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Simulation of Carbon Emission Reduction in Power Construction Projects Using System Dynamics: A Chinese Empirical Study

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Abstract: Power construction projects (PCPs) consume a large amount of energy and contribute significantly to carbon emissions. There is relatively little research on carbon emission reduction in PCPs, especially in predicting carbon emission reduction from a dynamic perspective. After identifying the influencing factors that promote the carbon emission reduction effect of PCPs, this study adopted a dynamic analysis method to elucidate the relationship between the variables. A quantitative carbon emission reduction system for PCPs with 51 variables was established using the system dynamics model, and the system simulation was performed using Vensim PLE software. Finally, a sensitivity analysis was conducted on four key factors: R&D investment, the prefabricated construction level, the scale of using energy-saving material, and the energy efficiency of transmission equipment. The results show that: (1) The reduction in carbon emissions from PCPs continues to increase. (2) R&D investment is the most significant factor for improving the carbon emission reduction in PCPs. (3) The value of the above four influencing factors should be increased within a reasonable range so that the four factors can work better to promote the carbon emission reduction effect of PCPs. This paper creatively proposes a dynamic prediction model for carbon emission reduction in the PCP, and the research results provide the scientific basis for government supervision and enterprise decision-making.

Keywords: carbon emission reduction; power construction project; system dynamics; simulation; sensitivity analysis

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1. Introduction

The power sector plays a significant role in climate change. The global carbon emissions of the power sector reached 13 billion tons, accounting for 38% of the total carbon emissions related to energy consumption, and they have continued to grow in recent years [1,2]. As the world's largest carbon emitter, China's power sector accounts for a high share of carbon emissions [3]. The "Annual Report on China's Carbon Neutralization and Clean Air (2021)" shows that the carbon emissions of the power industry exceed 40% of the total energy industry emissions. With the acceleration of urbanization, the demand for electricity consumption by various industries and by residents increases, increasing the number of power construction projects (PCPs) in China [4]. Due to its resource endowment, China's PCPs have to rely on traditional fossil fuels such as coal [5]. China's installed thermal power capacity will exceed 54% in 2021 [6], resulting in multiple impacts such as carbon emissions and atmospheric environmental pollution.

A PCP mainly involves power plants and substations, with many construction operation points, large-scale facilities, long construction cycles, and complex projects [7,8]. So, PCPs consume a lot of resources and produce a large amount of carbon emissions.

According to LCA theory, the carbon emissions of PCPs mainly include five aspects: the production phase, transportation phase, construction phase, operation and maintenance phase, and disposal and recycling phase. The main source of carbon emissions in the production phase is the carbon dioxide produced during the production of the main equipment materials; carbon emissions in the transportation phase mainly come from fuel emissions or energy consumption emissions during transport; the sources of carbon emissions during the construction phase mainly include site construction and installation; carbon emissions in the operation and maintenance phase come from energy consumption during the operation of the project; the source of carbon emissions in the disposal and recycling phase mainly includes building demolition and garbage transportation [9–11]. These stages all involve a lot of carbon-intensive products [12], among which the carbon emissions in the construction stage are the most significant, accounting for more than 50% of overall carbon emissions [8]. Although carbon emissions can be reduced to some extent by improving equipment, optimizing production processes, and using renewable energy, they require significant investment and technical support and it may take a long time to achieve results [13,14]. Therefore, the carbon emission reduction problem of PCPs deserves in-depth study.

To fill the knowledge gaps, this study presents a carbon emission reduction system for PCPs from a dynamic perspective. As an effective approach to modeling complex systems, system dynamics (SD) provides a holistic, nonlinear, and dynamic simulation tool to support decision-making for solving the carbon emission reduction problem of PCPs [15]. Therefore, this study uses SD to establish the carbon emission reduction model for PCPs, comprehensively analyzes the key drivers of PCP carbon emission reduction from a dynamic perspective, and conducts verification and simulation. The main contributions of the research are as follows: (1) It establishes an SD model of carbon emission reduction in PCPs and explore the carbon reduction mechanism from a dynamic perspective. (2) The key influencing variables of the carbon emission reduction system for PCPs are proposed. (3) It strengthens the top-level design to provide targeted suggestions for the carbon emission reduction strategies for PCPs.

The remainder of this study is organized as follows. Section 2 is a literature review, which combs the current research in related fields. Section 3 explains the study methodology and discusses the SD model. Section 4 is the model simulation and the sensitivity analysis. Section 5 is a discussion of the study findings. Section 6 concludes the study.

2. Literature Review

2.1. PCPs and Their Carbon Emissions

For a long time, scholars have focused on the technical and economic aspects of PCPs. For example, improving the quality of PCPs in the construction stage [16,17], enhancing the risk control level of PCPs [7,18], and evaluating the cost and economic performance of PCPs [19,20]. In addition, Zhang et al. evaluated the key characteristic indicators of PCPs, and the evaluation results are conducive to the investment decision for a PCP, and the research results show that the increase in PCPs is important for promoting economic growth [21].

In recent years, with the increasing focus on environmental protection, academia gradually turned its attention to the impact of PCPs on the environment [22]. Most scholars have begun to measure and analyze the carbon emissions of PCPs [23,24]. Existing studies mainly use traditional carbon emission calculation methods such as the carbon footprint method, the LCA method, and the input–output method to calculate the carbon emissions of PCPs. Sun et al. used the carbon footprint method to measure the carbon emissions at all stages of China's integrated energy stations. The calculation results showed that the percentage of carbon emissions in the production and materialization phases was as high as 87.21%, among which the carbon emissions of transformers account for more than half, which is considered the main influencing factor of carbon emissions in PCPs [11]. Li et al. analyzed the carbon emission sources and carbon emission paths of PCPs from the five phases of production, transportation, construction, operation, and recovery. They believed that carbon emissions in the material production and construction phases should be emphasized, and proposed carbon reduction suggestions from the perspective of the whole life cycle [10]. Some scholars have combined the input–output method with process analysis to calculate the carbon emissions of each part of a PCP, and the research results show that transmission equipment and construction engineering contribute the most to carbon emissions [12,25]. To more clearly quantify the carbon emissions of each process, Liu et al. established a carbon emission calculation method for substations under different data sources, compared the carbon emissions in different phases of a PCP, and proposed that the carbon emissions in the construction phase were the highest [8]. Ge et al. used a hybrid method to measure the embodied carbon emissions of China's PCPs in the construction phase and, based on the measurement results, put forward some suggestions to reduce the carbon emissions in PCPs from several key aspects such as formulating relevant policies, expanding the use of energy-saving materials, and improving construction technology [26].

The above studies deconstructed and calculated the carbon emissions in PCPs, determined the influencing factors of carbon emissions, and then quantified the contributions that each factor made to mitigate carbon emissions. However, they cannot predict future emissions reductions that each of the driving factors can contribute to, nor can they propose countermeasures from the perspective of carbon emission reduction.

2.2. The Application of SD in Carbon Emission Reduction

SD is a branch of management science that analyzes the internal dynamic structure and feedback mechanisms of a system through modeling and simulation [27]. SD models and systems thinking methods have been widely used in energy supply and demand [28]. SD is more suitable for exploring dynamic and complex carbon emission reduction systems than traditional qualitative research methods. For a long time, some scholars have used SD models to analyze carbon emissions from different aspects such as the drivers of urban carbon emission reduction potential [29,30], evaluating the level of industrial carbon emissions [31,32], and studying the carbon emissions of a building in China in the operation stage [33]. The SD method has demonstrated its effectiveness in PCP management research and carbon reduction research [34]. Some scholars have used the SD model to 0analyze the main factors that inhibit the increase in carbon emissions of public buildings [35], studied the carbon emission reduction path in Guizhou Province, predicted the carbon emissions of construction projects, and provided a theoretical basis for the realization of green and sustainable development of buildings [36]. Therefore, it is reasonable to use SD to explore the carbon reduction effect of PCPs.

Through the literature review, it can be found that the research gap in this field mainly exists in the following two aspects: (1) The existing research mainly determines the influencing factors by calculating the carbon emissions in PCPs, without a detailed explanation of the long-term complex interactions between various factors. (2) A lack of consideration of the dynamic feedback mechanism in the study of future scenarios. To fill these gaps, this study can scientifically and comprehensively analyze the driving factors and future trends of carbon emissions in PCPs, and apply the SD model that can solve the dynamic problems of complex systems to conduct simulation research on carbon emission reduction in PCPs.

3. Methodology

3.1. Data Sources

As the largest developing country in the world, China is currently in a stage of rapid development. Liaoning Province is located in northeast China, with a wide range of industries, and has become a pioneer in revitalizing northeast China. Liaoning Province has vigorously promoted the development of industry, and various industries in the province have increased requirements for power, so the number of PCPs in Liaoning province is gradually increasing. According to the "China Carbon Emission Database (2022)", Liaoning

Province's carbon emissions are not high compared with other provinces, but they far exceed the carbon emissions quota set by the state for Liaoning Province, which ranks third. Therefore, this study takes Liaoning Province as the research object and uses the relevant data for Liaoning Province to study the carbon emission reduction effect for PCPs.

3.2. Research Design

This study adopted a mixed research method, including three main stages, as shown in Figure 1.

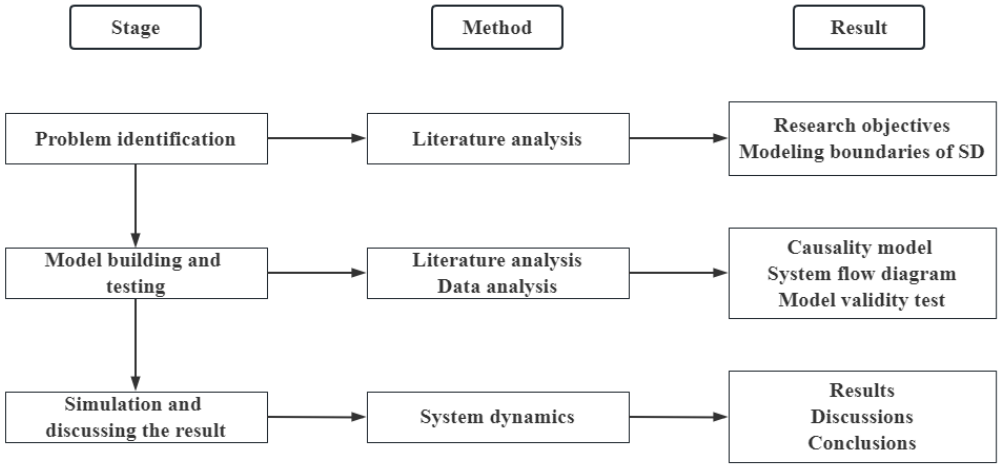


Figure 1. Research flowchart.

The purpose of this study is to analyze the carbon emission reduction effect for PCPs and to simulate carbon emission reductions in PCPs from four aspects: problem identification, simulation model formulation, model testing, and model implementation [37]. Figure 2 shows the modeling steps of the SD. First, according to the research objectives, the system boundaries of the SD model and the primary research assumptions are determined, which is the premise for system operation. Next, the variables affecting carbon emission reduction in PCPs were identified through the literature review and collected raw data. The data are from statistics publications such as the "China Statistical Yearbook", "Statistical Yearbook of China Science and Technology", and "Statistical Yearbook of Liaoning Province" [38–40]. Combined with the actual study, a causal map and a feedback loop were established. Then, a systematic flow diagram was developed to determine the quantitative relationship between the influencing factors. Vensim PLE software 7.3.5 was used to check whether the structure of the model is reasonable and to simulate the system. According to the relevant data pertaining to electric power construction projects Liaoning Province, the validity of the model was tested, and the model was constantly improved according to the test results until the error was controlled within 10% to ensure that the simulation results of the model are credible and that they reflect actual problems. After the model had reached the required confidence level, a sensitivity analysis was performed. Finally, according to the simulation results, this study proposed theoretical and practical implications.

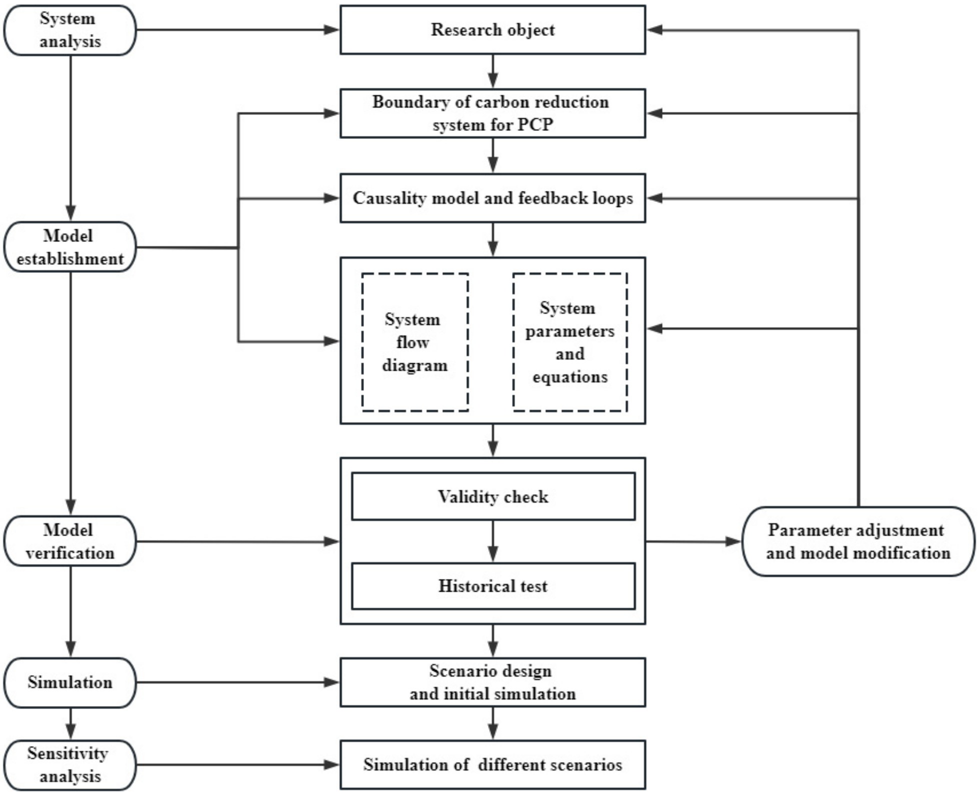


Figure 2. The framework of system dynamics.

3.3. Model Analysis

3.3.1. Basic Mathematical Model

Carbon emissions in PCPs are believed to be related to population, economy, and energy consumption [25,35,41]. In 1989, Toichi Kaya first proposed the "Kaya identity" to deconstruct carbon emissions [28]. As shown in Equation (1), the relationship is between CO_2 emissions (C) and total population (POP), per capita GDP, energy intensity (EI), and carbon emission coefficient (η) [42]. This study mainly considers carbon emission reduction in PCPs, and expands the "Kaya identity" by introducing government management, economy, market, technical level, population, and so on, and puts forward a calculation formula for carbon emission reduction in power construction projects, as shown in Equation (2). Carbon emission reduction in PCPs (C′) was defined as the product of the scale of the PCP (SPCP) and the carbon emission reduction coefficient (η′). Variables such as total population and per capita GDP are considered to be the main factors affecting the SPCP. With an increase in population and per capita GDP [28], an increase in regional electricity consumption leads to a growth in the SPCP [43]. The carbon emission reduction coefficient (η′) should consider technological progress, the use scale of energy-saving building materials, and the impact of energy efficiency of transmission equipment [11,26,28,44]. With the application of various carbon reduction technologies, energy-saving materials, and energy-saving transmission equipment to PCPs, the carbon emissions in PCPs can be reduced. In conclusion, this study identifies the system boundaries to provide a basis for the construction of a carbon emission reduction system for PCPs.

$$C = POP \cdot GP \cdot EI \cdot \eta \tag{1}$$

$$C' = SPCP \cdot \eta' \tag{2}$$

3.3.2. SD model

According to the basic mathematical model, the scale of PCPs and the carbon emission reduction coefficient of PCPs are closely related to government management, economic level, and the social environment. In this study, the carbon emission reduction system for PCPs is divided into four subsystems: the government management subsystem, the economic subsystem, the carbon emission subsystem, and the social subsystem [28,45]. The key variables in each subsystem are as follows: (1) government management subsystem: incentive policy support, R&D investment, prefabricated construction level, etc.; (2) economic subsystem: GDP, output value of secondary industry, per capita disposable income, etc.; (3) carbon emission subsystem: carbon emission reduction, SPCP, carbon trading price, etc.; (4) social subsystem: urban population, urbanization rate, population growth rate, etc.

The influence relationship between various factors of the carbon emission reduction system for PCPs is shown in Figure 3. The blue line represents the positive feedback loop to promote the system; the red line represents the negative feedback loop to inhibit the system.

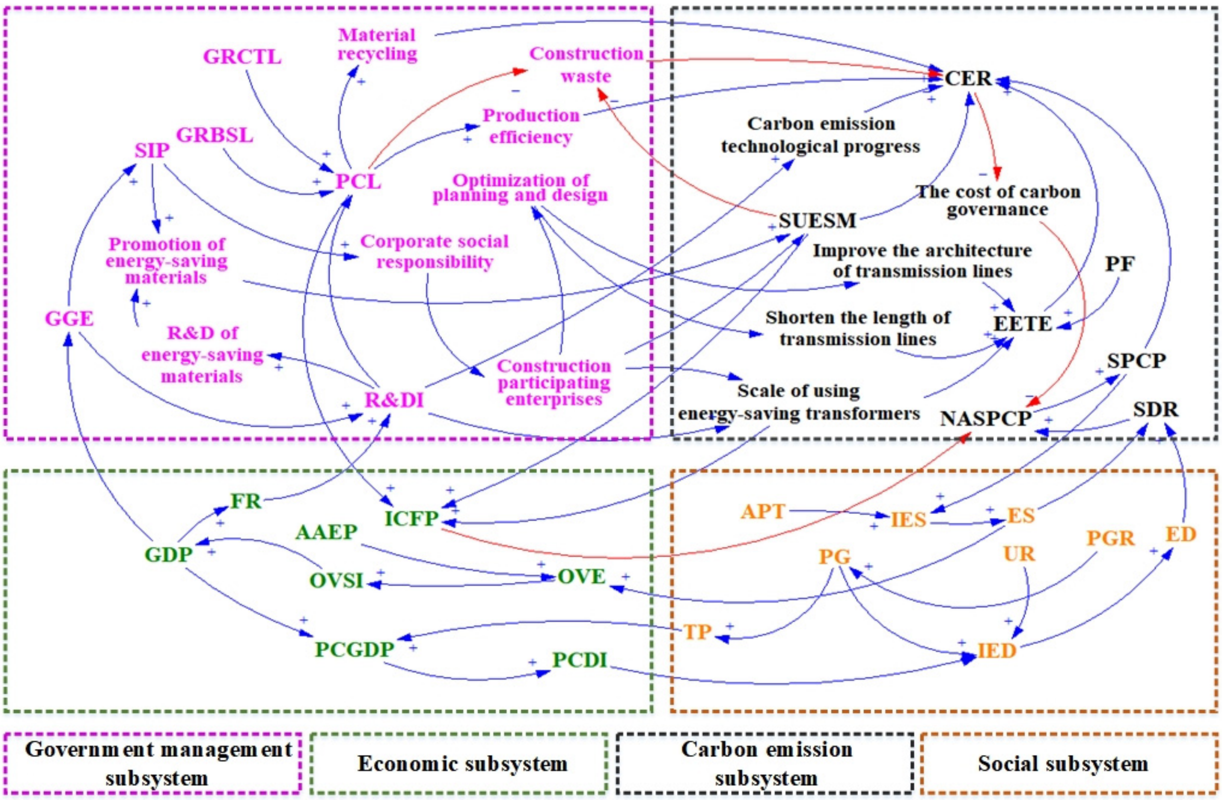


Figure 3. Causality model and feedback loop.

The main causal feedback loop includes: (1) The increase in R&D investment has promoted the development of energy-saving and carbon reduction technologies, increased the carbon emission reduction in PCPs, reduced the expenditure on carbon emission control, increased GDP, increased fiscal revenue, and helped the government further increase R&D investment, forming a positive feedback cycle [5,46,47]. (2) The improvement of PCL has promoted the standardized construction level of PCPs, reduced construction waste, improved construction efficiency, and thus reduced carbon emissions, reduced expenditure on carbon emission control, increased GDP, increased fiscal revenue, and helped the government further increase R&D investment, improve prefabricated construction technology, and form a positive feedback cycle [48–51]. (3) The research and promotion of energy-saving materials help to expand the scope of energy-saving building materials used during the construction process, reduce the carbon emissions of traditional construction materials, reduce expenditure on carbon emission control, increase GDP, increase fiscal revenue, and contribute to the research and development of energy-saving materials, forming a positive feedback cycle [10,52]. (4) Reasonable planning and design, as well as the improvement of transmission line architecture, can help improve the energy efficiency of transmission equipment, reduce carbon emissions, reduce expenditure on carbon emission control, increase GDP, increase fiscal revenue, and further increase the government's emphasis on the energy efficiency of transmission equipment, improve the energy efficiency of equipment, and form a positive feedback cycle [41]. (5) The widespread application of prefabricated technology and energy-saving materials increases the construction cost of PCPs, reduces GDP, reduces R&D investment, and forms a negative feedback loop [49].

To ensure the credibility of the model and the smooth development of the empirical research, the following basic assumptions are proposed [27,28]:

Hypothesis 1: *The impact of force majeure, such as war, disaster, and public health emergencies, is not considered in the system.*

Hypothesis 2: *Suppose that the national economic level and population of Liaoning Province maintain their existing state and develop steadily.*

Hypothesis 3: *Based on the availability of data, mainly consider the reality of 2016–2021.*

The causality diagram is a qualitative description of the structure, function, and correlation of the system. The system flow diagram is the concrete form of the causality diagram, combined with the carbon emission reduction system causality diagram while considering the simulation principles operability, logic, and availability of data to establish a system flow diagram, as shown in Figure 4. The carbon emission reduction system of PCPs includes five state variables, five rate variables, and 41 auxiliary variables, with a total of 51 variables.

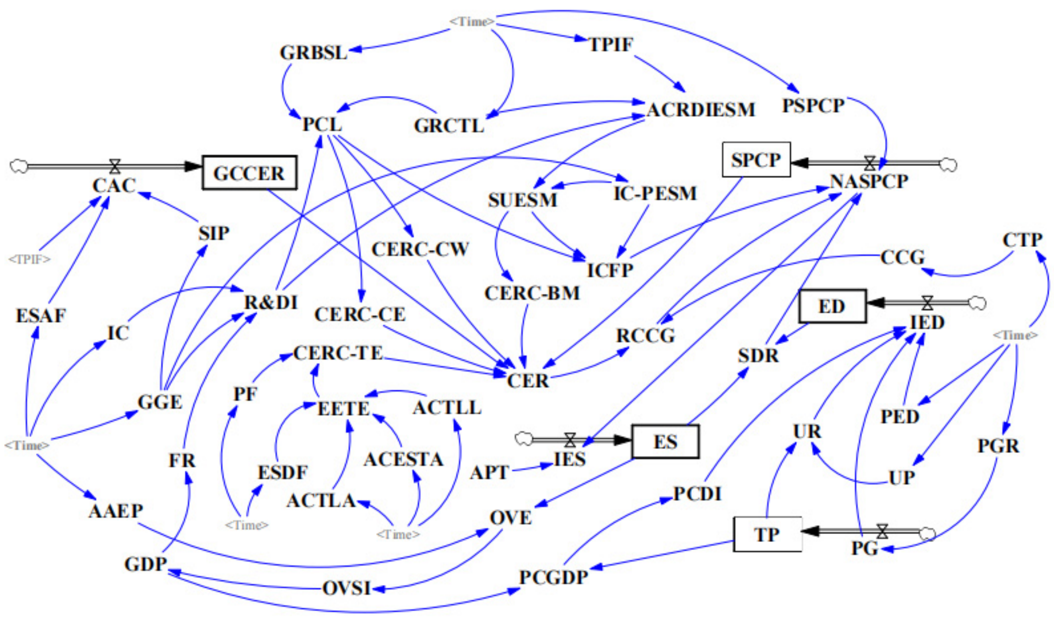


Figure 4. System flow diagram.

According to the causal feedback diagram and system flow diagram, we analyzed the factors governing the impact of carbon emission reduction in a causality tree and identified four important system driving factors: R&D investment (R&DI), prefabricated construction level (PCL), the scale of using energy-efficient materials (SUESM), and the energy efficiency of transmission equipment (EETE). As shown in Figure 5, they are essential factors for promoting carbon emission reduction in PCPs, affect system operation, and are easy to quantify.

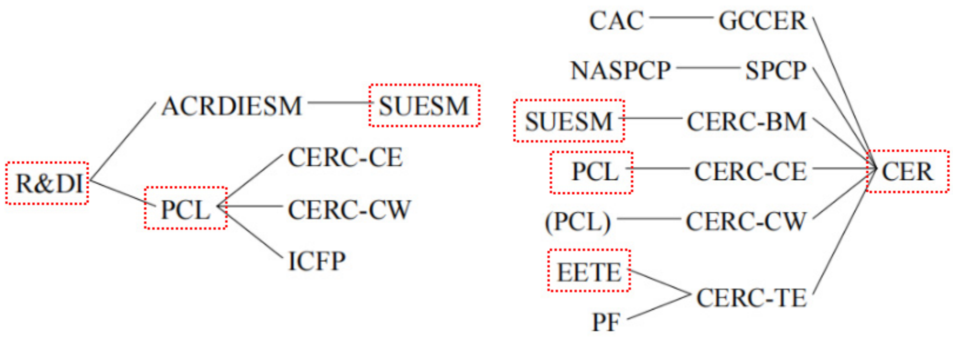


Figure 5. Key influencing factors.

3.3.3. Equation Design and Parameter Explanation

Referring to the analysis of carbon emissions in PCPs in the existing literature, the relationship between variables is obtained through historical data of real cases and provided by experts. The relationships between variables mainly include endogenous equations, regression equations, and table functions about time. (1) The expert interview and questionnaire survey were used to obtain the primary data on the relationship between various variables from relevant researchers and staff, such as the initial data of GGE, and the influence weight of GRBSL and GRCTL on PCL. (2) The relationship between relevant historical data and variables is obtained using the literature analysis and real cases, such as the initial data of PED and IC, the influence of the coefficient of SPCP on CER; (3) using a regression equation, such as the relationship between CRCTL and time, and the relationship between GDP and the output value of secondary industry. Therefore, this study assigns values to these parameters, which is reasonable to a certain extent. In this study, the spatial boundaries of the system are set to Liaoning Province, China; the temporal boundaries are set to the 2016–2030 period, and the simulation step is set to one year. The data from 2016 to 2021 are used to compare with real data to verify the effectiveness of the model, and the data from 2022 to 2030 are used to predict the key variables affecting the effects of carbon emission reduction. The variable setting and main equations for the carbon emission reduction system are shown in Appendix A.

3.4. Model Validation

To ensure the effective simulation results of the system dynamics model for the effect of implementing a prefabricated building incentive policy, the validity tests of the model itself and the initial simulation results are required. First, the "Model Check" function in the Vensim PLE software was used to run the test with "Model is OK", indicating that the model established in this study can be run. Then, the validity of the initial results was tested, the results of the model simulation were compared with the real data, and the error of the parameters of the equation was minimized to ensure the authenticity and effectiveness of the system simulation. It is generally believed that the error rate of the test is within ±10%, which means that the model is effective and can be used for simulation analysis. Because GDP has an influence relationship with key variables such as CER, NASPCP, SRI, ED, and ES in the model, participating in a large number of feedback pathways, and the historical real data of GDP is easy to obtain, so GDP is the most critical influencing factor that can be used for verification. The value of the GDP simulated by the system is compared with the data in the *Statistical Yearbook of Liaoning Province*. As shown in Table 1, the error rate of all the data is much less than ±10%, indicating that the dynamic model of the system is authentic and can truly reflect the actual operating state of the carbon emission reduction system for PCPs.

Table 1. Comparison of simulated values with actual values.

Year	Simulation Value (10^8 Yuan)	Actual Value (10^8 Yuan)	Error (%)
2016	21,941.55	22,246.90	−1.37%
2017	23,698.07	23,409.24	1.23%
2018	24,249.25	25,315.35	−4.21%
2019	25,454.93	24,909.45	2.19%
2020	26,107.80	25,114.96	3.95%
2021	26,993.24	27,584.08	−2.14%

4. Results

4.1. Initial Simulation Analysis

As per the initial simulation scenario, the existing policies and forces remained unchanged in this study. Then, the system model was simulated and the simulation results were obtained.

The simulation of carbon emission reduction in PCPs in Liaoning Province is shown in Figure 6. The results show that from 2016 to 2030, the reduction in carbon emissions increased year by year, from 545,100 tons in 2016 to 4.7553 million tons in 2030, with an obvious growth trend from 2018 to 2020. The predicted growth rate from 2022 to 2030 still has room for improvement, and certain measures are needed to improve the level of carbon emission reductions of PCPs in Liaoning Province.

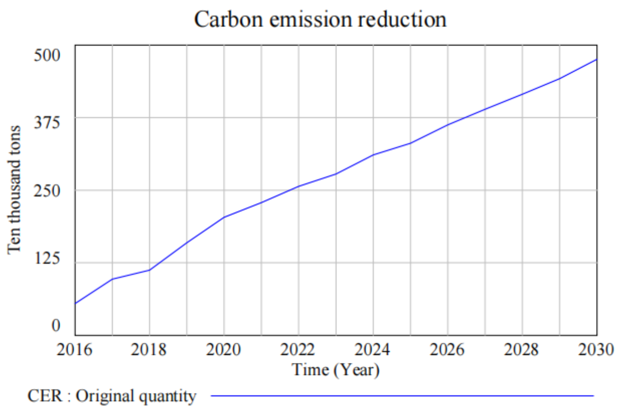
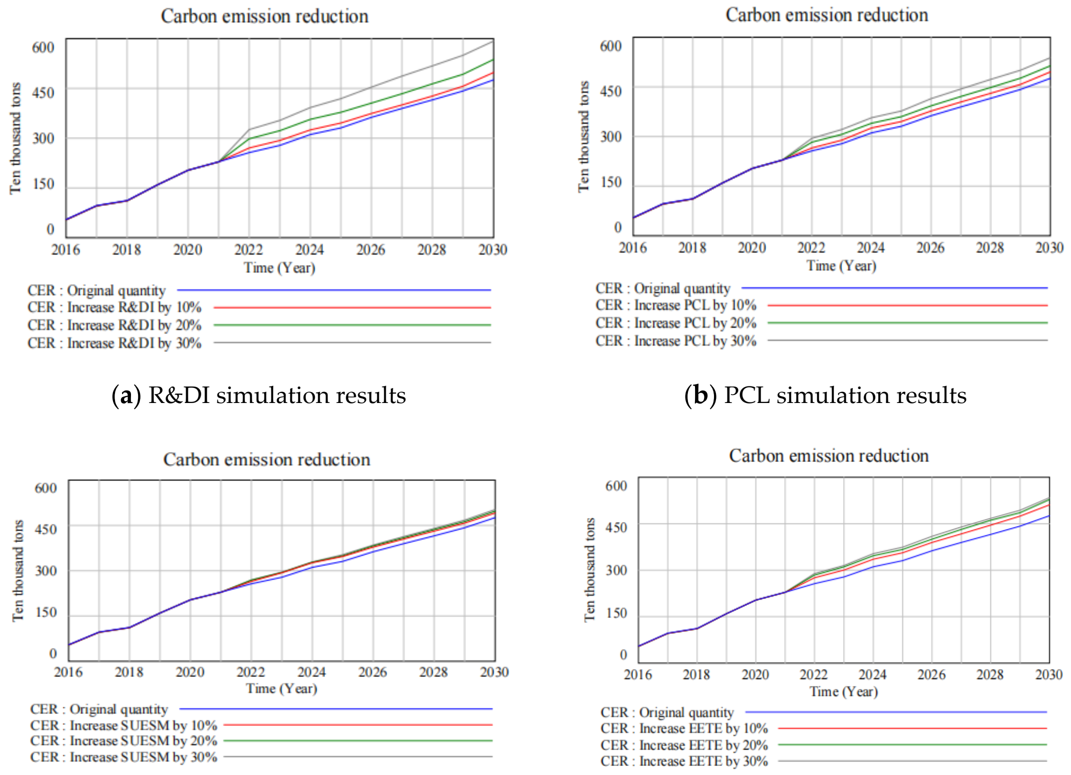


Figure 6. Initial simulation result.

4.2. Sensitivity Analysis

To observe the influence of a single factor variable on other variables and determine the influence of a change in the variable value on the whole model, this study conducted a sensitivity analysis of the carbon emission reduction system for PCPs from four aspects: R&DI, PCL, SUESM, and EETE. We adjusted the initial value of the target variable within a certain range while ensuring that other variables remained unchanged, and analyzed the impact of increasing the value of the target variable on carbon emission reduction. The results are shown in Figure 7. The blue line represents the initial simulation situation, indicating the change in carbon emission reduction when all variables remain unchanged. The red, green, and gray lines represent the changes in carbon emission reductions when the initial value of the target variable is increased by 10%, 20%, and 30%, while the other variables remain unchanged. The predicted time range is from 2022 to 2030.



(**a**) R&DI simulation results (**b**) PCL simulation results

(**c**) SUESM simulation results (**d**) EETE simulation results

Figure 7. Simulation results of single-factor variation.

First, we ran the simulation analysis for R&DI. With PCL, SUESM, and EETE unchanged, the initial values of R&DI in the model were increased by 10%, 20%, and 30%, respectively, for three adjusted simulations and compared with the results of the initial simulation. When the role of R&DI is increased by 10%, 20%, and 30%, the forecast reduction in carbon emissions in 2030 is 4.9778 million tons, 5.3697 million tons, and 5.9228 million tons, respectively. Compared to the initial simulation, the carbon emission reduction increased by 4.68%, 12.92%, and 24.55%. When R&DI is increased by 10%, the promotion effect of carbon emission reduction in PCPs is not apparent. When R&DI is increased by more than 20%, the impact on carbon emission reduction is significant, and the effect of carbon emission reduction is greatly improved. When R&DI is increased by 30%, the effect of carbon emission reduction in PCPs is more obvious. Therefore, only when the R&DI increases by more than 20%, does the carbon emission reduction system for PCPs have a significant promoting effect. The higher the R&DI, the more obvious the carbon emission reduction effect.

Then, we ran the PCL simulation analysis. With R&DI, SUESM, and EETE unchanged, the initial values of PCL in the model were increased by 10%, 20%, and 30%, respectively, and the three adjusted simulations were compared with the results of the initial simulation. When the role of PCL is increased by 10%, 20%, and 30%, the reduction in carbon emissions in 2030 is predicted to be 4.9518 million tons, 5.1353 million tons, and 5.3798 million tons, respectively. Compared to the initial simulation, the carbon emission reduction increased by 4.13%, 7.99%, and 13.10%. With the improvement in PCL, the carbon emission reduction effect of PCPs will also produce a matching improvement. The higher the PCL, the more significant the impact on the carbon emission reduction system for PCPs.

This was followed by a SUESM simulation analysis. With R&DI, PCL, and EETE kept constant, the initial values of SUESM in the model were increased by 10%, 20%, and 30%, respectively, and the three adjusted simulations were compared with the initial simulation results. When the role of SUESM is increased by 10%, 20%, and 30%, respectively, the reduction in carbon emissions in 2030 is predicted to be 4.9091 million tons, 4.9661 million tons, and 5.0243 million tons. Compared to the initial simulation, carbon emission reduction increased by 3.23%, 4.43%, and 5.66%. The sensitivity of SUESM is the lowest, and the impact on the system is not significant. When SUESM is increased by 10%, it will have a certain promotion effect on carbon emission reduction in PCPs, but when SUESM increases again, the promotion effect on carbon emission reduction in PCPs remains very small. Even if SUESM is increased by 30%, it will not have a significant promotion effect on the carbon emission reduction system for PCPs.

Finally, we ran the EETE simulation analysis. Under the premise that R&DI, PCL, and SUESM remain unchanged, the initial values of EETE in the model were increased by 10%, 20%, and 30%, respectively, and the reduction in carbon emissions in 2030 is predicted to be 5.1052 million tons, 5.2758 million tons, and 5.3397 million tons, respectively. Compared to the initial simulation, the carbon emission reduction increased by 7.35%, 10.95%, and 12.29%. When EETE is increased by 10%, it can produce a good promotion effect, but by 20%, the promotion effect cannot be doubled, and when EETE is increased by 30%, the promotion effect of carbon emission reduction is less pronounced.

4.3. Comprehensive Simulation Analysis

In the actual system, it is rare for the influencing factors to change independently, so it is necessary to consider how the four influencing factors analyzed above work together on the carbon reduction system to simulate the objective facts. Through the simulation analysis of the carbon emission reduction system for PCPs by the change of a single influencing factor, it was found that a higher improvement parameter for the influencing factor is not necessarily better. In order to maximize the effect of carbon emission reduction, a reasonable set of improvement parameters is needed to carry out a comprehensive simulation. Among them, when R&DI is increased by 10%, the change in the whole system is small, and the promotion effect on carbon emission reduction is also poor. Only when R&DI is increased by more than 20%, will it have a better promotion effect on the system. Therefore, in the comprehensive simulation, the R&DI is determined to increase by 20% and 30%. The improvement of PCL appears to have a continuous positive impact on the system, and produce a matching promoting effect on reducing carbon emissions. Therefore, in the comprehensive simulation, the PCL was determined to improve by 10%, 20%, and 30%. When SUESM is increased by 10%, it has a certain promoting effect on the system, while further improving SUESM cannot achieve a better promoting effect. Therefore, in the comprehensive simulation, the SUESM is determined to improve by 10%. When EETE is increased by 10%, it will promote the whole system. When EETE is further improved, the impact on the system is weak, so in the comprehensive simulation, it is determined that EETE increases by 10%. According to the above analysis, five regulation scenarios are set up for comprehensive simulation, as shown in Table 2.

Table 2. Simulation scenarios.

Scenario	**Content**			
	R&DI	**PCL**	**SUESM**	**EETE**
Initial scenario	—	—	—	—
Scenario 1	↑ 20%	↑ 10%	↑ 10%	↑ 10%
Scenario 2	↑ 30%	↑ 10%	↑ 10%	↑ 10%
Scenario 3	↑ 20%	↑ 20%	↑ 10%	↑ 10%
Scenario 4	↑ 30%	↑ 20%	↑ 10%	↑ 10%
Scenario 5	↑ 20%	↑ 30%	↑ 10%	↑ 10%

The five scenarios set up in Table 2 were, respectively, input into the carbon emission reduction system dynamics model, and the key index simulation diagram under different scenarios was obtained, as shown in Figure 8. The simulation value of carbon emission reduction in the PCPs of Liaoning Province in 2030 was predicted to investigate the promotion effect of the comprehensive simulation control scheme on the whole system.

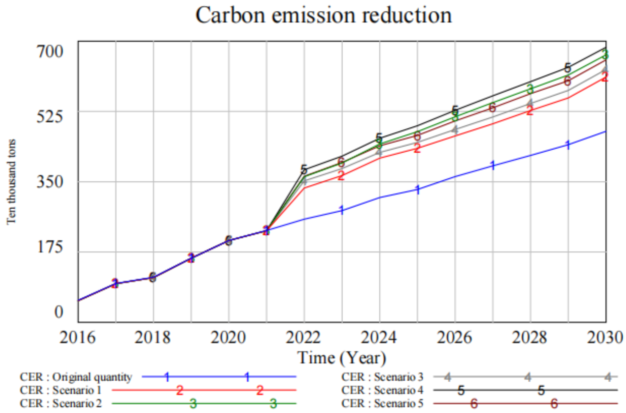


Figure 8. Comprehensive simulation result.

The results show that the carbon emission reduction system for the PCP needs the synergistic effect of multi-dimensional influencing factors, and that multiple factors and the actual situation of Liaoning Province should be considered comprehensively. Blindly increasing the intensity of the influencing factors not only consumes manpower and material resources but the promotion effect may also not be considerable. Reasonably improving the effect of the influencing factors will have the best-promoting effect on the carbon emission reduction level of PCPs. In general, the five scenarios played different roles, and the overall operation effect of the system was ranked as scenario 4 > 2 > 5 > 3 > 1 > initial value. Scenario 4 had the most significant promotion effect, and the reduction in carbon emissions increased to 6.8441 million tons. The carbon emission reduction promotion effect in scenario 2 followed closely with a reduction in carbon emissions increasing to 6.6597 million tons. The promotion effect of scenario 5 was also relatively good, with a reduction in carbon emissions reaching 6.5351 million tons. However, scenario 3 and scenario 1 have a more general impact on the promotion effect on carbon emission reduction, and the reduction in carbon emissions does not exceed 6.3 million tons.

5. Discussion

5.1. Increase R&D Investment and Strengthen R&D Personnel Training

The simulation results shown in Figure 7a show that the carbon emissions of PCPs decrease with increases in R&D investment, and a significant increase in R&D investment impacts the improvement of the carbon emission reduction effect of PCPs. The higher the investment in R&D, the higher the level of various energy saving and carbon reduction technologies, and the better the improvement effect on carbon emission reduction. In recent years, the R&D investment intensity in Liaoning Province has been lower than the national average level. For example, in 2021, the R&D investment intensity in Liaoning Province was 2.18%, and the national average level was 2.43%. The investment level was low and the investment structure was unreasonable. The Liaoning provincial government should continue to increase R&DI in carbon emission reduction technologies and prefabricated construction technologies, strengthen R&DI in energy-saving materials and transmission equipment needed for PCPs, and promote the effective transformation of scientific and technological achievements in the field of carbon emission reduction in PCPs [53,54]. They should also promote collaborative innovation by leading enterprises of the state grid and prefabricated buildings, and improve the innovation ability of enterprises. The Liaoning provincial government should guide enterprise funds, financial capital and other social funds to invest in the research and development of carbon emission reduction technologies, and establish a diversified investment guarantee mechanism for carbon emission reduction technologies in the whole society [55,56]. They should reasonably allocate a proportion of

R&DI to the R&D activities of universities, research institutes, and enterprises to ensure the research and development of key core technologies for energy conservation and carbon reduction; set the minimum proportion of R&DI increase year by year. Although the research and development of carbon emission reduction-related technologies is difficult, the value-added potential is high. In the long run, the research results of carbon emission reduction technologies are the key to bringing environmental benefits [57]. In addition to the R&DI cost, the loss of technical talents in various carbon reduction industries in Liaoning Province is also a major factor. It is necessary for the government to set up a talent training fund within R&D funds and increase investment in R&D talent introduction and R&D talent training. On the one hand, attracting the relevant professionals to work in Liaoning Province, and, on the other hand, urging universities, research institutes, training institutions, and PCP-related enterprises to cultivate a group of high-quality talents. Enterprise employees and scientific researchers should actively cooperate to explore new carbon-saving technologies for PCPs [58].

5.2. Improve Precast Construction Level

As shown in the simulation results in Figure 7b, the carbon emission reduction effect of PCPs increases with the improvement of the prefabrication construction level. Improving the level of prefabrication helps to improve construction efficiency, reduce construction waste, and implement modular construction and standardized production of PCPs [59]. The government needs to actively support enterprises, universities, and research institutes in cooperating to research prefabrication technology, promote the effective transformation of scientific and technological achievements in the field of prefabrication, and improve the level of prefabrication in PCPs [58]. They should vigorously promote the application of "four new" technologies, strengthen the use of "Internet+", "BIM technology", "RFID technology", "UAV + AI technology", and other new technologies in the prefabrication of PCPs. Government departments should further promote cooperation between prefabrication construction enterprises and focus on improving the level of prefabrication technology. And they should rely on universities, scientific research institutions, and training bases to strengthen the training of prefabrication technology professionals. Since the cost of prefabricated construction is higher than traditional construction costs, government departments should strengthen market guidance, and incentive policies to improve the enthusiasm of the relevant enterprises involved in prefabrication, provide transportation support for component transportation [49], especially foreign component transportation into Liaoning Province, provide support in aspects of logistics, transportation, improve the efficiency of prefabricated transportation, reduce wear costs, etc. [60]. Finally, timely updates to policy according to the actual situation, increasing the publicity of the "dual carbon" target, and holding regular training activities to improve the importance of energy conservation and carbon reduction in enterprises are also important.

5.3. Expand the Use of Energy-Saving Materials

As shown in the simulation results in Figure 7c, SUESM has less influence on the carbon emission reduction effect the PCPs, yet expanding the application range of energy-saving materials can improve carbon emission reduction. The extensive use of energy-saving materials will cause a significant increase in the cost of PCPs, but the impact on carbon emission reduction is not significant enough. Therefore, it is necessary to increase the use of energy-saving building materials within a reasonable range. First of all, the government should increase the R&D investment in energy-saving building materials, improve the energy-saving effect of building materials, and reduce the production cost of energy-saving building materials [61]. Government departments should formulate incentive policies for the promotion of energy-saving materials, such as tax reductions, fund returns, providing discounted interest loans and government subsidies, and giving certain rewards to the PCPs that actively use energy-saving materials [62]. The government should cooperate with enterprises to jointly establish an industry service platform for energy-saving materials, continuously extend the application scope of energy-saving materials, increase the publicity of the use of energy-saving building materials, and improve the recognition of energy-saving building materials by the relevant enterprises.

5.4. Improve the Energy Efficiency of Transmission Equipment

As shown in the simulation results in Figure 7d, the improvement of EETE has some influence on the carbon emission reduction effect of PCPs. Increasing EETE by 10% can achieve the desired effect. Therefore, there is no need to increase EETE further. A significant increase in EETE will increase the construction cost and will not help to double the carbon emission reduction. First of all, reasonable planning and design are particularly important, and site planning of PCPs has a great impact on transmission energy efficiency [63]. The government should optimize the power point, line architecture, and substation layout, to make the power grid structure more reasonable. The appropriate voltage level and its gradient are adopted in the power grid to make the comprehensive power supply efficiency as high as possible [64]. In the design process of the power grid, if the transmission capacity is large and distant, UHV transmission lines can be selected. If the line passes through regions with good meteorological conditions, compact transmission lines can be selected to shorten the length of transmission lines, save on the line corridor and increase the transmission capacity [62]. In addition, the use of highly conductive materials and efficient transformers in the construction process helps to increase the level of carbon emission reduction in PCPs.

5.5. Comprehensive Measures

Through comprehensive simulation analysis it became clear that increasing the influencing factors to the highest level will not achieve the ideal effect. Increasing R&DI by 30%, PCL by 20%, SUESM by 10%, and EETE by 10% results in the best carbon emission reduction. However, increasing R&DI by 30% will greatly increase the financial burden on the government. In addition, the increased construction cost of PCPs also has a negative impact on carbon emission reduction. By increasing R&DI by 20%, PCL by 30%, SUESM by 10%, and EETE by 10%, the promotion effect is also considerable, reducing carbon emissions by 6.5352 million tons. The difference between the two scenarios is only 4.7%, but it also greatly eases the financial pressure on the government. If the government budget is sufficient, R&DI can be increased to more than 30%. If government finances are limited, then the R&DI budget can be increased within its capacity, and the focus can be on PCL.

6. Conclusions

This study mainly takes three steps to solve the knowledge gap and conduct an in-depth analysis of the carbon reduction system for PCPs. First of all, using the literature analysis method, this study analyzed the factors influencing carbon emission reduction in PCPs, defined the research boundaries of the carbon emission reduction system for PCPs, and clarified the promotion effect of various influencing factors on the process of carbon emission reduction in PCPs. Then, the causality model and the system flow diagram were produced. Factors such as government, economy, technology, and population were introduced to explore the relationship between carbon emission reduction in PCPs and various influencing factors, and a relationship equation for each variable was proposed. The actual data of Liaoning GDP from 2016 to 2021 were used as controls to verify that the simulated values of the SD model in this study were consistent with the actual values. This showed that the simulation values can be used to predict carbon emission reduction in PCPs from 2022 to 2030, guiding the analysis of similar problems in other regions. Finally, the simulation and sensitivity analysis of the carbon emission reduction effect of PCPs were performed using the Vensim PLE software. The preliminary simulation results show that the carbon emission reduction capacity of PCPs in Liaoning province continues to increase from 2022 to 2030, but there is still room for improvement. The results of the sensitivity analysis show that the different influencing factors have different effects on the carbon emission reduction in PCPs. Blindly improving the intensity of various influencing factors will not necessarily achieve the ideal effect. Taking government finance into consideration, a reasonable combination scheme best improves carbon emission reduction in PCPs.

6.1. Implications

Academics have recognized the importance of carbon emissions in PCPs to sustainable development, but there is still a research gap in the carbon emission reduction effect of PCPs. In particular, a comprehensive study of the dynamic carbon emission system in PCPs is lacking. This study further enriches carbon emission research in PCPs for policymakers and academia. For decisionmakers, this study explores the extent to which different influencing factors affect carbon reduction in PCPs, and proposes a complete carbon reduction system for PCPs. This study complements the study of carbon emission reduction in PCPs and, according to the results of the sensitivity analysis, the government can choose appropriate strategies to improve the carbon reduction effect of PCPs. For the academic community, this study explores the relationship between variables in a complete carbon reduction system for PCPs that changes dynamically over time, filling a previous research gap. The main variables and research hypotheses of the system dynamics model established in this study are sourced from the literature, and the model has a certain degree of universality, which can provide a theoretical reference for carbon emission reduction in PCPs in other regions. The R&DI, PCL, SUESM, and EETE variables had positive effects on carbon emission reduction in PCPs. The sensitivity results also further verify the degree to which the changes in the above influencing factors promote the carbon reduction effect of the whole system. Therefore, the study model contributes to a better understanding of the operating mechanism of the carbon emission reduction system for PCPs and provides insights for further research.

6.2. Limitations and Further Directions

After explaining the results, some limitations should be noted. The carbon emission reduction system for PCPs is a complex dynamic system, and only the key indicators were studied in this study. In the future, abstract indicators related to China's carbon emission standards and policies should be included in the system dynamics model. This study focuses on exploring the carbon emission reduction effect of PCPs from the perspective of the government. In future studies, it is necessary to explore the carbon emission reduction effect of PCPs from the perspective of different stakeholders, such as power-related enterprises, carbon emission verification institutions, and scientific research institutions. In addition, using only the data from Liaoning Province to verify the model may produce accidental and random errors, and subsequent studies should compare and analyze data from different regions. Also useful would be using real-world examples to modify and validate the model to ensure accuracy and reliability in predictions across different scenarios and longer timescales.

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Appendix A

The variables and their abbreviations in the system flow diagram are shown in Table A1, and the equation relationship between variables is shown in Table A2.

Table A1. Variable introduction.

Types of Variables	Variables	Variables Abbreviation	Units
State variable	General coefficient for carbon emission reduction	GCCER	Dmnl
	The scale of power construction projects	SPCP	Ten thousand kW
	Electricity demand	ED	Ten thousand kWh
	Electricity supply	ES	Ten thousand kWh
	Total population	TP	Person
Rate variable	Comprehensive adjustment coefficient	CAC	Dmnl
	Scale of newly added power construction projects	NASPCP	Ten thousand kW
	Increase in electricity demand	IED	Ten thousand kWh
	Increase in electricity supply	IES	Ten thousand kWh
	Population growth	PG	Person
Auxiliary variable	Growth rate of building standardization level	GRBSL	%
	Growth rate of construction technology level	GRCTL	%
	Prefabrication construction level	PCL	Dmnl
	Carbon emission reduction coefficient for construction efficiency	CERC-CE	Dmnl
	Carbon emission reduction coefficient of construction waste	CERC-CW	Dmnl
	Carbon emission reduction coefficient of building materials	CERC-BM	Dmnl
	Fiscal revenue	FR	Yuan
	Research and development investment	R&DI	Yuan
	Government guidance efforts	GGE	Dmnl
	Support for incentive policies	SIP	Dmnl
	Technological progress impact factor	TPIF	Dmnl
	Elasticity structure adjustment factor	ESAF	Dmnl
	Population growth rate	PGR	%
	Urbanization rate	UR	%
	Average production time	APT	h
	Supply–demand ratio	SDR	%
	Average annual electricity price	AAEP	Yuan
	Output value of electricity	OVE	One hundred million Yuan
	Output value of the secondary industry	OVSI	One hundred million Yuan
	Gross domestic product	GDP	One hundred million Yuan
	Per capita gross domestic product	PCGDP	Yuan/person
	Per capita disposable income	PCDI	Yuan/person
	Carbon trading price	CTP	Yuan
	The cost of carbon governance	CCG	Yuan/ton
	Reduce the cost of carbon governance	RCCG	Yuan
	Carbon emission reduction	CER	Ten thousand Tons
	Incremental cost factor of the project	ICFP	Dmnl
	Planned scale of power construction projects	PSPCP	Ten thousand kW
	Planned electricity demand	PED	Ten thousand kWh
	Urban population	UP	Person
	Investment coefficient for promoting energy-saving materials	IC-PESM	Dmnl
	Scale of using energy-saving materials	SUESM	Dmnl
	Energy efficiency of transmission equipment	EETE	Dmnl
	Power factor	PF	Dmnl
	Input coefficient	IC	Dmnl
	Adjustment coefficient for the research and development level of energy-saving materials	ACRDIESM	Dmnl
	Carbon emission reduction coefficient of transmission equipment	CERC-TE	Dmnl
	Energy-saving design factor	ESDF	Dmnl
	Adjustment coefficient for transmission line length	ACTLL	Dmnl
	Adjustment coefficient for transmission line architecture	ACTLA	Dmnl
	Adjustment coefficient for energy-saving transformer applications	ACESTA	Dmnl

Table A2. The relationship between variables.

Variable Abbreviation	Equations
CER	SPCP × (GCCER × 0.174 + CERC-CE × 0.212 + CERC-TE × 0.229 + CERC-CW × 0.201 + CERC-BM × 0.197) × 0.00026
SPCP	INTEG(NASPCP, 0), the initial value is 0.
NASPCP	[(SDR × 0.576 − ICFP × 0.502) + RCCG ÷ 976.366] × PSPCP
PSPCP	WITH LOOKUP{[(2016,0)-(2030,2000)],(2016,907),(2017,968),(2018,985),(2019,1057),(2020,1064),(2021,1142),(2022,1180),(2023,1224),(2024,1279),(2025,1306),(2026,1338),(2027,1414),(2028,1491),(2029,1573),(2030,1703)}
PCL	(GRBSL × 0.763 + GRCTL × 0.237) × 0.487 + (R&DI ÷ 460.88) × 0.513
CAC	TPIF × 0.373 + SIP × 0.341 + ESAF × 0.286
GCCER	INTEG(CAC, 0), the initial value is 0.
GRBSL	WITH LOOKUP{[(2016,0)-(2030,1)],(2016,0.631),(2017,0.656),(2018,0.682),(2019,0.693),(2020,0.714),(2021,0.721),(2022,0.729),(2023,0.733),(2024,0.737),(2025,0.748),(2026,0.755),(2027,0.761),(2028,0.767),(2029,0.774),(2030,0.779)}
GRCTL	0.01037 × Year-20.643
SUESM	ACRDIESM × 0.327 + IC-PESM × 0.673
ACRDIESM	TPIF × 0.701 + GRCTL × 0.299
EETE	ESDF × 0.404 + ACTLA × 0.257 + ACESTA × 0.211 + ACTLL × 00.128
SDR	ES/ED
ES	INTEG(IES, 0), the initial value is 0.
ED	INTEG(IED, 0), the initial value is 0.
IES	NASPCP × APT
IED	(PCDI ÷ 27,831.12 × 0.337 + UR × 0.482 − PG ÷ 115,491 × 0.263) × PED
RCCG	CER × CCG
GDP	OVSI × 1.9954 + 5517.875
OVSI	OVE × 9.672 + 632.571
OVE	ES × AAEP
PCGDP	GDP/TP
PCDI	0.627 × PCGDP-711.405
FR	(GDP − 8855.272) ÷ 6.089
R&DI	(IC + 0.00219 × GGE) × FR
UR	UP/TP
TP	INTEG(PG, 0), the initial value is 0.

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