year of carbon emissions usually appears earlier than the peaking year of energy demand in the commercial building sector. Furthermore, by applying the uncertainty measured by the scenario analysis, to achieve the energy peak goal the earliest, a strict energy demand benchmark of the commercial building sector suggests a control at 465.99 Mtce, and its peaking year is estimated for 2035, which is 13 years ahead of the BAU scenario, with energy savings of 112.90 Mtce. For the earliest peaking time of emissions, if the commercial building sector aims to achieve its emission peak in 2030 (one negative standard deviation value scenario compared to the BAU scenario), the emission peak should be controlled at 958.03 $MtCO_2$ approximately.

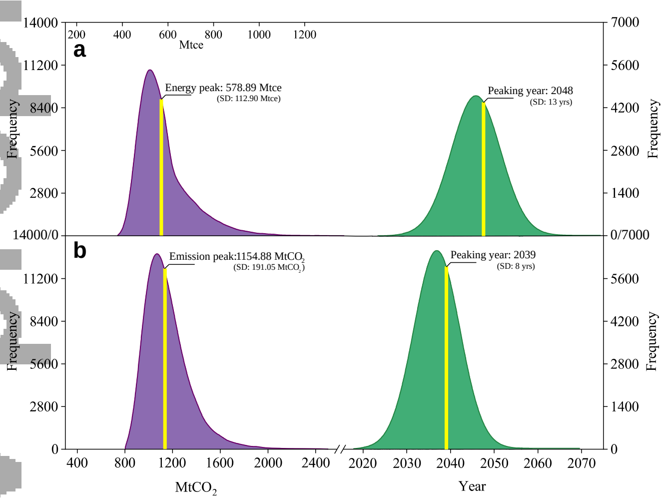

Fig 4 Distributions of (a) energy peak with its peaking year and (b) emission peak with its peaking year of the commercial building sector.

3.3 *Sensitivity analysis for the emission uncertainty*

The scenario analyses shown in Figs. 3 and 4 indicate the existence of the uncertainty of carbon emission peak and its peaking time based on the Monte Carlo simulation. Therefore, a sensitivity analysis is proposed for the uncertainty of the peak and peaking time of carbon emissions from the commercial building sector, as shown in Fig. 5. It can be observed that the impact of emission factor of commercial buildings on the uncertainty of the emission peak was the most significant, and its contribution reached 31.7%. GDP per capita and the industrial structure also positively contributed to the uncertainty of the emission peak, and their contributions reached 31.1% and 22.6%, respectively. The above factors contributed to approximately 85.4% (i.e., ± 176.55 $MtCO_2$) of the future carbon emission peak of the commercial building sector.

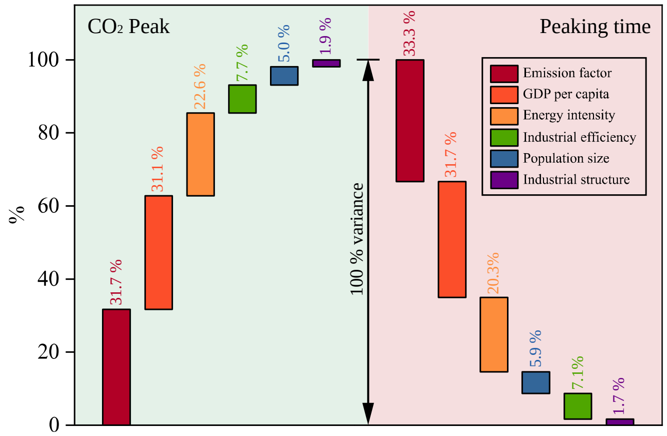

Fig 5 Sensitivity analysis in the commercial building sector for the uncertainty of (a) carbon emission peak and (b) the peaking time.

Regarding the uncertainty of peaking time, the sensitivity analysis result was similar to the one shown in the emission peak. The top three factors affecting the uncertainty of peaking time in decreasing order are as follows: the emission factor (33.3%), GDP per capita (31.7%), and the industrial structure (20.3%). The above three factors contributed to over 85.3% (i.e., ± 6.82 years) of the peaking time of carbon emissions in the commercial building sector. The above sensitivity analysis reveals that the emission factors, GDP per capita, and the industrial structure are determining to the uncertainty of emission peak. Therefore, they should be further discussed for the identification of a low carbon pathway for the commercial building sector in China.

4. CONCLUSIONS

This study proposed a historical carbon mitigation assessment and a dynamic emission scenario analysis to identify the low carbon pathways of the commercial building sector in China up to 2070. For that, a building emission model was established and the carbon mitigation during 2000–2016 was assessed by the decomposition analysis. Then, the prospective energy and emission scenarios up to 2070 were analyzed via Monte Carlo simulation. Based on the simulation result, the strict target schemes on the energy demand of the commercial building sector were proposed. Moreover, the emission benchmarks for the future commercial building sector in the 2030 peaking scheme were discussed. Furthermore, the uncertainty sources with their impacts were discussed to reinvent the future commercial building sector for it to achieve its earliest emission peak. The most important new findings are organized as follows.

Carbon mitigation of the China's commercial building sector during 2000–2016 is 1221.50 (± 486.89) MtCO$_2$. This study established the emission model via Kaya identity to characterize the carbon emissions of the commercial building sector. Then, the decomposition analysis was applied to investigate the contribution of each factor to the carbon emissions of commercial buildings. Furthermore, the carbon mitigation of the commercial building sector was assessed based on the decomposition result. Considering the uncertainty impacts, the total carbon mitigation of the commercial building sector in 2000–2016 is 1221.50 (± 486.89) MtCO$_2$. Specifically, the emission mitigation values during the following three periods are: 211.13 (± 152.15, 2000–2005), 391.40 (± 152.15, 2006–2010), and 618.97 (± 182.58, 2011–2016) MtCO$_2$, respectively. It is believed that the continuous increase of carbon mitigation at different scales is significant.

The commercial building sector is expected to achieve its carbon emission peak in 2039 (± 8) with a peak of 1154.88 (± 191.05) MtCO$_2$. This study set the static emission scenario of the commercial building sector at the BAU level. Then, the BAU scenario was modeled using 100,000 Monte Carlo simulations. Considering the uncertainty impacts, it was observed that the commercial building sector would achieve its emission peak in 2039 (± 8) with a peak of 1154.88 (± 191.05) MtCO$_2$. Furthermore, the sensitivity analysis revealed that the emission factor, GDP per capita, and the industrial structure are determining to the uncertainty of emission peak and peaking time of the commercial building sector. For the earliest peaking time, if the commercial building sector aims to achieve its emission peak in 2030, the emission peak should be controlled at 958.03 MtCO$_2$ and the carbon mitigation will be over 195 MtCO$_2$ nationwide compared to the BAU scenario.

Due to the space limitation, several gaps that exist in this study can be addressed in the future. For example, although this study has successfully performed a dynamic emission scenario analysis to identify low carbon roadmaps of the commercial building sector in China to 2070, the specific contribution of theses mitigations to the global 1.5–2 °C goals have yet to be clarified and assessed. Therefore, there should be a considerable effort by upcoming studies to illustrate a low carbon pathway of the global commercial buildings in 1.5–2 °C scenarios.

ACKNOWLEDGEMENT

This study was supported by the National Key R&D Program of China (2018YFC0704902), the National Planning Office of Philosophy and Social Science Foundation of China (19BJY065), and the Shuimu Tsinghua Scholar Program of Tsinghua University (2019SM139).

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