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Original Research

Can China Achieve its CO_2 Emission Mitigation Target in 2030: a System Dynamics Perspective

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Abstract

To predict the feasibility of whether China can achieve an up to 65% of carbon emissions intensity (CEI) reduction goal from 2005 levels by 2030, we performed dynamic simulations and predictions of China's CO_2 emissions at the national scale from a system dynamics perspective. More specifically, we developed a system dynamics model based on LMDI analysis to simulate and estimate CO_2 emissions under 10 different scenarios in China during 1991-2030. The result shows that China's CEI will decrease by 67.86-84.63% in 2030 compared to the 2005 level, which means that China will be able to meet the emission reduction goal by 2030, and China's CO_2 emissions will peak sometime between 2020 and 2025. In addition, the quantitative evidence suggests that transforming the energy structure will make a significant contribution to CO_2 emissions reduction. As the proportion of renewables increases, CO_2 emissions decrease in terms of both scale and peak value and peaks earlier. So, the findings also indicate that the optimization for energy structure by replacing fossil fuels (especially coal) with renewables at a suitable growth rate can promote the coordination between economic growth and CO_2 emissions mitigation.

Keywords: CO_2 emissions, CO_2 emission mitigation goal, system dynamics, China

Introduction

According to the Copenhagen Accord, climate change is one of the biggest challenges the world is facing today, which has been threatening human survival and socio-economic developments. The scientific view is that carbon dioxide (CO_2) emissions are widely regarded as the primary anthropogenic driver of climate change [1-3]. Hence, CO_2 emissions and mitigation have drawn intense attention from both governments and the academic side.

As energy consumption and CO_2 emissions steadily increased over the past decades, China has become the largest CO_2 emitter in the world in terms of total quantity. Facing increasing pressure to reduce CO_2 emissions, the Chinese government made a promise to cut CO_2 emissions per unit GDP (i.e., carbon emissions intensity, CEI) by 40-45% in 2020 compared to 2005 levels at the 2009 Copenhagen Climate Change Conference [4]. In 2015, China issued the "intended nationally determined contributions" and set a new target to reduce CEI by 60-65% from 2005 levels by 2030 [5].

So, some questions appeared: 1) Can China achieve its CO_2 emission mitigation target in 2020 and 2030?

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2) When will China reach its CO_2 emission peak? CO_2 emissions are generally acknowledged as a dynamic and complex system with various interrelated, interacting factors. In order to answer these questions, it is essential to investigate the dynamic complexity of CO_2 emissions under the integrated impacts of multiple factors such as economic growth, rigid demand for energy, coal-dominated energy structure, population change, etc. from a holistic view, which is important for policy decision making and meeting the CO_2 emission mitigation goal. However, it is difficult to accurately describe and clarify the relationship between CO_2 emissions and factors because the integrated impacts of various factors do not simply equal the sum of impacts of each individual factor [6]. Therefore, these factors must be considered simultaneously in a model to shed light on the dynamic complexity of CO_2 emissions through simulations and forecasting under different scenarios [7].

Literature Reviews

Previous studies on the relationship between CO_2 emissions and influence factors can be divided into 3 categories [8]: 1) the relationship of CO_2-GDP-energy or GDP-energy-CO_2 emissions, including the causality relationships; 2) the different aspects of the environmental Kuznets curve (EKC) hypothesis; and 3) the forecast of CO_2 emissions. The common approaches and models employed in the literatures are partly summarized as follows: EKC analysis [9-12]; statistics model such as cointegration [13-14], Granger causality [15-16] generalized method of moments (GMM) estimators [17]; input-output model [1, 18-22]; reduced-form econometrics model [3, 23]; decomposition analyses, including structural decomposition analysis (SDA), index decomposition analysis (IDA), and production-theoretical decomposition analysis (PDA) [20, 24-29]; data envelopment analysis (DEA) [30-31]; causality relationship analysis [32-33]; indicator analysis [34]; scenario analysis [35-36]; and system dynamics (SD) model [7, 36-37]. Whether it is a top-down approach, a bottom-up approach, or a hybrid model, each method has strengths and weaknesses and plays important roles in the study of CO_2 emissions.

System dynamics, initially developed by Jay W. Forrester from MIT in the 1950s-1960s, is a method for modeling, simulating, and analyzing a complex system that aims to show and understand how a given system evolves, and even more importantly understand the causes that govern its evolution. SD has been generally recognized as a powerful system simulation methodology for describing, visualizing, and analyzing complex dynamic system issues with non-linear relationships, causal loops, information feedback, and time delays, which improves the understanding of dynamic behavior of systems over time [7, 38-40]. An SD model can be used to qualitatively analyze the inner causal relationship among the factors in a system by developing causal loop diagrams that represent dynamic factor interaction and to quantitatively analyze the structure of the information feedback system and the dynamic relationship between function and behavior by stock-flow modeling and computer simulation [40]. So, SD modeling can act as a "policy laboratory" that allows decision makers to simulate and test possible different policies, the results of which can enable them to improve their decisions in terms of both efficiency and results [41]. After many years of development, SD has been used for a broad spectrum of applications, including ecological and economic systems, energy-efficiency analysis, and electricity substitution, environment sustainability, energy policy making and evaluation, etc. Some SD models have been proposed to study GHG/carbon emissions forecasting and mitigation at regional and national scales [7, 36-37, 42-46]. Thus, SD can be adopted to describe the inner interactions and structures impacting CO_2 emissions and to illuminate the feedback mechanisms and the evolving trend of CO_2 emissions.

China's CO_2 emission and emission reduction target have aroused researchers' concerns, and some literature has analyzed China's carbon emission peak, peak year, the feasibility of realizing the target, etc. using different methods from different perspectives [47-53]. However, not much attention has been paid to the study on dynamic simulation and prediction of China's CO_2 emissions at national scales from a system dynamics perspective. Thus, this paper uses system dynamics to develop a model based on LMDI to ascertain whether China can achieve its CO_2 emission mitigation goal by simulating and estimating CO_2 emissions during the period of 1991-2030, which is important and useful to policymakers.

Material and Methods

Log-mean Divisia Index

LMDI has been widely used to analyze the factors that influence CO_2 emissions, because it can be used to quantitatively decompose CO_2 emissions into several effects with zero residual errors and relatively low data requirements [54]. Some studies had used LMDI to investigate CO_2 emissions at regional [55-56] and national scales [6, 26, 57] in China. In this paper, we use LMDI to explore the factors affecting China's CO_2 emissions from a national perspective, which could be used as a structural guide for SD modeling of China's CO_2 emissions.

We use a model based on a variation of the general Kaya identity to decompose the CO_2 emissions in China. Here is the model equation:

$$C = \sum_i \frac{GDP}{P} \times \frac{E}{GDP} \times \frac{E_i}{E} \times \frac{C}{E_i} \times P \quad (1)$$

…where C denotes the total CO_2 emissions of China, P is the population scale of China, GDP is gross domestic product, E is the total energy consumption each year in China, and E_i represents the total consumption of energy i.

Set $Q = \frac{GDP}{P}$, $I = \frac{E}{GDP}$, $S_i = \frac{E_i}{E}$, $F_i = \frac{C}{E_i}$ and the Equation (1) can be rewritten as:

$$C = \sum_i Q \times I \times S_i \times F_i \tag{2}$$

…where Q is per capita GDP, I is energy intensity, S_i denotes energy structure, and F_i is the CO_2 emission coefficient of different energy.

Then, the factors that influence CO_2 emissions in China can be decomposed into the effect of economic output (ΔC_Q), the effect of population scale (ΔC_P), the effect of energy intensity (ΔC_I), the effect of energy structure (ΔC_S), and the effect of CO_2 emissions coefficient (ΔC_F). We define C^0 and C^t as total carbon emissions in the base period and period t, respectively. So, the total effect on CO_2 emissions can be expressed as:

$$C = C^t - C^0 = \Delta C_Q + \Delta C_I + \Delta C_S + \Delta C_F + \Delta C_P \tag{3}$$

$$\Delta C_Q = \sum_i W_i \times \ln \frac{Q^t}{Q^0} \tag{4}$$

$$\Delta C_I = \sum_i W_i \times \ln \frac{I^t}{I^0} \tag{5}$$

$$\Delta C_S = \sum_i W_i \times \ln \frac{S_i^t}{S_i^0} \tag{6}$$

$$\Delta C_F = \sum_i W_i \times \ln \frac{F_i^t}{F_i^0} \tag{7}$$

$$\Delta C_P = \sum_i W_i \times \ln \frac{P^t}{P^0} \tag{8}$$

$$W_i = \frac{(C_i^t - C_i^0)}{\ln C_i^t - \ln C_i^0} \tag{9}$$

System Dynamics Model Development

Following the modeling steps of SD, we constructed the qualitative causal loop diagram and quantitative stock-flow model of China's CO_2 emissions.

Causal Loop Diagraming

Economic development and population growth are the reasons for constantly increasing CO_2 emissions. The abolition of single-child policy will, to some extent, accelerate China's population growth, and net demographic growth will increase the total population, together with improving living standards, and can also be the stimulus to social energy consumption. Although economic growth is the fundamental target of China, GDP growth will directly lead to increasing energy consumption of the entire society. On the one hand, with the rapidly growing economy and per capita GDP (generally speaking, China's GDP growth rate is far greater than its population growth rate) bringing the boosted CO_2 emissions and the degradation of the eco-system, demand for better living environment and their willingness to improve the environment is getting stronger. On the other hand, the increasing CO_2 emissions brought strong international pressure to the

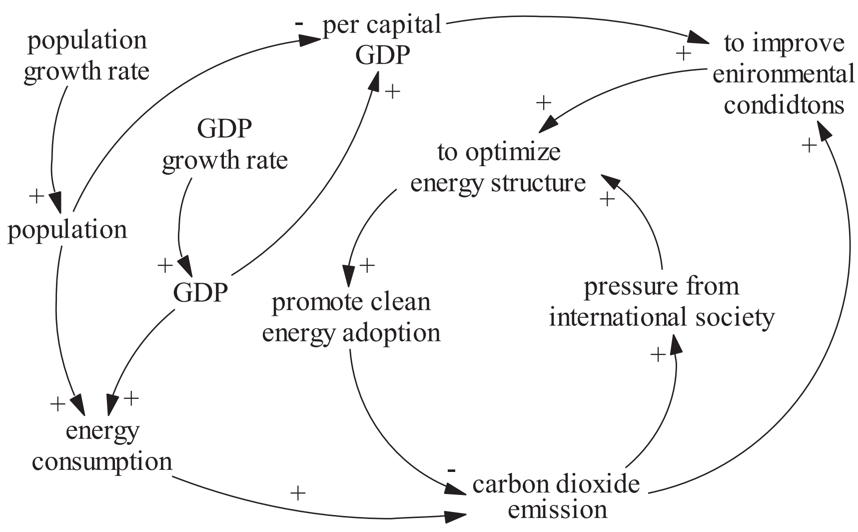


Fig. 1. Causal loop diagram for CO_2 emissions in China.

Chinese government. Based on these facts, the Chinese government had to announce an energy conservation and CO_2 emissions reduction goal. In fact, the Chinese government has vowed to reduce its CEI by 40-45% from 2005 levels by 2020 in 2009 and by 60-65% from 2005 levels by 2030 in 2015.

Fossil fuel, especially coal, is the main source of CO_2 emissions. Accounting for more than 60% of total energy use at present, coal is always acting as the main energy resource in China. But now the situation will last for a long time, the major reason being the response to China's growing CO_2 emissions. To break the dilemma, the Chinese government will optimize the energy structure and upgrade power usage effectiveness, which are generally recognized as effective measures to mitigate CO_2 emissions. However, considering the technological advancement of energy effectiveness improvement has very little chance to have a breakthrough in a short while, so optimizing the energy structure is probably the most promising method for reducing CO_2 emissions. Furthermore, on the one hand, replacing the fossil fuel with renewable energy is a common method to improve the ratio of clean energy. On the other hand, even among the fossil fuel family, the efficiency of various fuels is different. So gradually replacing the use of coal with natural or oil, which has higher efficiency in terms of unit CO_2 emissions per energy generation, is one of the most feasible means for CO_2 emission reduction in China.

Based on the aforementioned analysis, we created a causal loop diagram of China's CO_2 emissions system that describes how the factors qualitatively influenced each other (Fig. 1).

Stock-Flow Modeling

We used the CLD in Fig. 1 as a structural guide for the construction of the SF model developed in NetLogo. Fig. 2 shows the complete SF model with stocks, flows, and auxiliary parameters that reveals the correlation between CO_2 emissions and GDP, energy structure, energy consumption, and population in China. In order to determine CO_2 emissions in China, we present a definition for four subsystems that influence CO_2 emissions, such as effect of economic growth, effect of population, effect of energy structure, and effect of energy intensity. The effect of economic growth means the part of CO_2 emissions contributed by GDP growth, the effect of population measures on CO_2 emission rise due to population growth, how energy structure changes the proportion of specific energy (such as coal, natural gas, and renewable energy) to affect CO_2 emissions, and the effect that energy intensity represents in influencing CO_2 emissions contributed by energy intensity. Eventually, 10 stock variables, 10 flow variables, and many auxiliary variables are involved in the SF model.

Validation of SF Model

1. Data source.

Statistics in the model mainly come from [58-60]. To make the data more comparable, GDP has been deflated

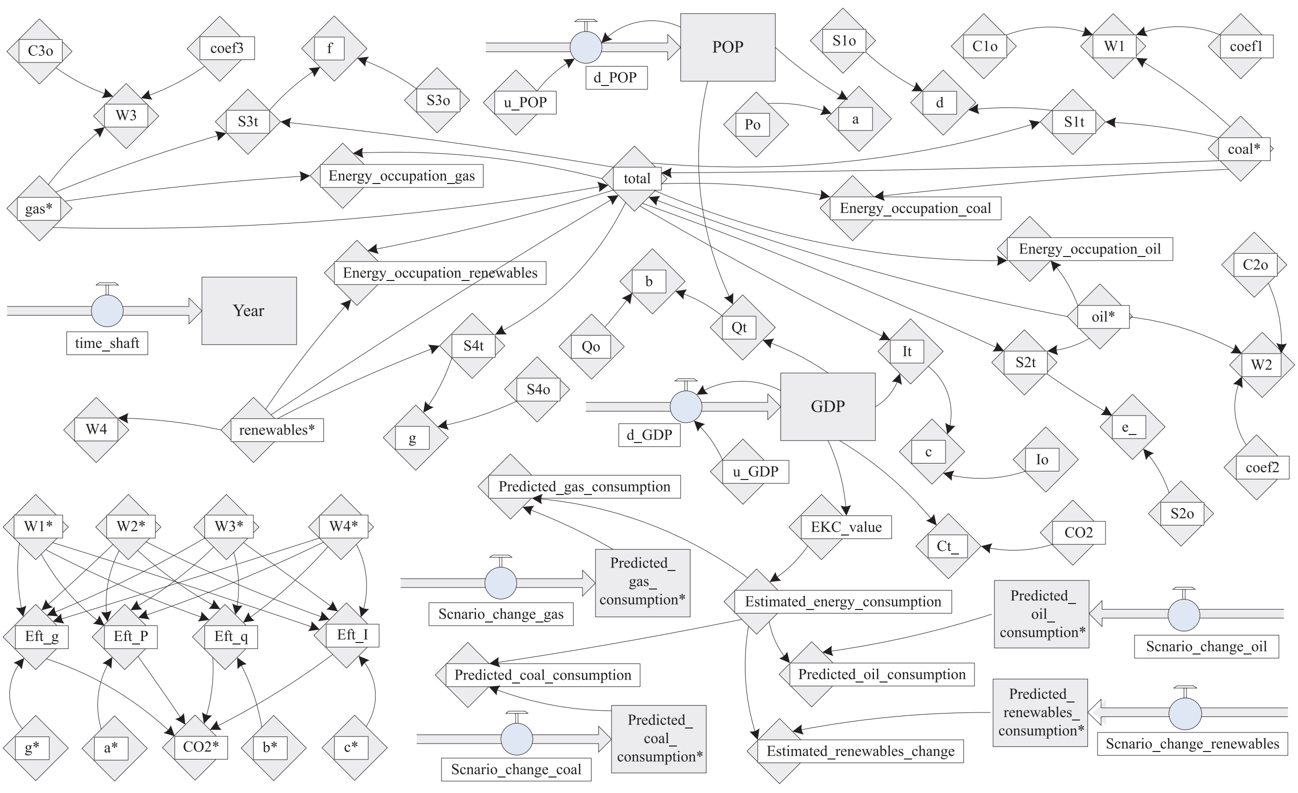


Fig. 2. Stock flow model for CO_2 emissions in China.

Table 1. Parameters for simulating CO_2 emissions in China from 1990 to 2012.

Parameter	Value
Initial number of carbon dioxide	2,433.92 million ton
Initial GDP	1,877.43 billion CNY
Initial POP	1.14 billion
Initial coal*	752.11 million tons of standard coal
Initial oil*	163.84 million tons of standard coal
Initial gas*	20.72 million tons of standard coal
Initial renewables*	50.33 million tons of standard coal
Starting year	1990
Initial predicted gas consumption*	0.052
Initial predicted coal consumption*	0.666
Initial predicted renewables consumption*	0.094
Initial predicted oil consumption*	0.188

according to the unchanged price in 1990 and its unit is 100 million CNY; energy consumption is measured by 10,000 tons of standard coal; the CO_2 emissions of coal, oil, gas, and non-fossil energy are calculated using an IPCC method that first converts the consumption into the low heating value and then multiplies it by carbon emission coefficient (0.93% for coal, 0.73% for oil, 0.55% for gas, and 0 for non-fossil energy) [61]. The units are respectively 10,000 tons for CO_2 emissions, CNY per person for per capita GDP, and tons of standard coal per 10,000 CNY for energy intensity. The parameter values adopted for the simulation are seen in Table 1.

2. Compared to historical data.

In this section, we used historical data on CO_2 emissions between 1990 and 2012 in China to validate the results of the system dynamics model developed in this study. A comparison between simulation results and the historical data on CO_2 emissions is shown in Table 2, from which we can find that the deviations were always under 0.3% except for the first and last years, and overall precision can be concluded as higher than 99.7%, which suggests that this model is valid.

Results and Discussion

Results

According to the above-mentioned analyses of driven factors, 10 scenarios combining GDP growth rates, population growth rates, energy structures, etc. are set to simulate and project China's CO_2 emissions and CEIs.

Economic growth speed has slowed down since 2015. Compared to GDP growth rates from 2003 to 2011 (around 10%), the annual growth rate GDP of 2015 and 2016 has declined to 6.9% and 6.7%. And it is estimated that the economic recession will last for a long period. According to [62], when China's economic reform is stable and suffered no crisis, the average annual GDP growth rate from 2011-2015 achieved 8.6% (real statistics: 9.5% for 2011, 7.9% for 2012, 7.8% for 2013, 7.3% for 2014 and 6.9% for 2015). The average annual GDP growth rate comes to 7% for 2016-2020 and declines to 5.9% for 2021-2025. Finally, the economic growth rate is predicted to decrease to 5% for 2026-2030. Therefore,

Table 2. Comparisons between simulation results and historical data on CO_2 emissions in China from 1990 to 2012 (unit: million tons).

Year	Simulation results	Actual results	Model error	Year	Simulation results	Actual results	Model error
1990	13,327	13,462	-1.00%	2002	204,757	205,057	-0.15%
1991	26,482	26,627	-0.55%	2003	276,325	276,688	-0.13%
1992	42,575	42,735	-0.37%	2004	330,821	331,233	-0.12%
1993	57,722	57,895	-0.30%	2005	386,891	387,353	-0.12%
1994	77,203	77,392	-0.24%	2006	439,536	440,046	-0.12%
1995	87,440	87,638	-0.23%	2007	459,381	459,910	-0.11%
1996	87,782	87,980	-0.23%	2008	495,341	495,903	-0.11%
1997	88,100	88,298	-0.22%	2009	532,726	533,322	-0.11%
1998	101,055	101,264	-0.21%	2010	593,438	594,090	-0.11%
1999	111,385	111,603	-0.20%	2011	613,269	613,940	-0.11%
2000	119,007	119,232	-0.19%	2012	665,955	641,536	3.81%
2001	141,721	141,966	-0.17%				

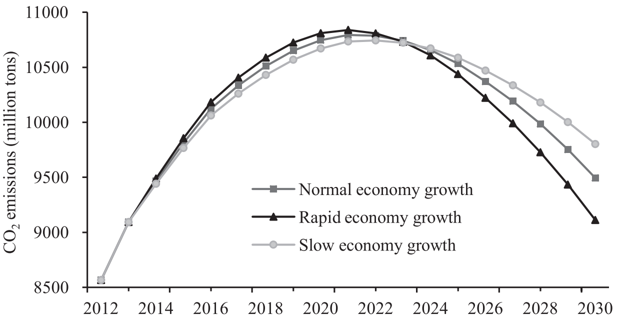


Fig. 3. CO_2 emissions under different GDP growth rates in China.

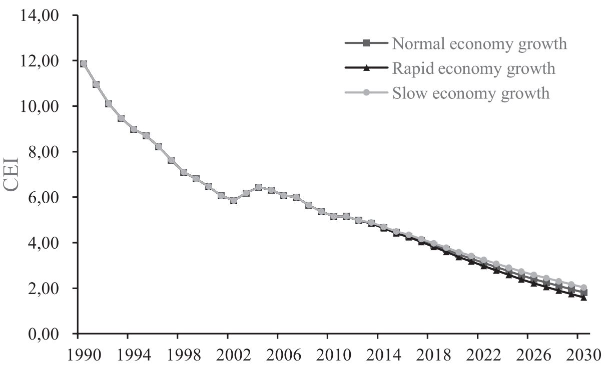


Fig. 4. CEIs under 3 different GDP growth rates in China.

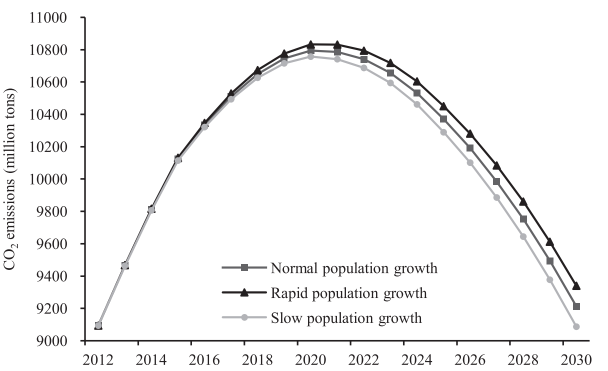
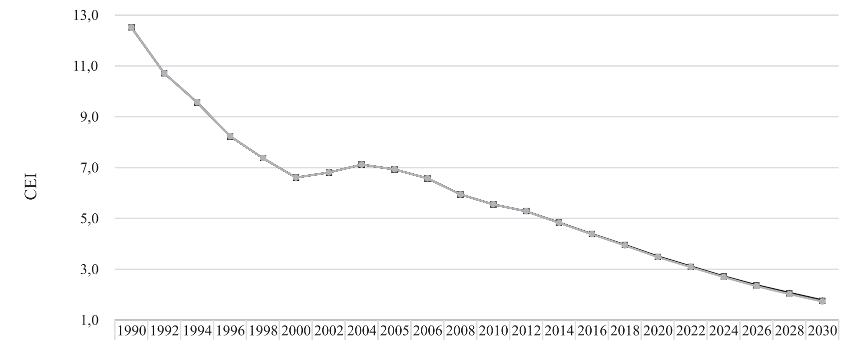


Fig. 5. CO_2 emissions under different population growth rates in China.

we designed 3 scenarios with different annual GDP growth rates: Scenario 1, normal economic growth; Scenario 2, rapid economic GDP growth of 0.5% greater than scenario 1; Scenario 3, the annual GDP growth rate is 0.5% lower than scenario 1. For the 3 scenarios, the population growth rate is set as 0.189% [63], and the percentage of renewable energy will increase to 22% in total energy use by 2030 [64]. The simulation results of CO_2 emissions and CEIs under different GDP growth rates are shown in Figs 3 and 4.

As per [63], Chinese total population in 2015 will reach 1.376 billion (real statistics is 1.37462 billion quoted from the National Bureau of Statistics of China) and it is predicted that in 2030 the gross population will reach its peak of 1.415 billion, followed by a decline to 1.348 billion in 2050. Thus the annual population growth rate is set at 0.189%, acting as the standard scenario. The study considered 3 population growth rates: Scenario 1 is the baseline scenario with annual population growth rate of 0.189%; Scenario 2 adds 0.05% to Scenario 1, so the rapid population growth is 0.239%; Scenario 3 subtracts from scenario 1 with 0.05%, and the slow population growth is 0.139%. To evaluate how population growth will influence CO_2 emissions, the economic growth and energy structure are set as the baseline scenario where the GDP growth rate is set as 5% [62] and renewable energy will reach 22% of total energy consumption by 2030 [64]. Figs 5 and 6 show the simulation results under different population growth rates.

According to [64], until 2020 the occupation of coal, gas, oil, and renewable energy in China will be 60%, 10%, 15%, and 15%, respectively. In 2030 the percentage of coal is going to be 49%, while the occupation of gas, oil, and renewable energy is believed to rise to 12%, 17%, and 22%, respectively. At the beginning of the prediction part of simulation (2012), coal explained 66.6% of the total energy consumption, while oil, gas, and renewable energy took 18.8%, 5.2%, and 9.4%, respectively. In our simulation, from 2012 to 2020, the percentage of coal ought to be lowered by 0.82% annually and the oil will also be decreased by 0.475%. Then the consumption of gas and renewable energy is expected to increase by 0.6%



	1990	1992	1994	1996	1998	2000	2002	2004	2005	2006	2008	2010	2012	2014	2016	2018	2020	2022	2024	2026	2028	2030
Normal population growth	12,5	10,7	9,6	8,2	7,4	6,6	6,8	7,1	6,9	6,6	5,9	5,6	5,3	4,8	4,4	3,9	3,5	3,1	2,7	2,4	2,0	1,8
Rapid population growth	12,5	10,7	9,6	8,2	7,4	6,6	6,8	7,1	6,9	6,6	5,9	5,6	5,3	4,8	4,4	4,0	3,5	3,1	2,7	2,4	2,1	1,8
Slow population growth	12,5	10,7	9,6	8,2	7,4	6,6	6,8	7,1	6,9	6,6	5,9	5,6	5,3	4,8	4,4	3,9	3,5	3,1	2,7	2,3	2,0	1,7

Fig. 6. CEIs under 3 different population growth rates in China.

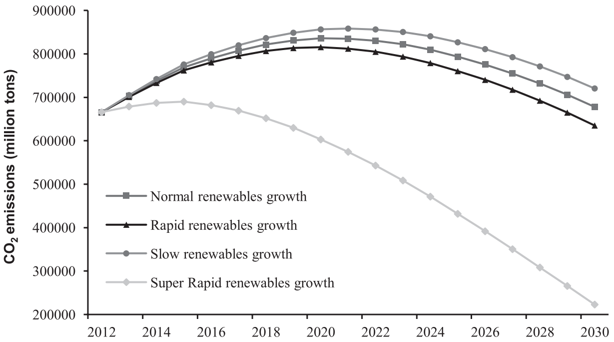


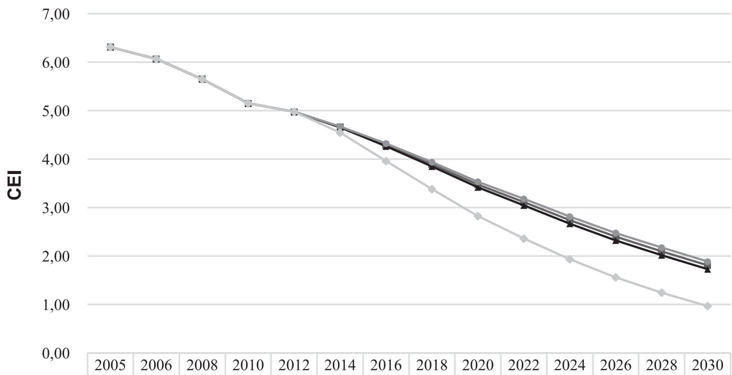
Fig. 7. CO_2 emissions under different scenarios of energy structures in China.

and 0.7% per year. From 2020 to 2030, the proportion of coal will be reduced by 1.1% annually, while oil, gas, and renewable energy will increase by 0.2%, 0.2%, and 0.7%. Under which circumstance where coal, oil, and gas are measured by standard coal, so in this paper coal, oil, and gas are all converted into standard coal, then the energy structure can be calculated by two parts, such as standard coal and renewable energy. Thus, we can set the scenarios in terms of standard coal and renewable energy. Scenario 1: the standard scenario where the trend of coal and renewable energy consumption is the same as that described in "China Energy Outlook" [64]. Scenario 2: the more eco-friendly scenario is set as that the coal consumption is annually replaced by other energy at the rate of 1.02% for 2012-2020 and 1.3% for 2021-2030, while the average annual increasing percentage of renewable energy is set as 0.9% for 2012-2030. Scenario 3: the renewable energy slowly developing scenario, where the proportion of coal is expected to annually decrease by 0.62% for 2012-2020 and 0.9% for 2021-2030, while the renewable energy will annually increase by 0.5% from 2012-2030. To further the analysis of how energy structure will influence CO_2 emission reduction, the rapid growth of renewable energy is considered in scenario 4, namely the percentage of coal will equably decrease from 66.6% to 10.41%, and the proportion of renewable energy will increase to 61.20% in 2030. In the 4 energy structure scenarios, the annual GDP growth rate is 8.6% for 2012-2015, 7% for 2016-2020, 5.9% for 2012-2025, and 5% for 2026-2030 [62], and the annual population growth rate is set as 0.189% for 2012-2030 [63]. Figs 6-7 exhibit the simulation results under different energy structures.

Discussion

As to 3 GDP growth scenarios, China's CO_2 emissions follow the inversed U-type curve in which CO_2 emissions first increased then after its peak point will decrease from 2012 to 2030 (Fig. 3). Generally speaking, the higher the economic growth rate, the earlier the CO_2 emissions turning point will come. More specifically, in Scenario 2 with rapid GDP growth, CO_2 emissions will come to its peak of 10,839 million tons in 2021, and in Scenario 1 with the baseline of GDP growth, CO_2 emission also achieve its peak of 10,794 million tons, which is slightly lower than Scenario 2. While in slow economic growth (Scenario 3), the peak of CO_2 emissions in 2022 with 10,743 million tons is smaller than the peaks in Scenarios 1 and 2. In all 3 scenarios, the decline trend of CO_2 emissions appears after peak year. In Scenario 2, where in 2020 CO_2 emissions will decrease by 1,727 million tons compared to 2030, the decline of CO_2 emissions is the most significant. In Scenario 3, however, with slow economic growth, the decline of CO_2 emissions is also slower. More specifically, the CO_2 emissions in 2030 will be 9,802.18 million tons, and the decrease of 941.67 million tons than the peak value in Scenario 3 is only around half that of Scenario 2.

As can be seen from Fig. 4, under the normal economic growth scenario, the CEI will drop from 6.31 in 2005 to 3.48 in 2020, accounting for 55.07% of 2005 levels, and achieve its policy goal; the CEI in 2020 is 3.37 under



	2005	2006	2008	2010	2012	2014	2016	2018	2020	2022	2024	2026	2028	2030
Normal renewables growth	6,31	6,07	5,65	5,15	4,98	4,66	4,29	3,89	3,48	3,11	2,74	2,40	2,10	1,81
Rapid renewables growth	6,31	6,07	5,65	5,15	4,98	4,65	4,26	3,85	3,42	3,05	2,67	2,32	2,02	1,73
Slow renewables growth	6,31	6,07	5,65	5,15	4,98	4,67	4,32	3,94	3,53	3,18	2,81	2,48	2,17	1,89
Super rapid renewables growth	6,31	6,07	5,65	5,15	4,98	4,55	3,96	3,38	2,83	2,36	1,93	1,56	1,25	0,97

Fig. 8. CEIs under 4 different scenarios with energy structure in China.

rapid economic growth, which is only 53.38% of that in 2005, beyond policy expectation. In the slow economic growth scenario, the CEI will be 3.58 in 2020, lowered by 43.24% than 2005 level and also achieve the policy goal. Thus, in 2020, under all 3 economic growth scenarios, the policy target that the CEI in 2020 will be reduced by 40-45% than 2005 levels can be achieved. In 2030 the CEI of normal economic growth, rapid economic growth, and slow economic growth scenario is 1.81, 1.59, and 2.03, respectively, accounting for 28.62%, 25.24%, and 32.14% of 2005 levels. This means that, under all 3 economic growth scenarios, the CEIs will meet the policy goal that in 2030 the CEI will be lowered by 60-65% compared to 2005 levels.

With regard to scenarios of population growth, from Fig. 5 we can find that the CO_2 emissions in rapid population growth is always higher than other scenarios, which means the abolition of a single-child policy will to some degree slow down the reduction of CO_2 emissions. It can be explained that population growth can bring more energy consumption and will accelerate CO_2 emission growth when the energy structure and energy utilization efficiency remain unchanged. Furthermore, for the same level of GDP, a higher growth rate of population will cut down the per capita GDP, and then the decline trend of CO_2 emissions will be gentler based on the description of the ECK model.

The simulation results in Fig. 6 exhibit that, under normal population growth, the CEI is 3.49 in 2020, lowered by 49.6% over 2005 levels, reaching the policy goal; under rapid population growth, counting as 50.57% of 2005 levels, the CEI in 2020 is 3.50 and also achieves the policy goal; under the slow population growth scenario, accounting for 50.22% of 2005 levels, the CEI in 2020 will be 3.48, which also meets the emission reduction target. Thus in 2020 all three population scenarios will reach the policy target. In 2030, the CEIs of normal, rapid, and slow population growth will respectively lower to 1.75, 1.78, and 1.73, equaling 25.30%, 25.65%, and 24.96% of 2005 levels, which means that all scenarios can reach the policy target.

As to energy structure scenarios, Fig. 7 shows that the CO_2 emissions in scenarios 1, 2, and 3 all obey the inverted U-type curve, which first increases to its peak before declining to the end of the simulation period. More specifically, the percentage of renewable energy weighs more in total energy consumption, and the lower the CO_2 emission peak and the sooner the turning point will come. Thus replacing fossil energy with renewable energy is an effective method to reduce CO_2 emissions, especially for Scenario 4, where CO_2 emissions plunge after the peak year, and there is only 2,230 million tons of CO_2 in 2030. The simulation results reflect that optimizing the energy structure by striving to develop renewables will significantly reduce CO_2 emissions, which correspond with some relevant studies.

From Fig. 8, we can find that the CEI in 2020 is 3.48 for the baseline scenario, 3.42 for Scenario 2, 3.53 for Scenario 3, and 2.83 for Scenario 4, respectively representing reductions of about 44.85%, 45.80%, 55.15%, and 44.06% from the 2005 level of 6.31. Obviously, the CEI reduction target in 2020 would be achieved in all scenarios of energy structures. The decreases of CEI in scenario 4 even surpass the 45% ceiling of reduction target in 2020. By 2030, the CEI is respectively 1.81 for Scenario 1, 1.73 for Scenario 2, 1.89 for Scenario 3, and 0.97 for Scenario 4, representing reductions of 71.32%, 72.58%, 70.05%, and 84.63% over the 2005 level of 6.31, which suggests that China could meet the policy goal in 2030 under all scenarios of energy structures.

Conclusions

This study aims at ascertaining the feasibility of whether China can achieve the carbon emissions intensity (CEI) reduction goal by 2030 and when China will achieve its CO_2 emissions peak, which has created great concern in the international community. To this end, we proposed an LMDI-based system dynamics model to illuminate the evolving process of China's CO_2 emissions and predict its evolution trend under various scenarios combining different GDP growth rates, combinations of energies, population growth rates, etc. The simulation results show that China's CO_2 emissions would peak sometime between 2020 and 2025 with 8,157-10,839 million tons, and China's CEI will decrease by about 43.23-55.15% in 2020 and 67.86-84.63% in 2030 compared to the 2005 level, which suggest that, as long as China can keep the normal development of the economy, population, renewables, etc., China can achieve the CO_2 emission mitigation goal in 2020 and 2030. The findings also indicate that the larger the proportion of renewables weighs in total energy use, the earlier the CO_2 emissions will peak and the lower the peak value will be. However, in order to realize the coordination between economic growth and CO_2 emission reduction, the government should strengthen macro-economic control and replace fossil fuels (especially coal) with renewables at a suitable growth rate to avoid an over-rapid economic depression and great social pressure due to a dramatic CO_2 emission mitigation.

By contrast with the previous studies pertaining to China's CO_2 emission mitigation target, there are the same conclusions for whether China can realize the emission mitigation target; however, the CO_2 emissions will peak earlier with different values presented in this study. In summary, this work enriches the methods for systematically analyzing CO_2 emissions by combining system dynamics and LMDI, which is of important practice implications for facilitating the policy planning and regulation of CO_2 emission mitigation and further boosting the coordination between economic growth and CO_2 emissions reduction. Offering a realistic platform for estimating CO_2 emissions, the proposed model can be implemented with minor adjustments by other countries to test their scenarios related to CO_2 emissions and identify the influence factors that may be responsible for

CO_2 emissions, and then policymakers can understand the evolution of CO_2 emissions in order to enact effective policies or put forward suggestions for environmental protection. Furthermore, not only CO_2 emissions in the future can be estimated by this model, but also other environmental research topics from ecological and economic systems, environment sustainability, air and water pollution, etc. can be analyzed and predicted.

Considering the possible steps for China to hit the carbon peak goal by 2030 (strengthen regional emissions targets, improve the reporting and verification of emissions data, enhance the regulation and supervision of the nationwide emissions-trading market, and incentivize the uptake of green technologies, especially in underdeveloped regions) [65], more factors should be integrated in this model to find more comprehensive policy implications for promoting the coordination between economic growth and CO_2 emissions reduction, e.g. economic structure, the utilization efficiency of fossil energies, regional emissions targets, carbon emissions-trading, etc.

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