Research of CO_2 emissions based on system dynamics model

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Abstract. In recent years, with the continuous development of China, the economic level has been rapidly developed, and the comprehensive strength has made tremendous progress. However, at the same time, the negative impacts caused by excessive exploitation of natural resources have also followed one after another. The imbalance of the ecosystem has also had a huge negative impact on the national economy, social construction and other aspects. This paper starts with a social survey questionnaire, summarizes the data, analyzes the importance that social citizens attach to ecosystem construction, and proposes effective measures. Then, starting from objective data, several main influencing factors of CO_2 emissions were analyzed. The impact of the digital economy on CO_2 emissions was simulated and predicted through the construction and analysis of system dynamics models.

Keywords: Ecological construction, System dynamics model, Green and low-carbon.

1. Introduction

In the 21st century, the earth seems to be constantly evolving towards the ideal state of human civilization.During the period, however, the concept of "mutual benefit and symbiosis between man and nature" has been blindly forgotten, and people have to face the tragic situation of rapid deterioration of the environment. The concept of "Beautiful China" was first proposed in 2012 and the urgent need to give prominence to the construction of ecological civilization was emphasized. Carbon emissions can be used as an important indicator to measure the status of ecological environment governance. Only by instilling the concept of environmental protection in the hearts of the people can a strong synergy be formed to protect the environment and build a good ecosystem. At the same time, in-depth analysis of various factors affecting carbon emissions can fundamentally alleviate the carbon emission problem. In the early stage, the members of the group developed and distributed an environmental awareness questionnaire to the public, collected a wide range of public views, and presented the data in the form of text and statistical charts. In the later stage, the fitting model is established through the analysis of various factor characteristics, the simulation prediction is carried out. Compared with the traditional model, we creatively introduces the system dynamics model. They are more accurately and intuitively used to fits the impact of Chinese digital economy on carbon emissions. As a result, we put forward creative ideas and innovative views on the effective governance of carbon emissions through the model.

2. Preliminary

2.1. Questionnaire method

The questionnaire method is used as the main method in this survey report, supplemented by the interview method. Questionnaires are produced on the Internet and distributed through social media such as QQ and WeChat. They are released to randomly interview passers-by on and off campus. The content of the interview was basically the same as the content of the questionnaire offline. The questionnaire is distributed on March 24, 2023, and the collection time falls on March 29, 2023. The entire process of the investigation lasted five days.

The questionnaire was released to the public, and 509 questionnaires were finally returned, of which 478 were valid. The statistical chart is shown in Figure 1. According to the statistical results, men accounted for 37.34% and women accounted for 62.66% among the valid filling times. women accounted for more. In the statistics of the age group, the maximum age of the filler is generation X(60s) and the minimum age is generation Z(10s). The post-60s to post-10s age groups accounted for 2.53%, 12.03%, 5.06%, 0.63%, 73.42% and 6.33% of the total sample respectively. It can be seen that the number of post-90s fillers is the smallest, and the number of post-00s is the largest,accounting for the majority, which can also reflect the strong interest of post-00s (students) in such questionnaire. In terms of education data, taking into account the epochality of educational level, 14.56% of the questionnaire respondents were junior high school students and below, 32.28% were among high school/technical secondary school/vocational education, 50% were undergraduate/junior college, and 3.16% were graduate students and above. Undergraduate and junior college students occupy the largest number,and the proportion of graduate students and above is the smallest. This data objectively reflects the breadth and diversity of the survey group, and the sample size is large. According to the statistical principle, with 95% confidence, the survey data is basically valid and can be used as a valid sample to estimate the overall characteristics.

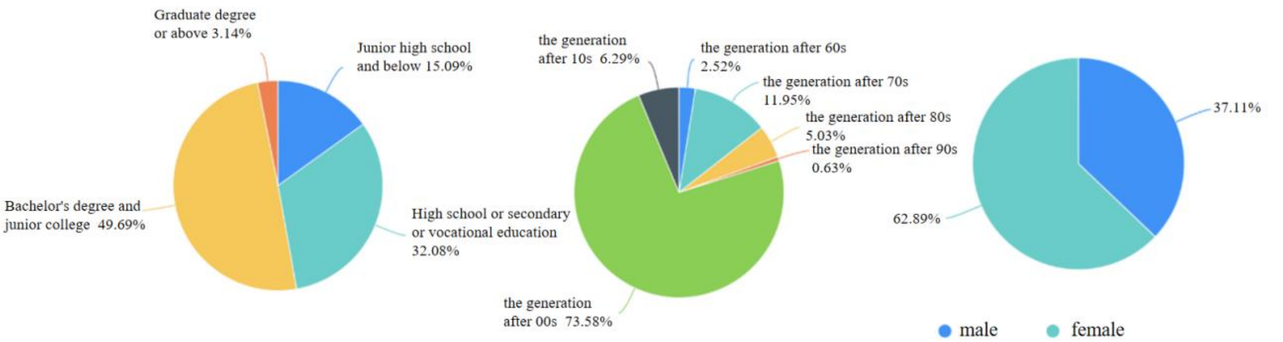


Figure 1. Data analysis of survey respondents

2.2. Sample CSI(Customer Satisfaction Index) questionnaire scoring system

"Satisfaction" is an index concept that measures satisfaction by weighting the evaluation score. The internationally accepted evaluation standard is CSI (User Satisfaction Index).The purpose of the assessment is to grasp the current situation of satisfaction, help customers focus limited resources on the aspects that customers value most so as to establish and enhance customer loyalty and retain customers.

This survey report is sampled with CSI criteria to form a scoring table for more intuitive observation of survey data.

2.3. Questionnaire scoring table

Based on the original data of the questionnaire, this group sampled the CSI criteria, and the options of each question in the questionnaire were converted into different scores according to the environmental protection concept and awareness level of the survey audience, and paid attention to the summation to obtain the overall data of the questionnaire scoring system.

To facilitate comparison, the group set the total score to 100 points, of which the maximum score for each of the 9 objective questions was 10 points. If there are three options for objective questions, they are set to 10 points and 6 points respectively according to the severity and severity. If the objective question has two options, it will be divided into 10 points and 6 points according to its severity.

Given the statistical results, the statistics of the final score part are shown in Figure 2.

gender	age	degree	Consciously conserve resources	Choice of chopsticks	Eco-friendly bags	Garbage sorting	Collect used batteries	Caring about environmental issues
female	00	high school	10	10	6	6	2	Occasionally
female	00	high school	10	10	6	6	2	Occasionally
female	00	high school	10	6	6	10	2	Occasionally
female	00	high school	10	10	10	10	10	Occasionally
male	00	middle school	10	10	10	10	10	Occasionally
male	00	high school	10	6	2	6	2	Occasionally
female	00	high school	10	10	2	6	2	Occasionally
female	00	university	10	10	6	6	2	Occasionally
male	00	high school	10	10	10	6	2	Occasionally
female	00	high school	10	10	6	10	10	Always
female	00	university	10	10	2	10	2	Always
female	00	high school	10	10	10	10	2	Always
female	00	high school	10	10	10	10	10	Always
male	00	university	10	10	6	10	2	Occasionally
female	00	university	6	10	6	10	2	By chance
male	00	university	10	10	2	10	2	Always

Figure 2. Partial statistical results of the scoring te

According to the total score obtained by each person, the self-presentation awareness and environmental awareness of the respondents were divided into four levels as explicit variables, and the division criteria were as follows——90-100 is excellent, 80-89 is good, 70-79 is fair, and 60-69 is unqualified.

In the statistical sample, 57 people had excellent environmental awareness, accounting for about 12%. The number of people who reached good was 153, approximately 32%. There were 173 people who reached the level of justice, accounting for about 36%. The number of unqualified people was 96, accounting for 20% of the total sample. It can be seen that the vast majority of the public still has a certain level of understanding of the environment, but it is difficult to go deeper.

2.4. Analysis of relevant factors

In statistics, the Pearson correlation coefficient measures the linear correlation between the sum of two variables, with values between -1 and 1. In the natural sciences, this coefficient is widely used to measure the degree of linear correlation between two variables.

Based on the collected data, a Pearson correlation analysis was carried out to produce a thermal map of the above factors and CO_2 emissions. The result was shown in Figure 3.

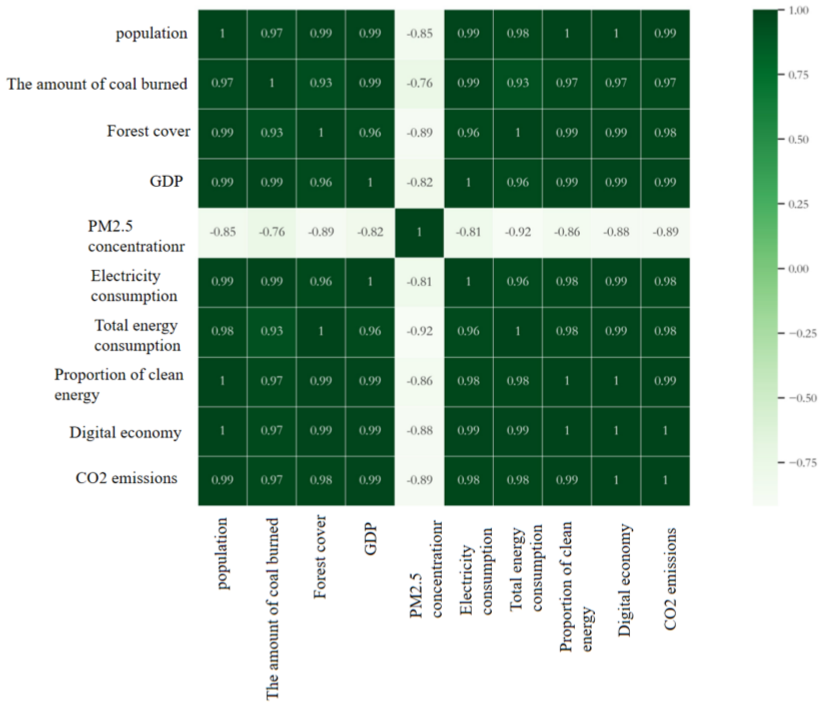


Figure 3. Heat map of factors related to CO_2 emissions

It can be seen from the figure that the Pearson correlation coefficient of CO_2 emissions and its influencing factors is almost between 0.8 and 1.0, indicating that they are both strongly correlated. Among them, the Pearson correlation coefficient between CO_2 emissions and the digital economy reached 1, indicating that its change trend is almost exactly the same as the change trend of CO_2 emissions. In order to achieve the goal of green and low-carbon, the government and the people should work together in the above mentioned aspects to jointly promote energy conservation and carbon reduction, and achieve carbon peak and carbon neutrality at an early date.

3. A system dynamics model of CO_2 emissions from the digital economy

The increase in fossil energy consumption has led to a sharp increase in CO_2 emissions. Global warming caused by CO_2 emissions is a huge threat to the global environment, production and life [1]. Reducing CO_2 emissions is critical to sustainable development. It is an urgent policy challenge worldwide.

The government has issued a series of implementation plans for carbon peaking and established a "1+N" CO_2 policy system. The policy recommends accelerating the application of digital technologies such as big data, 5G, and artificial intelligence in green and low-carbon industries. The digital economy has become a key force for China to achieve its carbon peaking and carbon neutrality goals and sustainability. The digital economy has a complex impact on CO_2 emissions. On the one hand, it can reduce CO_2 emissions caused by fossil energy combustion, stimulate green technology innovation, optimize energy structure and use efficiency, and contribute to sustainable development[2]. On the other hand, the more electricity and energy it consumes itself, putting more pressure on China's sustainable development[3]. Past studies have barely addressed the impact of the digital economy on CO_2 emissions, or the difficulty of predicting multiple indicators in complex situations.

3.1. System dynamics model

The system dynamics model (SD model) was proposed by Professor J.W. Forrester in 1956. This theory is based on feedback theory, with computer simulation technology as the main method, which can analyze nonlinear, high-order and multi-feedback problems of complex time-varying systems, which is helpful to study the interaction and dynamic evolution between different factors [4]. Figure 4 shows the research framework diagram of the system dynamics model.

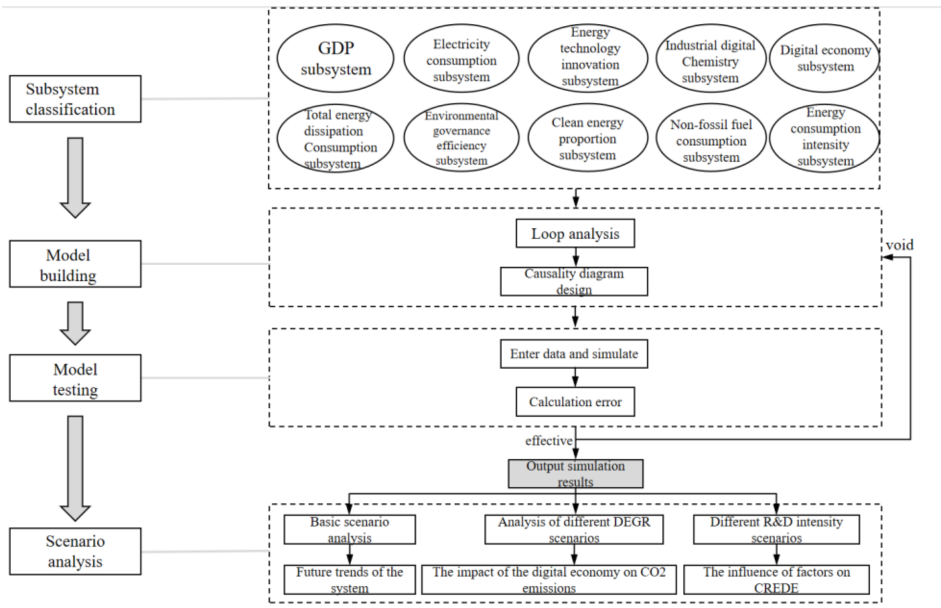


Figure 4. System dynamics model study framework diagram

(1) Subsystem classification

Based on the previous article and the available literature, this section divides the factors influencing CO_2 emissions into ten subsystems as shown in Figure 4.

(2) Model establishment

Based on the subsystem classification, this section quantifies the impact of the digital economy on CO_2 emissions, and its causal circuit is shown in Figure 5, where "+" means that the two variables have the same trend and "-" means that the two variables have opposite trends.

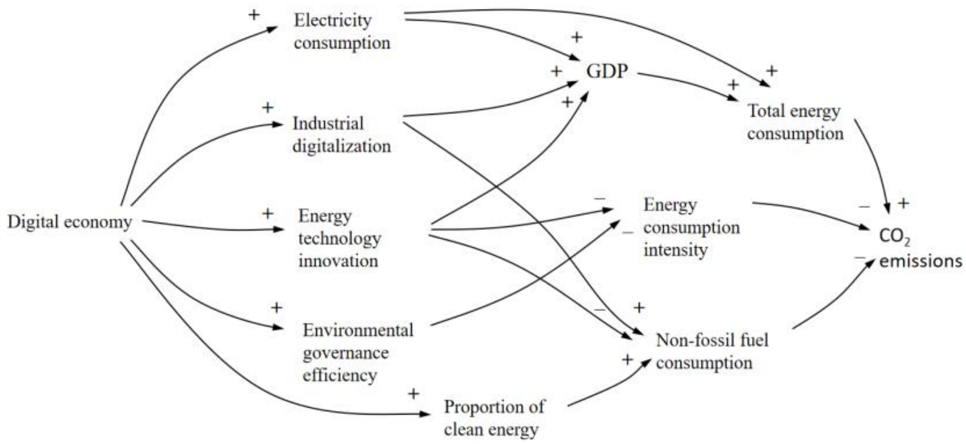


Figure 5. Diagram of the causal circuit of the digital economy

1. Digital economy → + electricity consumption/industrial digitalization/energy technology innovation→ + GDP → + total energy consumption → + CO_2 emissions. The production and use of digital products, the construction and operation of telecommunications infrastructure have greatly increased electricity consumption[5], according to the European Commission, digital industry accounts for 5-9% of total global electricity consumption[6]. There is a complementary relationship between capital accumulation, economic growth and energy consumption, so that the growth of the digital economy can increase the digitalization of industry. It has been documented that the application of digital technology in the energy field can promote energy technology innovation[7]. And when technological innovation, industrial digital products and infrastructure are improved, GDP must also increase. As a result, economic growth increases total energy consumption in the process of production, which in turn leads to an increase in CO2 emissions.
2. Digital economy → + environmental governance efficiency→ - energy consumption intensity → + CO_2 emissions. Digital technology helps the government establish an ecological environment data information management system, implement policies related to non-fossil energy development, and strengthen cooperation among government departments, thereby improving the efficiency of government environmental governance[8]. After the government's environmental management efficiency improved, the energy consumption intensity can be reduced accordingly, thereby reducing CO_2 emissions.
3. Digital economy → + proportion of clean energy → + non-fossil fuel consumption →-CO_2 emissions. The application of digital technology in the field of energy innovation makes the access and use of clean energy more convenient, while national policies and people's green and low-carbon awareness increase the proportion of clean energy in energy consumption. The increase in the proportion of clean energy can promote the acceptance and stability of non-fossil energy[9], improve its utilization and transportation efficiency, and reduce production costs, thereby promoting the development of non-fossil energy. The development of non-fossil energy sources has made people less dependent on fossil fuels, thereby reducing CO_2 emissions
4. Digital economy → + industrial digitalization/energy technology innovation→ + non-fossil fuel combustion →-CO_2 emissions. As in 1, the digital economy can promote the digitalization of

industry and the development of energy technology innovation. According to the 2020 Renewable Energy Generation Report[10] released by the International Renewable Energy Agency (IRENA), the cost of global grid-connected, large-scale solar photovoltaic power generation fell by 85% between 2010 and 2020, making it possible to replace coal power generation with large-scale renewable energy. CO_2 emissions are reduced when non-fossil fuels or renewable energy replace some fossil fuels.

(3) Model testing

In the causal circuit diagram of the system dynamics model, the simulation period is from 2023 to 2040 with a step size of 1 year. Considering the availability of data, we have selected historical data for China from 2010 to 2022. The relevant historical data on digital economy and industrial digitalization mainly comes from the "White Paper on the Development of China's Digital Economy" released by CAIT. Other data, such as GDP, energy consumption, population, etc., mainly come from the National Bureau of Statistics[11], China Statistical Yearbook[12] and China Energy Statistical Yearbook[13].

In order to ensure the reliability and accuracy of the system dynamics model, we test the true values of the data from 2010 to 2022 for relative error. The expression for relative error is:

$$e_t = \frac{|F_t - H_t|}{H_t} \times 100\% \tag{1}$$

where F_t is the analog value of year t, H_t is the true value of year t, and e_t is the relative error value of year t. The smaller the e_t, the better the fitting of the system dynamics model.

(4) Scenario analysis

After the model is verified, different research scenarios can be designed according to the research objectives and the corresponding simulation results can be output. This topic sets up the following scenarios:

1. Base scenario: The underlying scenario assumptions are unlimited, and each factor will be derived from a reasonable analysis of trends in historical data. Based on historical data, trend projections from 2023 to 2040 are mainly derived from ARIMA models.
2. Different DEGR (Digital Economic Growth Rate) scenarios: In order to discuss the impact of the digital economy on CO_2 emissions, the function expression of DEGR in the base scenario can be adjusted appropriately. Based on the base scenario, this paper designs that DEGR decreases by 1%, 2%, and 3% (DEGRs are 8%, 7%, and 6%, respectively), and increases by 1%, 2%, and 3% (DEGRs are 10%, 11%, and 12%, respectively). In addition, in order to facilitate comparative analysis with the base scenario, other parameters in the system are consistent with the base scenario.

3.2. Simulation results and discussion

3.2.1 Model validity validation

We use Vensim to simulate the system dynamics model and calculate to validate it. Due to space constraints, Table 1 shows only test results for core variables, including digital economy (DE), total energy consumption (TEC), and CO_2 emissions. As can be seen from Table 1, from 2010 to 2022, the values of DE, TEC and CO_2 emissions were basically controlled within 5%, and their MAPE was 0.00%, 3.47% and 3.52% respectively, all within 5%. In addition, to fully verify the reliability of the model, we calculate the root mean square error (RMSE) of the prediction. The RMSE for DE, TEC and CO_2 emissions is also low, so the accuracy of the model is higher.

Table 1. Simulation results and relative errors

	Digital economy/trillions			Total energy consumption/100 million tons of standard coal			CO2 emissions/100 million tons		
year	F_t	H_t	$e_t(\%)$	F_t	H_t	$e_t(\%)$	F_t	H_t	$e_t(\%)$
2010	7.93	7.93	0.00	34.81	36.06	3.47	79.13	81.29	2.66
2017	27.20	27.20	0.01	46.30	45.58	1.58	99.54	95.97	3.72
2018	31.30	31.30	0.01	49.31	47.19	4.49	105.18	97.91	7.43
2019	35.80	35.80	0.01	50.13	48.75	2.83	105.70	99.88	5.83
2020	39.20	39.20	0.00	48.47	49.83	2.74	100.61	101.16	0.55
2021	42.80	42.80	0.01	49.74	50.92	2.32	102.98	103.79	0.78
2022	45.92	45.92	0.00	51.97	52.03	1.15	104.25	104.82	0.54
MAPE		0.00			3.47			3.52	
RMSE		0.00			1.46			3.75	

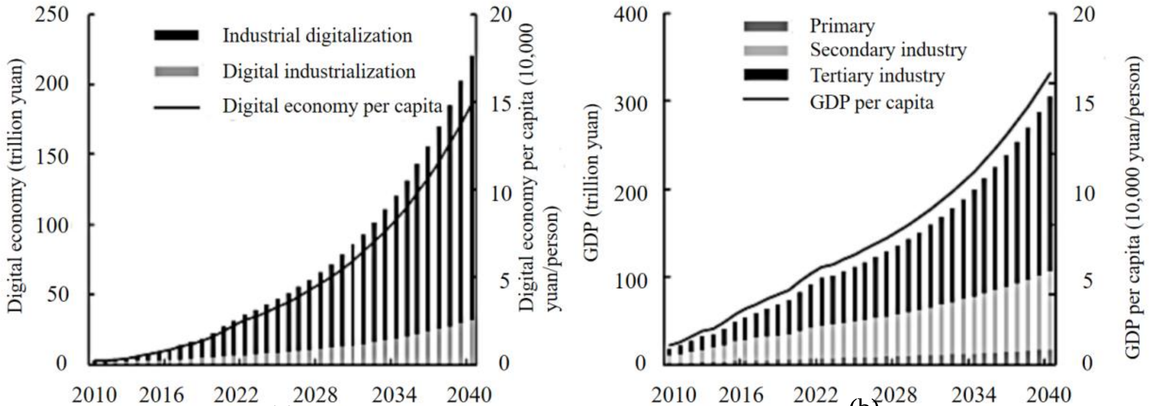
4. Analysis of development trends under the research results

After the system simulation prediction and its reliability test, we carried out the research on the analysis of development factors under different factor subsystems, and obtained the analysis results and realistic response policies.

4.1. Development trend analysis of basic scenarios

4.1.1 Analysis of the development trend of digital economy subsystem

The simulation results of the core variables in the digital economy subsystem under the basic scenario are shown in Figure 6. The core variables in the digital economy subsystem showed a rapid growth trend during the period from 2010 to 2040. From 2023 to 2040, the average annual growth rates of digital economy, industrial digitalization, per capita digitalization, per capita GDP, primary industrial GDP, secondary industrial GDP, tertiary industrial GDP and per capita gross output value will reach 9%, 7.6%, 8.8%, 5.7%, 4.2%, 4.3%, 6.6% and 5.4% respectively. As shown in Figure 6(a), by 2040, the value of digital economy, digital industrialization and industrial digitalization will be 220.19 trillion yuan, 32.15 trillion yuan and 188.04 trillion yuan separately, which is about 4.80 times, 3.79 times and 4.93 times that of 2022. By 2040, digital industrialization and industrial digitalization will account for 15% and 85% of the digital economy respectively, and industrial digitalization will become a key driving force for the development of China's digital economy.



(a) (b)

Figure 6. Simulation results of the digital economy subsystem

It can be seen from Figure 6 (b) that secondary industrial GDP and tertiary industrial GDP will get to 305.73 trillion yuan, 1773 trillion yuan, 88.66 trillion yuan and 199.34 trillion yuan respectively, which are 2.53 times, 2.01 times, 2.12 times and 2.93 times that in 2022. In 2040, the per capita GDP will reach 207,700 yuan, and the digital economy, digital industrialization and industrial digitalization will account for 72%, 10.5% and 61.5% of GDP respectively, which means that the digital economy may take charge of the economic growth.

4.1.2 Analysis of the development trend of energy consumption subsystem

The digital economy has an important impact on the energy industry. The simulation results of the core variables in the energy consumption subsystem under the basic scenario are shown in Figure 7. As can be seen from Figure 7(a), total energy consumption is on an upward trend between 2010 and 2040. From 2023 to 2040, the average annual growth rates of total energy consumption, industrial energy consumption, residential energy consumption and per capita energy consumption will be 2.16%, 3.92%, 1.84% and 1.94% separately. By 2040, the standard coal equivalent of total energy consumption, industrial energy consumption and residential energy consumption will be 7.485 billion tons, 6.102 billion tons and 1.383 billion tons. Energy consumption will be 5.08 tonnes per capita.

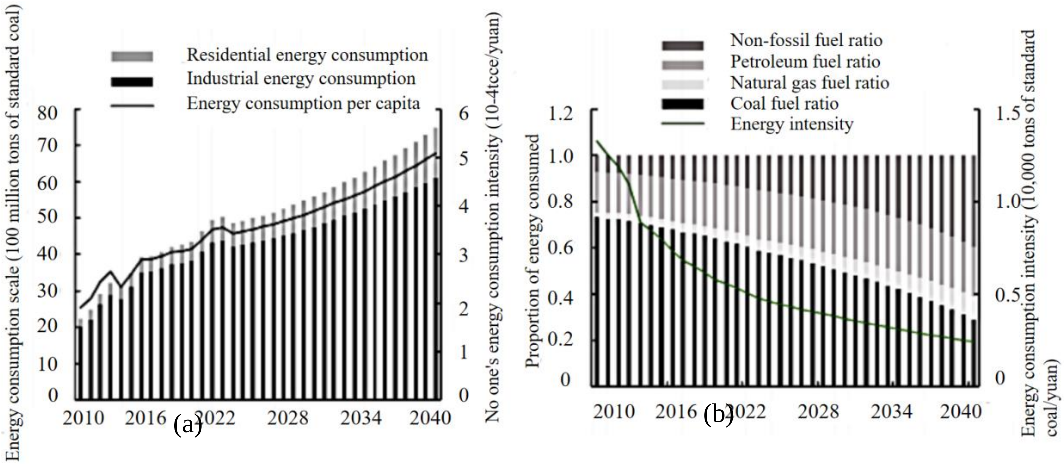


Figure 7. Simulation results of the energy consumption subsystem

As can be seen from Figure 7(b), the proportion of coal consumption will show a downward trend between 2023 and 2040. The share of petroleum fuels will peak in 2033 at about 23.2%. The proportion of natural gas fuels and non-fossil fuels is on the rise. By 2040, the share of coal, oil, natural gas and non-fossil energy consumption will be 29.2%, 21.2%, 10.02% and 39.6%, respectively.

4.1.3.Analysis of the development trend of CO_2 emission subsystem

The simulation results of the core variables in the CO_2 emission subsystem under the basic scenario are shown in Figure 8. As can be seen from Figure 8(a), CO_2 emissions and per capita CO_2 emissions increased rapidly and then decreased in general between 2010 and 2040. CO_2 emissions would peak in 2034 at around 10.79 billion tonnes. If we want to peak carbon emissions before 2030, special efforts are still needed to increase green and low-carbon efforts. As is depicted in Figure 8(b), CO_2 emissions from coal are on a downward trend during the period 2023-2040. CO_2 emissions from oil will peak in 2039 at around 3.307 billion tonnes. CO_2 emissions from natural gas are on the rise. Compared with 2010, the CO_2 emissions of natural gas will increase by 3.66 times by 2040. This phenomenon mainly results from the increase in natural gas consumption due to the promotion of natural gas as it replaces more coal and oil with digital technology and environmental protection policies.

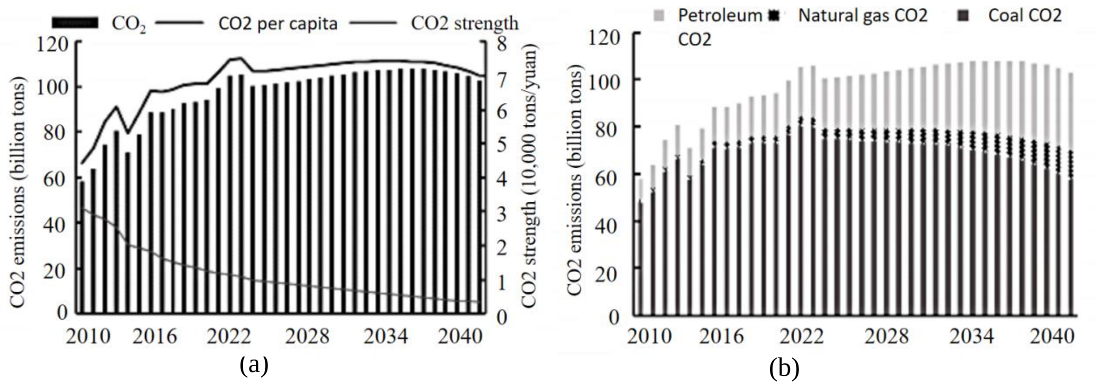


Figure 8. Simulation results of the CO2 emission subsystem

4.2. Development trend analysis of different DEGR and R&D scenarios

This paper sets up different DEGR scenarios to discuss the impact of the digital economy on CO_2 emissions. Some of the simulation results are shown in Figure 9.

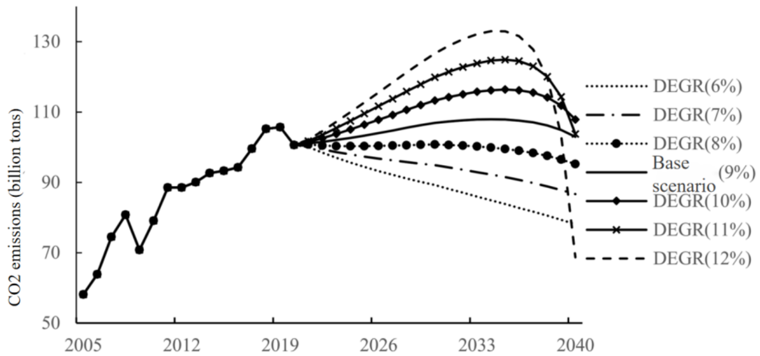


Figure 9. Simulation results for different DEGR scenarios

CO_2 emissions will always be lower than in the base scenario during the period 2023-2040 when the DEGR is lower than the base scenario. The downward trend in CO2 emissions is the same as that of DEGR. When the DEGR is higher than the base scenario, CO_2 emissions are first higher than the base scenario and then lower than the base scenario. After 2038, CO2 emissions will be lower than the base scenario, or even below the 6% DEGR scenario, which means that the impact of the digital economy on CO_2 emissions is beginning to become significant. Therefore, under the low level of the digital economy, the growth of the digital economy increases CO_2 emissions, and at the high level of the digital economy, CO_2 emissions can be significantly reduced.

4.3. policy recommendations based on social level

(1) By 2040, the scale of digital economy, digital industrialization and industrial digitalization will reach 220.19 trillion yuan, 32.15 trillion yuan and 188.04 trillion yuan, accounting for 72%, 10.5% and 61.5% of GDP respectively. CO_2 emissions will peak in 2034 at around 10.79 billion tonnes. In 2025 and 2030, the share of non-fossil energy consumption will be 18.47% and 23.18% respectively, and more efforts will be needed to achieve the goal of carbon peaking.

(2) From 2023 to 2040, when the DEGR is lower than the base scenario, CO_2 emissions will always be lower than the base scenario. The downward trend in CO2 emissions is the same as that of DEGR. When the DEGR is higher than the base scenario, CO_2 emissions will be first higher than the base scenario and then below the baseline scenario. This shows that there is an inverted U-shaped relationship between the digital economy and CO_2 emissions.

Based on the above analysis, this paper puts forward some policy recommendations.

(1) The government promotes the development of the digital economy and fully releases the dividends brought by the digital economy, and can build a "digital economy + CO_2" service platform

led by the government and digital enterprises. Using digital technology to comprehensively analyze the status quo and future development trends of various factors such as digital economy, energy supply and consumption, climate, and environmental quality will promote the digital industry and digital infrastructure to be more intelligent, efficient, low-carbon and sustainable.

(2) Increase the intensity of R&D and environmental investment. Governments need to coordinate and integrate strategic plans for R&D investment, environmental investment, digital economy and CO_2 investment. At the same time, in the relevant strategic planning of R&D investment and environmental pollution control, green digital technology, "digital economy + energy + CO_2" compound talents and digital governance should be supported.

5. Conclusion

In terms of low-carbon environmental protection, the most effective way to prevent global warming is to reduce carbon emissions. Therefore, on the basis of a preliminary understanding of citizens' awareness of environmental protection and ecological civilization construction, this paper conducts Pearson correlation analysis of the main influencing factors of CO_2 emissions, obtains its heat map, and finds that these factors are closely related to CO_2 emissions, of which the largest coefficient is the digital economy. This paper uses the system dynamics model to simulate the impact of China's digital economy on CO_2 emissions. The digital economy, energy consumption and CO_2 emissions from 2010 to 2040 are simulated, and through data mining and analysis, specific solutions and optimization measures based on different factors of carbon emissions are proposed. In the long run, it provides creative ideas for the effective mitigation of carbon emissions and the construction of a "beautiful China" ecological civilization.

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