Global warming is primarily attributed to the significant increase in atmospheric CO₂ concentration, which is caused mainly by carbon emissions generated from fossil fuel combustion [1]. Efficient measures are required to control these emissions and reduce global warming. However, socio-economic developments are inevitably accompanied by an increase of carbon emissions [2–4], especially in developing countries, which are experiencing rapid industrialization [5–8].

As a developing country with the greatest carbon emissions per annum, China is among the countries that have been urgently requested to adopt and implement carbon reduction programs. The Chinese government set a target at the 2009 Copenhagen Climate Change Conference to cut CO₂ emissions per unit GDP (carbon emission intensity, CEI) by 40%–45% by 2020, relative to 2005 levels (hereafter referred to as the Copenhagen Commitments) [9].

In its 12th Five-Year Plan, China proposed to reduce its CEI by 17% from the 2010 level by the end of 2015 (referred to as the Five-Year Goal) [10]. Subsequently, in the ‘China–U.S. Joint Statement on Climate Change’, China promised to achieve peak CO₂ emissions around 2030, making every effort to achieve that goal earlier (referred to as the 2030 Goal) [11]. Recently, China has documented ‘the Intended Nationally Determined Contributions’ (INDC) and reemphasized that goal and pledged to reduce CEI by 60%–65% from the 2005 level (referred to as the INDC Target) [12].

The 2015 Paris Agreement will clarify emission reduction targets for each country [13]. Comprehensive analyses of possible pathways to reach carbon reduction goals and examine the evidence as to whether China can achieve the INDC Target are urgently needed. Previous studies used model simulations (e.g. environmental Kuznets curve and carbon emission model) to create a carbon emissions peak scenario [14,15]. Based on the Kaya identity [16], the present study used six emission scenarios to analyze the pathways of the potential emissions for China between 2011 and 2050, and to evaluate the feasibility and the social implications of the INDC Target.

**DATA AND METHODS**

**Data sources and definitions**

The CEI data from China and major developed countries were obtained from fossil fuel emissions and GDP data from 1980 to 2010. Data from major developed countries were taken from the Group of Eight (G8): the USA, Japan, Germany, France, UK, Italy, Canada and Russia.

The data of fossil fuel emissions was sourced from the Carbon Dioxide Information Analysis Center (Oak Ridge National Laboratory, USA), which documents annual emissions from solid, liquid and gas fuel combustion, cement production and gas flaring as a global total and for all countries [17], although recently the data have been disputed [18]. GDP data are from the World Bank [19], which summarizes annual GDP for 222 countries. All GDP data were treated as constant 2005 US dollars.

The projection data of the annual growth rate for China’s GDP from 2011 to 2050 (Table 1) are from the Organization for Economic Cooperation and Development (OECD), which provides predictive growth rates of GDP each year through to 2060 for OECD countries [20]. China’s annual GDP from 2011 to 2050 was calculated according to China’s historical GDP and future growth rates.

We estimated CEI and cumulative carbon emissions of the G8 countries using carbon emission and GDP data. Specifically, the CEI is equal to the ratio of carbon emissions to GDP for the same country [13]. The 2015 Paris Agreement will clarify emission reduction targets for each country [13]. Comprehensive analyses of possible pathways to reach carbon reduction goals and examine the evidence as to whether China can achieve the INDC Target are urgently needed. Previous studies used model simulations (e.g. environmental Kuznets curve and carbon emission model) to create a carbon emissions peak scenario [14,15]. Based on the Kaya identity [16], the present study used six emission scenarios to analyze the pathways of the potential emissions for China between 2011 and 2050, and to evaluate the feasibility and the social implications of the INDC Target.

**Emission scenarios and predictions**

We used Equation (1) to predict carbon emissions \( C \), based on the relationship between GDP \( G \) and CEI \( I \):

\[
C = G \left( \frac{C}{G} \right) = G \times I \tag{1}
\]

**Table 1. Calculated GDP growth rates of China from OECD.**

| Period   | Average growth rates of GDP |
|----------|----------------------------|
| 2001–2010| 10.5%                      |
| 2011–2020| 6.9%                       |
| 2021–2030| 4.0%                       |
| 2031–2040| 3.3%                       |
| 2041–2050| 2.3%                       |
I is estimated by an exponential Equation (2) [21]:

\[ I_t = I_0 \times e^{-b(t-t_0)} \]  

where \( I_t \) is the CEI of year \( t \), \( I_0 \) is the CEI of the base year, and \( b \) is the attenuation coefficient of CEI. In all six scenarios, the base year is 2010, therefore \( I_0 \) equals 0.59 t C per thousand of constant 2005 US dollars, and \( b \) changes with different scenarios (See Table S1, Supporting Information). Based on Equations (1) and (2), we constructed the following six scenarios for China’s carbon emissions between 2011 and 2050.

1. **Past China scenario**: setting the attenuation coefficient (\( b \)) of China’s CEI from 2011 to 2050 as that from 1980 to 2010. The CEI decreased rapidly from 1980, and is well fitted by an exponential function (\( b = 0.0426 \), \( R^2 = 0.95 \), Fig. 1a). Assuming that China’s CEI during 2011–50 will continue to decrease following Equation (3), then \( b \) would be 0.0426 (Table S2, Supporting Information):

\[ I_t = 0.59 \times e^{-0.0426(t−2010)} \quad (2011 \leq t \leq 2050) \]  

2. **Past G8 scenario**: assuming the same average attenuation coefficient of CEI for China as that for the G8 countries from 1980 to 2010. We assume that China’s CEI decreases between 2011 and 2050 in accordance with Equation (2) (Fig. 1b). The CEI continues to decrease through 2050, with \( b = 0.0253 \) (Table S3, Supporting Information).

3. **Five-Year scenario**: in accordance with its 12th Five-Year Goal, China’s CEI would decrease 17% during 2010–15, depicting that the CEI would decrease 3.7% per year with \( b = 0.0373 \). This decreasing rate would be maintained through 2050 (Table S4, Supporting Information).

4. **Copenhagen scenario**: following the Copenhagen Commitments, the CEI would experience an exponential decay beginning in 2011, decline 40% by 2020 from the 2005 level, and maintain this decline through 2050. The \( b \) value would be 0.0341 (Table S5, Supporting Information).

5. **INDC scenario**: in accordance with the INDC Target, the CEI would experience an exponential decay beginning in 2011, decrease 60% by 2030 over the 2005 level, and maintain this decrease through 2050 (\( b = 0.0367 \)) (Table S6, Supporting Information).

6. **Peak scenario**: the CEI would experience an exponential decay beginning in 2011, peak in 2030, and maintain this decrease through 2050 (\( b = 0.0339 \)) (for details, see Box 1 and Table S7, Supporting Information).

Substituting the CEI under the six scenarios and the corresponding projected data of Chinese GDP into Equation (1), we therefore predict the pathway of carbon emissions, and calculate their peak values and the peak year, respectively.

**RESULTS AND DISCUSSION**

During 2011–2050, the annual rates of CEI decline under the Past China, Past G8, Five-Year, Copenhagen, and INDC scenarios would be 4.2%, 2.5%, 3.7%, 3.4% and 3.6%, respectively. The decline rate of the Past G8 scenario is the lowest, followed by the Copenhagen scenario, and then the other three scenarios. Based on these predictions, the year of peak carbon emissions (from soonest to latest) would be 2023 (Past China, with an emission at the peak of 2.89 Pg C yr\(^{-1}\)), 2026 (Five-Year, 3.11 Pg C yr\(^{-1}\)), 2026 (INDC, 3.14 Pg C yr\(^{-1}\)), 2030 (Copenhagen, 3.29 Pg C yr\(^{-1}\)) and 2043 (Past G8, 4.25 Pg C yr\(^{-1}\)) (Fig. 2). Cumulative emissions during 2011–50 corresponding to these peak years would be 104.33, 116.10, 117.54, 124.05 and 149.82 Pg C, respectively. In other words, lowering the rate of CEI decline will delay the carbon emissions peak, with greater cumulative emissions.

All five scenarios reached a peak before or in 2030, except the Past G8 scenario, which would achieve a peak in 2043. Compared with a later peak, an earlier peak would require less time for

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**Figure 1.** Changes in CEI in China (a) and average CEI of the Eight Countries Group (G8) (b) from 1980 to 2010. Solid points and the red line represent historical and fitted values of CEI, respectively. Data = means ± sd, \( n = 8 \).
commercial, corporate and consumer interests to adjust to lower energy consumption rules. Infrastructure would need to be replaced more quickly, stricter requirements for energy-related and technological improvements would need to be established and greater pressure for emissions reduction applied [22].

The CEI in 2020 for the Copenhagen scenario would be 0.419, a 40% decrease compared with the 2005 level. In contrast, 2020 CEI based on the Past China, INDC, Five-Year and Past G8 scenarios would be 0.384, 0.408, 0.405 and 0.457, respectively. These amounts represent CEI decreases of 45.1%, 41.7%, 42.1% and 34.7% relative to that in 2005, indicating that these levels will attain the Copenhagen Commitments goal (40%–45%) with the exception of the Past G8 scenario.

According to the INDC scenario, China’s CEI would become 0.282 in 2030, a decrease of 60% compared with the 2005 level. In contrast, the 2030 CEI of the other four scenarios would be 0.251 (Past China), 0.355 (Past G8), 0.279 (Five-Year) and 0.298 (Copenhagen). These CEI levels would represent respective decreases of 64.1%, 49.3%, 60.1% and 57.5%, relative to the 2005 level. These results show that the Past China and Five-Year scenarios would achieve the INDC Target, but the Copenhagen scenario would reduce emissions slightly below this target. This finding signals a need for a more stringent reduction plan after China achieves the Copenhagen Commitments goal in 2020.

Carbon emissions of the Peak Scenario would peak (3.31 Pg C) in 2030, with CEI decreasing by 3.3% yr\(^{-1}\) from 2011 to 2050 (Fig. 2). Emissions would increase by an average rate of 1.9% yr\(^{-1}\) through the peak year and decrease by an average rate of 0.6% yr\(^{-1}\) thereafter. Cumulative emissions during 2011–50 would be 124.57 Pg C.

In summary, all scenarios would achieve peak carbon emissions before 2030 and reach the Copenhagen Commitments goal except the Past G8 scenario. However, the Chinese government would be under pressure if required to reach the peak at an earlier year [22]. Comparison between the Past G8 and INDC scenarios indicates that the INDC Target is much harsher than the 1980–2010 emission standards of the G8 countries (CEI decreased by 60% over 25 years vs. 40% over 30 years). This would necessitate China’s utmost efforts in addressing climate change and taking on greater responsibility for emission reductions.

UNCERTAINTIES

We constructed six scenarios to simulate China’s carbon emissions over 2011–50, and evaluated the feasibility of achieving the 2030 Goal and other targets. However, there are two uncertainties related to the outcomes in our scenarios.

1. Uncertainty of projection data. The predicted GDP growth rates from the OECD may be lower than actual rates. Most of China’s GDP projection data before 2010 estimated by the OECD were less than actual GDP [23,24]. Indeed, the OECD predicted that GDP growth rates for China are lower than those of similar studies [25–27]. Underestimated GDP growth rates would cause predicted future carbon emissions to be artificially low and result in underestimating the time required to reach peak carbon emissions.

2. Uncertainty of policy implementation, technological innovation, and financial support. China is expected to optimize its carbon emission configuration by implementing a series of climate-related actions and building carbon emission trading pilots. These actions will work through market mechanisms, urging enterprises to conserve energy and reduce emissions, and stimulate public participation in environmental management [28,29]. The development and promotion of carbon capture and storage and other innovative technologies may enable an accelerated decline in CEI [30]. Developed countries may agree to provide financial support and transfer technologies to developing countries during the 2015 Paris Agreement [13], which would accelerate the decline of CEI in China. Any of the aforementioned actions could cause carbon emission decline rates to accelerate, which
Figure 2. CEI (a) and the corresponding carbon emissions in China (b) under the six prediction scenarios, including the Past China, Past G8, Five-Year, Copenhagen, INDC and Peak scenario. Colored dots represent the corresponding peak years at different scenarios.

CONCLUDING REMARKS

Under the five scenarios, China’s carbon emissions would peak from 2023 to 2030, with peak values from 2.89 Pg C to 3.29 Pg C/yr, except the Past G8 scenario, which predicts the peak emission at 2043 and is obviously inapplicable currently. The CEI would decrease by 2.4%–4.2% yr\(^{-1}\) over 2011–50. The Five-Year, Copenhagen and INDC scenarios represent three different CEI reduction targets. The annual decline rate in the Five-Year scenario is the greatest (3.7%) among these three scenarios, followed by the INDC (3.6%) and Copenhagen (3.4%). The CEI in the Peak scenario would decrease by 3.3% yr\(^{-1}\) over 2011–50. This implies that if China can achieve the Five-Year goal, the Copenhagen Commitments and INDC Target, its carbon emissions will peak before or in 2030. According to China’s historical trend of CEI, carbon emissions will also maximize before that year.

Wang et al. [6] holds that industrialization and urbanization are inevitably accompanied by an increase of carbon emissions. Thus, reducing carbon emissions could narrow the amount of energy that can be consumed for development. Moreover, reaching peak carbon emissions too early would place increased pressure on social and economic factors for China. The ideal situation is one in which China achieves all emission reduction goals and arrives at peak carbon emissions around the year 2030. It will be difficult to achieve this goal because regulations only apply to CEI without regard for changes in GDP. Therefore, economic macrocontrol and carbon emissions reduction must be promoted in a coordinated manner in the future. Future studies should further explore how to coordinate the emission reduction and economic developments, thus reducing the adverse impact on economic developments. Furthermore, the Chinese government should optimize the combination of energies used, promote technological innovation, and establish carbon emission trading mechanisms. This could lead to multiple gains in sustainable development and emission reduction [31].

SUPPLEMENTARY DATA

Supplementary data are available at NSR online.

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Is lunar magma ocean (LMO) gone with the wind?

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The Moon is the only natural satellite of the Earth, and has been the subject of numerous works of arts, literature, mythology, astrology and astronomy for millennia. The scientific speculation of its origin has also been in the literature for centuries. But it is the manned landing of Apollo missions 11–17 (1969–1972) with returned lunar rocks and soils and the unmanned post-Apollo spacecraft with remote-sensing data that allow the development of geological models on the origin of the Moon, its internal structure and its subsequent histories [1].

Several models have been proposed for the origin of the Moon, but the single generally accepted model today is the ‘giant impact’ hypothesis [1]. It assumes that the Earth–Moon system formed as the result of a giant impact by a Mars-sized body that collided with the proto-Earth, blasting material into its orbit to form the Moon. This Moon formation mechanism would help explain the high angular momentum of the Earth–Moon system and the small size of the iron lunar core.

The energy released during such a giant impact would have been sufficient to melt the outer few hundreds of kilometers (<1000 km?) of the Moon, forming the postulated global lunar magma ocean (LMO; Fig. 1a). The evidence for this ‘LMO hypothesis’ came from the highly anorthositic compositions of the lunar highland crust. The ‘anorthositic compositions’ refer to rocks dominated by CaO-rich plagioclase (CaAl2Si2O8), which is less dense than the magma and would float to form the lunar crust and highlands (Fig. 1b) [2]. This is the ‘plagioclase floatation hypothesis’. As noted [3], the ‘LMO hypothesis’ was initially based on a few anorthositic particles of Apollo 11 soil [2]. These two interdependent hypotheses are actually based on a single observation—the Moon’s anorthositic upper crust has