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Research on the Impact of Rural Energy Transition in China Based on System Dynamics

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Abstract: Rural energy is an important component of China's energy system, and promoting the green transformation and development of rural energy plays an important strategic role in improving the national green, low-carbon and circular development economic system and helping to achieve carbon peak and carbon neutrality goals. Considering the complexity and dynamism of rural energy transformation, this article establishes a system dynamics model for rural energy transformation in China, which includes three subsystems: energy, socio-economic, and environmental. The energy subsystem is divided into two sub modules: renewable energy and traditional energy substitution. The changes in the energy, socio-economic, and environmental subsystems under the background of rural energy transformation in China from 2010 to 2030 are simulated, and the development of rural energy and the impact of rural energy transformation are predicted and analyzed. last. Using scenario analysis to test the effectiveness of different rural energy measures. The results show that: (1) The total energy supply in rural areas of China is showing a trend of "first increasing and then decreasing", and the energy structure is undergoing significant changes. Biogas, solar energy, and renewable electricity are gradually replacing traditional energy sources such as coal, straw, and firewood, effectively improving rural energy utilization efficiency; (2) The overall development prospects of solar energy are better than biogas, and it will continue to grow from 2020 to 2030. The development of biogas is facing a transformation scenario. Household biogas is gradually being abandoned by rural residents due to various reasons such as urbanization, intensive agriculture, and raw material shortages. With strong policy support, biogas engineering will develop rapidly. (3) The substitution of renewable energy for traditional energy has outstanding contributions to reducing CO2, SO2, NOx, and PM2.5 emissions, and can improve the ecological environment in rural areas; (4) The development of renewable energy in rural areas can broaden the income channels of rural residents, provide more job opportunities, and at the same time, the development of biogas can provide high-quality organic fertilizers for agriculture, treat agricultural waste, and promote the sustainable development of agriculture in China. These pieces of information are of great significance for China's future low-carbon energy transformation and will provide recommendations for policy-making.

Keywords: Energy Transition; Rural Energy; Scenario Analysis; System Dynamics.

1. Introduction

With the large-scale exploitation and use of fossil energy, it has caused multiple dilemmas such as resource tension, environmental pollution, climate change and so on. Energy transformation is imminent. In recent years, China's total carbon dioxide emissions have continued to grow. According to the BP statistical yearbook of world energy 2022, China's total carbon dioxide emissions in 2022 reached 10.55 billion tons, an increase of 2.865 billion tons compared with 2009. In order to cope with climate change, China needs to accelerate the process of energy transformation. Rural energy is an important part of China's energy system. Promoting the green transformation and development of rural energy and building a clean, low-carbon and multi-energy integrated modern rural energy system are important supports for consolidating and expanding the achievements of poverty alleviation, comprehensively promoting rural revitalization and achieving the goal of carbon neutrality.

Energy transformation is a social and technological process, involving all levels of economy, society and environment. It is an important way to achieve the coordinated development of energy system, economy, society and ecological environment. When simulating the path of energy transformation, we should consider the relative stability of related subsystems. As people gradually realized the importance of economy, energy and environment, scholars began to study the relationship between energy transformation and economy and environment. As for the research on energy transformation and economy, some scholars believe that energy transformation can promote economic growth, and there is a long-term equilibrium relationship between the two. Alpera and Oguz o (2016) used ARDL test method to test the relationship between energy transformation and economic growth based on the data of European Union countries from 1990 to 2009. The results showed that the clean transformation of energy consumption structure was conducive to economic growth [1]. Asiedu Ba et al. (2020) tested the relationship between energy transformation and economic growth in 26 European countries from 1990 to 2018, and found that there was a long-term equilibrium relationship between the two. Energy transformation had a significant positive impact on economic growth [2]. Some scholars believe that energy transformation has a negative effect on economic growth. Shahbaz m et al. (2017) took the panel data of India's economic development from 1960 to 2015 as the research sample, and discussed the asymmetric impact effect between India's energy consumption and economic growth. The research results showed that energy transformation would inhibit economic growth. The main reason was that compared with traditional energy, the development and utilization of clean energy required a larger initial cost investment, and enterprises needed to innovate the supporting production processes and equipment, which would increase the production cost of enterprises, reduce the market competitiveness, and then have a negative impact on economic growth. In addition, energy transformation is closely related to the environment. Improving energy efficiency and accelerating the transformation of energy structure can alleviate the pressure of the environment. Scholars discuss the relationship between energy transformation and the environment from many aspects. Meirong su et al. (2016) used the multi-objective optimization model of city scale to integrate the method of product life cycle to assess the impact of environmental pollution caused by energy in the whole link of the supply chain from production, transportation and finally to the consumer terminal, and concluded that the multi-objective optimization model of comprehensive environmental impact was useful for the rational allocation of urban energy resources, helping to balance economic, energy and environmental objectives, and providing more detailed and practical support for urban energy system management [3]. With the development of sustainable development theory, economic growth theory and energy economics, more and more scholars, considering environmental degradation, ecological imbalance and energy depletion, prefer to study the energy transformation and economy, environment and society in the same system. The economic energy environment social system is a unified whole which is interconnected, mutually restricted and mutually promoted. In the process of economic and social development, once the relationship between the three is not well handled, it is easy to cause the imbalance of the whole economic and social development system. Accelerating the transformation of energy structure is an important measure to promote the coordinated development of energy economy environment system. Baleta et al. (2019) emphasize the integration of energy, water and environmental systems to make the by-products of one system become the resources of another system, develop circular economy, improve the economic efficiency of the whole circular chain and reduce the environmental burden [4].

At present, the research on energy transformation is mainly concentrated in urban areas. Under the "double carbon" goal, carrying out rural energy transformation plays a positive role in accelerating the Rural Revitalization and energy power strategy. Some scholars put forward their own opinions on carrying out rural energy transformation. Sun et al. (2013) made a comprehensive evaluation of the rural new energy development decision in Liaoyang City by using analytic hierarchy process based on a comprehensive investigation of the current situation and development and utilization of rural new energy resources in Liaoyang City [5]. Han et al. (2018) based on the provincial panel data of China's rural areas from 1991 to 2014, showed that the energy transformation from traditional biomass energy to traditional commercial energy significantly reduced the residential per capita energy consumption, while the energy transformation from traditional biomass energy or traditional commercial energy to advanced commercial energy significantly increased the residential per capita energy consumption [6]. Matthias et al. (2020) combined energy social science research with rural research, and identified three intersection points of two research traditions, namely, rural areas are the place to realize energy transformation, the debate on energy issues in rural areas and the liberation potential of rural energy transformation [7]. Li et al. (2022) showed the transformation of rural energy in China to understand the location, mode and reasons of this transformation in rural households. The research results showed how accessibility and affordability affected the fuel preference of rural residents, so that we could determine the mechanism of rural energy transformation [8]. Wu et al. (2022) based on the data of 2608 provincial rural energy policies and rural energy consumption from 1994 to 2014, investigated how China's rural energy policies evolved with the energy transformation and intensity growth [9].

Because rural energy transformation involves many fields such as economy, environment and social development, the research on energy transformation should not be limited to a single system, but should be comprehensively considered using modeling methods. System dynamics can intuitively show the changes of subsystems. At present, the number of literatures using system dynamics (SD) method to study energy problems has increased sharply, and the application of system dynamics to energy research has also gradually increased. For example, Dongjie Guan et al. (2011) used system dynamics and regional information system modeling to model the trend of energy consumption and carbon dioxide emissions in Beijing from 2005 to 2030 based on system dynamics, and concluded that the transformation of energy structure from coal and other carbon rich fuels to natural gas and other low-carbon fuels will play a vital role in Beijing's carbon emission reduction activities [10]. Mao et al. (2013) based on system dynamics in the context of industrial upgrading, studied the reduction of China's carbon emissions [11]. Feng et al. (2013) modeled the trend of energy consumption and carbon dioxide emissions in Beijing from 2005 to 2030 based on system dynamics, and concluded that the transformation of energy structure from coal and other carbon rich fuels to natural gas and other low-carbon fuels will play a vital role in Beijing's carbon emission reduction activities [12].

This paper takes the rural energy transformation as the research object. Firstly, it analyzes the current situation of China's rural energy transformation, and studies the changes of rural socio-economic and environmental subsystems under the background of rural energy transformation based on system dynamics. Through scenario simulation, it puts forward suggestions on the corresponding rural energy environmental policies, so as to promote China's rural energy utilization, rural revitalization, environmental protection and sustainable development of rural economy. The second part introduces the research process and the framework of SD model; The third part discusses the results of the model simulation, including historical and future trends, key influencing factors and scenario analysis; Finally, the fourth part gives the conclusion and policy implications.

2. Methodology

2.1. Research Framework

SD is a method to study the causal relationship and dynamic changes among various elements in a complex system. This study uses the system dynamics software Vensim to build and simulate the model. The object of this study is the impact of rural energy transformation. We try to study it from the social, economic, energy, environmental and other aspects. The modeling process of this paper is as follows: in the first step, according to the rural energy consumption and the objects before and after the development of rural renewable energy, the constituent elements and the correlation of the system are determined, and the causal loop diagram is drawn. Rural energy transformation involves many factors, such as rural energy consumption, agricultural economic growth, rural energy carbon emissions, rural energy pollutant emissions, rural renewable energy development capital investment, rural clean energy development and so on. The second step is to establish a simulation model of rural energy transformation system based on the historical data from 2010 to 2020, and determine the variable parameters and system dynamics equations. It is the key step of system dynamics modeling, and the subsequent simulation depends on the stock flow diagram. The third step is to test the validity of the model. Before operation, the validity and stability of the model should be tested. Including visual inspection, operation inspection, and the fitting degree between the prediction results of the model and historical data, to ensure the accuracy and reliability of the system. In the fourth step, we used the model to simulate and analyze, focusing on three main issues: (1) what is the history and future trend of China's rural energy transformation without constraints? This can be inferred from the historical model, which can be regarded as the baseline scenario. (2) What are the impacts of China's rural energy transformation on society, economy and environment? (3) What rural energy policies may be adopted in the future, and what are their mechanisms and effects? On the basis of the benchmark scenario, we set up four emission reduction scenarios: Technological Innovation scenario, funding scenario, renewable energy development scenario and comprehensive measures scenario. Finally, some conclusions are given, and corresponding policy suggestions are put forward for China's rural energy transformation. The research framework of this study is shown in the flow chart shown in Figure 1.

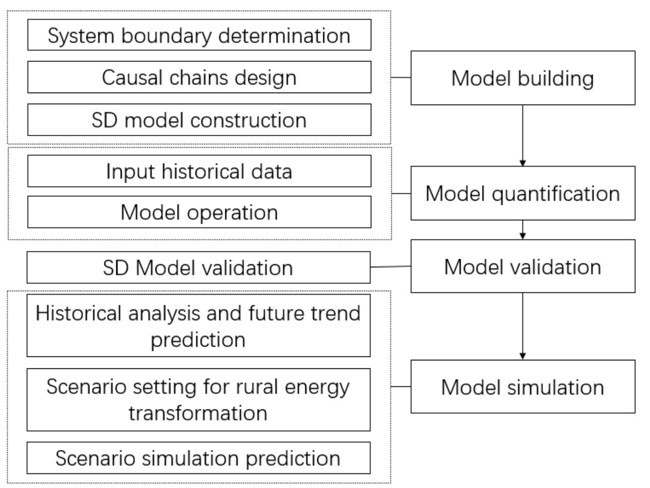

Figure 1. Research framework

2.2. Model Building

2.2.1. System Boundary Determination

The regional boundary of this model is rural China, the time boundary is 2010-2030, and the simulation step size is 1 year. The data from 2010 to 2020 are used for model verification, the base year of simulation is 2010, and the data from 2020 to 2030 are used for simulation prediction.

Rural energy transformation is a complex development process, taking the whole rural area of China as the boundary, involving the interaction between the three subsystems of socio-economic, energy and environment. It mainly considers the interaction between various factors within the boundary of the system, and takes the overall change of the system within the boundary as the research core. The energy system provides energy for the operation of the economic system, while the environmental system provides spatial support for the operation of the socio-economic subsystem. The increase of energy consumption in the energy system will increase the pressure on the environmental subsystem. The economic subsystem will also affect the other two subsystems. On the one hand, economic development will increase energy consumption, waste emissions, and the pressure on the environment subsystem and energy subsystem will increase; On the other hand, the development of the socio-economic subsystem will increase the investment in environmental protection, increase the investment in rural energy, upgrade the rural energy equipment, and increase the substitution of rural new energy for traditional energy, so as to improve the rural energy efficiency and reduce the energy consumption level and pollution emissions.

2.2.2. SD Model

By defining the internal composition and exogenous variables of each subsystem, in-depth analysis of the causal relationship between the variables, understanding the causal feedback and constraint mechanism between the elements, and using Vensim software to draw a causal relationship diagram, as shown in Figure 2.

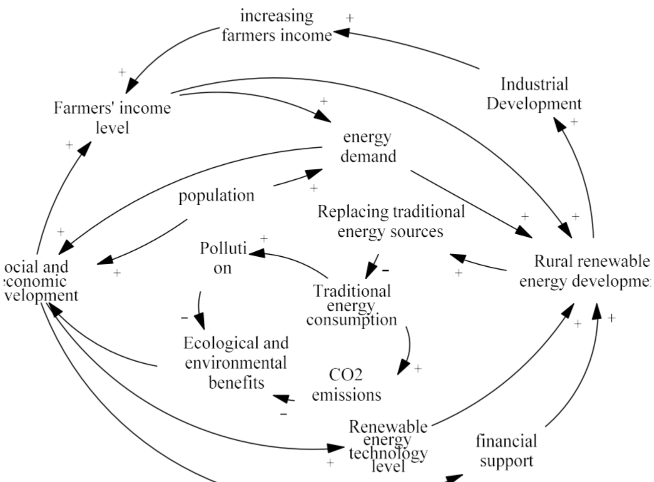

Figure 2. Casual Chain

Then, we need to distinguish the types of system variables on the basis of structural analysis, so as to build a system flow diagram, which is convenient for further establishing the functional relationship between variables.

2.2.3. Data Input

In this study, the main parameters of the model are determined by directly using the collected data, or using the research data of existing papers for relevant calculation and derivation, and by negotiating with experts to discuss the boundary of the model. The data sources are as follows: the main data sources are the statistical data of relevant departments. For example, the main data collected in this paper include China Agricultural Yearbook, China energy statistical yearbook, China rural energy Yearbook, etc. In addition, a small number of data are statistical data released from government websites, the national energy administration, the National Bureau of statistics and other official websites. This data acquisition method is also convenient, fast and has high reference value. For example, the setting of some exogenous variables in the model is mainly based on the government's overall and industrial development plans and reports on future development, such as the 13th five-year plan for National Rural Biogas

Development and the 14th five year plan for renewable energy development. There are also some data from the research results of domestic and foreign research institutions and scholars, such as the calculation of firewood and straw. In this paper, the 2010 level value is taken as the initial value of the system level variable simulation.

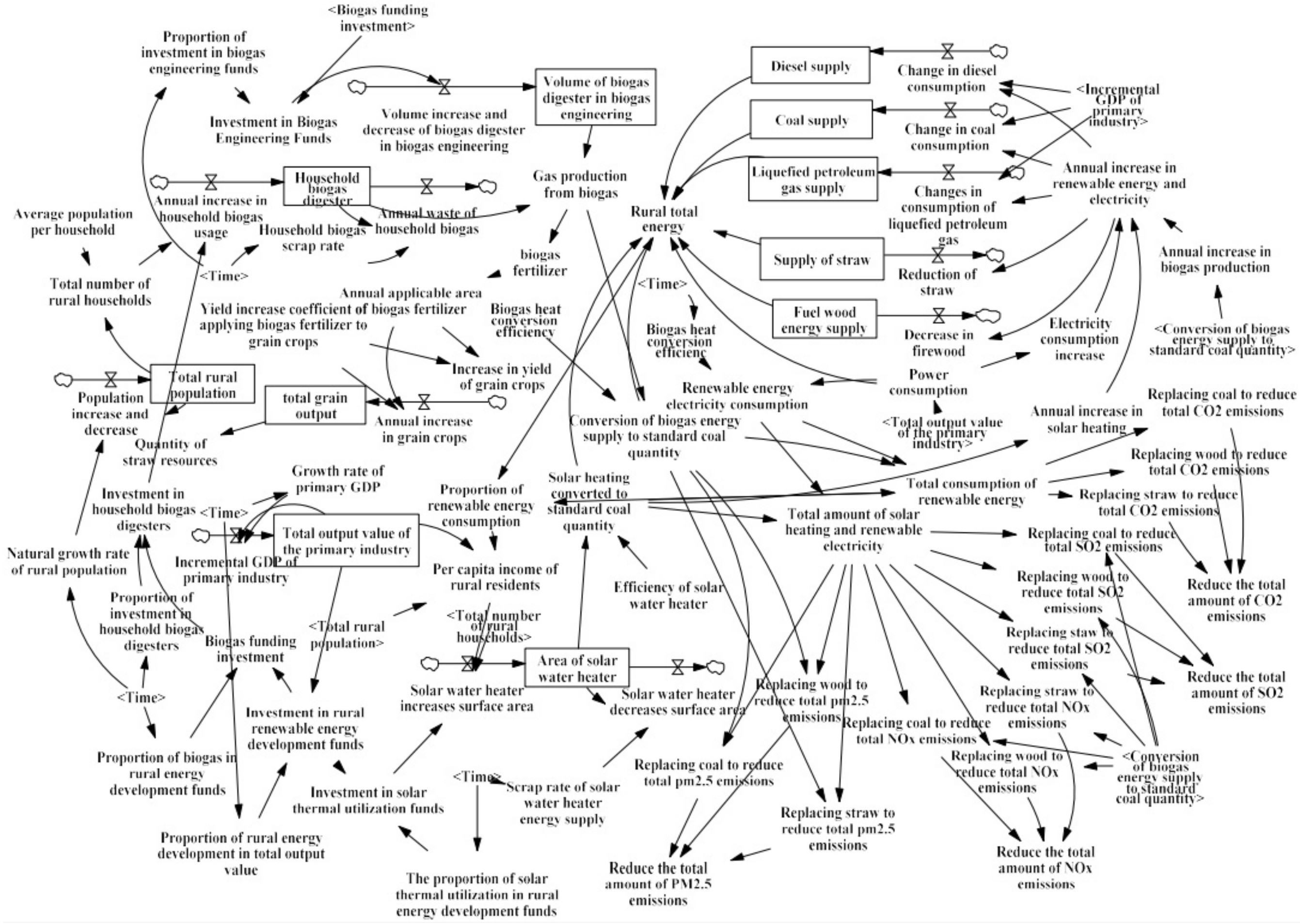

Figure 3. SD Model

2.3. Model Validation

After establishing and quantifying the SD model, the validity must be checked to ensure the credibility of the simulation results. In order to verify the effectiveness of the model, we selected the historical data from 2010 to 2020 as the known quantity, and then compared the simulated value with the actual value. It is mainly tested from the following three aspects: (1) in the process of building China's rural energy transformation model, this paper consulted a large number of classical literatures to ensure the correctness of the results. In addition, Vensim's built-in model verification system was used to select check model to test the model. The test results showed that the model was ok, which proved that the equation verification was completed and the model could run. (2) In order to test whether the system dynamics simulation model of rural energy transformation is stable and whether it is possible to produce ill conditioned structure, four cases of current1, current, current2 and current3 are set, and the simulation steps are set to 0.5, 1, 1.5 and 2 respectively to test, and the simulation results are compared. (3) In this paper, the simulation results of model variables are compared with the historical statistical data collected from 2010 to 2020, and the error rate is compared. In order to avoid the particularity and contingency of variables, this section selects several model variables such as the volume of biogas digesters in biogas projects, the area of solar water heaters, the number of straw energies converted into standard coal, and the number of coal energy converted into standard coal for historical test and analysis. The error rate is within 10%. After verification, the model has good simulation and prediction performance.

2.4. Scenario Designs

In order to promote the development of rural renewable energy, optimize the energy structure, realize the clean transformation of rural energy, and promote the sustainable development of rural areas, the variables that can be regulated in the rural energy transformation system are selected. The scenario analysis method is used to design the clean transformation policy of rural energy. The experimental scheme is designed with different values of each parameter variable, and the simulation is carried out to predict its development trend. The simulation results of the scheme are compared and analyzed to find the better development scheme, so as to provide decision support for the development of rural energy. Among them, rural energy investment, renewable energy technology innovation and the proportion of renewable energy power generation are closely related to rural energy transformation, so this paper mainly regulates it. The adjustment of parameters is mainly based on the development trend of rural energy in China, the "14th five year plan" for renewable energy development and relevant literature, which divides the policies for realizing rural energy transformation into three categories: (1) Adjustment of rural energy investment. Promote the development of renewable energy in rural areas and increase the proportion of renewable energy through government funding. (2) Renewable energy technology optimization. By promoting the technological innovation of rural energy, improve the thermal conversion efficiency of biogas and solar water heaters, improve the efficiency of rural energy utilization, reduce the energy cost in rural areas, and reduce the burden of farmers. (3) Increase the proportion of renewable energy power generation. Electricity consumption plays an increasingly important role in the lives of rural residents. Reducing the proportion of thermal power generation and increasing the proportion of clean energy power generation will also reduce the carbon emissions of rural residents' lives and production to a certain extent.

3. Results and Discussion

3.1. Analysis of Historical Trend and Baseline Scenario

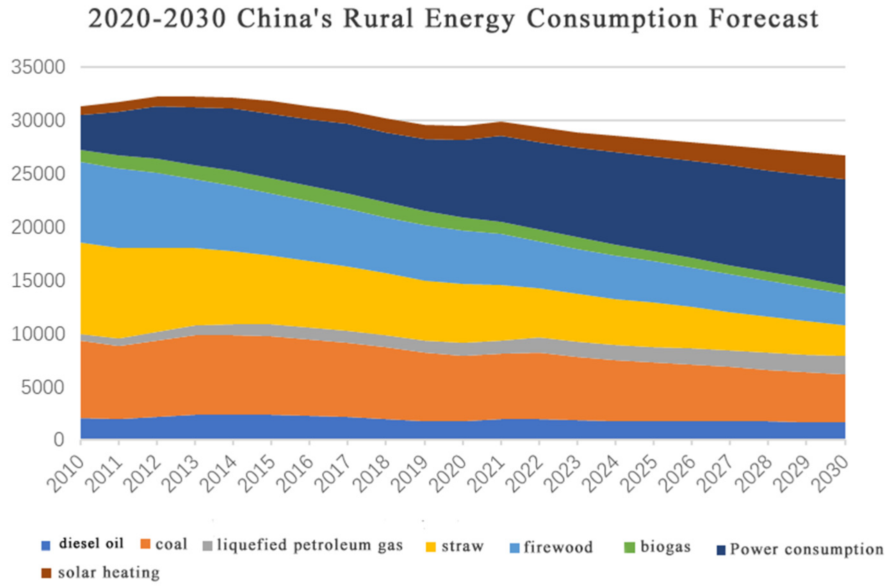

Figure 4. Rural Energy consumption Forecast

Rural energy demand includes the total demand for straw, firewood, coal, diesel, liquefied petroleum gas, electricity, biogas, solar energy and other energy. Through simulation and prediction, it is found that the energy consumption in rural areas shows a trend of first increasing and then decreasing. It is estimated that the energy demand in rural areas in China will be 267.123 million tons of standard coal by 2030. There are many reasons for the reduction of rural total energy consumption, including the change of energy consumption structure, the improvement of energy efficiency, the change of rural lifestyle, policy promotion and technical support, and the comprehensive effect of other factors. These factors work together to promote the development of rural energy consumption in a more efficient, clean and sustainable direction. With the promotion and subsidy of clean energy by the state, the utilization of renewable energy such as solar energy and biogas in rural areas has gradually increased, replacing some traditional high energy consumption energy. The energy consumption in rural areas gradually got rid of the dependence on traditional biomass energy (such as straw and firewood), and the energy consumption structure was more reasonable. The efficient use of commercial energy reduced the total energy consumption. At the same time, rural residents' awareness of energy conservation has gradually increased, and energy-saving appliances, energy-saving rural residential design in colleges and universities have also gradually reduced the total rural energy consumption. In addition, with the acceleration of urbanization, part of the rural population has transferred to cities, and the energy demand in rural areas has decreased accordingly.

According to China's resource endowment, the development of renewable energy in China not only has good environmental benefits, but also has good social benefits. In terms of economy, renewable energy has made important contributions in broadening the income channels of rural residents, promoting the increase of farmers' income, and creating jobs [13]. As the income of rural residents is affected by various aspects, how to separate the effect of other factors on the income of rural residents from the complex system has become the focus of analysis. When studying the impact of renewable energy popularization on the income of rural residents, this paper sets up a control group (current0), and adjusts the change behavior of the subsystem to 0. Comparing the simulation values of current and current0, it can be concluded that under the current0 scenario, the per capita income of rural residents will be 38501 yuan by 2030, and under the current scenario, the per capita income of rural residents will be 39273.8 yuan by 2030, 772.8 yuan more than that under the current0 scenario.

Due to the development of renewable energy projects and the rapid popularization of electricity, a large number of straws, firewood and other traditional bioenergy and coal have been replaced by clean and efficient energy, which has improved the ecological environment in rural areas and reduced the emissions of CO_2, SO_2, PM2.5, NOx and other gases. Through simulation, the change trend of annual CO_2 emission reduction and the total amount of various polluting gases is shown in Figure 5-7. By 2030, rural renewable energy is expected to replace traditional energy to achieve a total annual emission reduction of 178million tons of CO_2, 3713600 tons of SO_2, 219800 tons of NOx and 804500 tons of PM2.5. From 2010 to 2030, rural renewable energy is expected to replace traditional energy to achieve cumulative CO_2 emission reduction of 2.642 billion tons, SO_2 emission reduction of 5.4614 million tons, NOx emission reduction of 3.296 million tons and PM2.5 emission reduction of 11.8739 million tons.

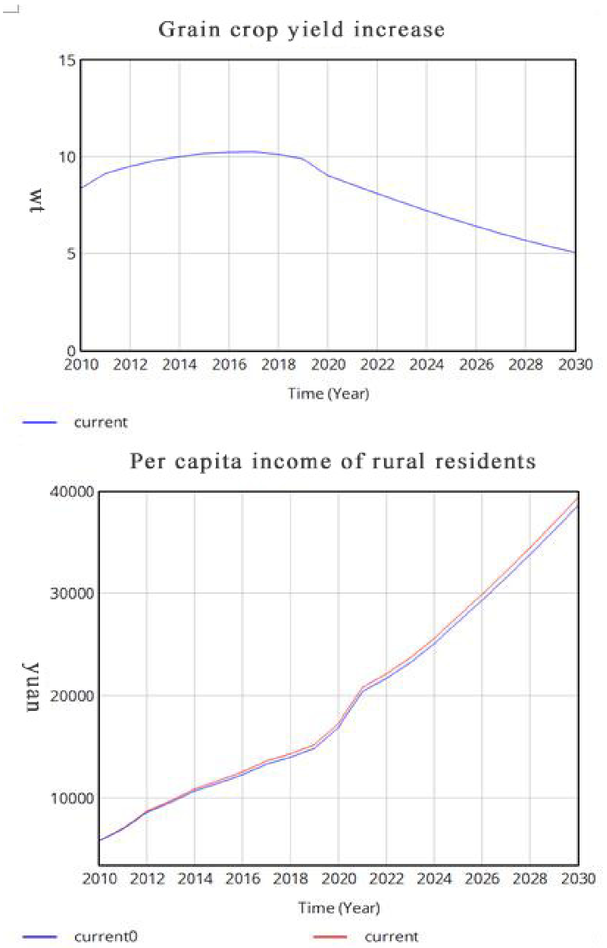

Figure 5. Changes in Socio-economic Subsystem

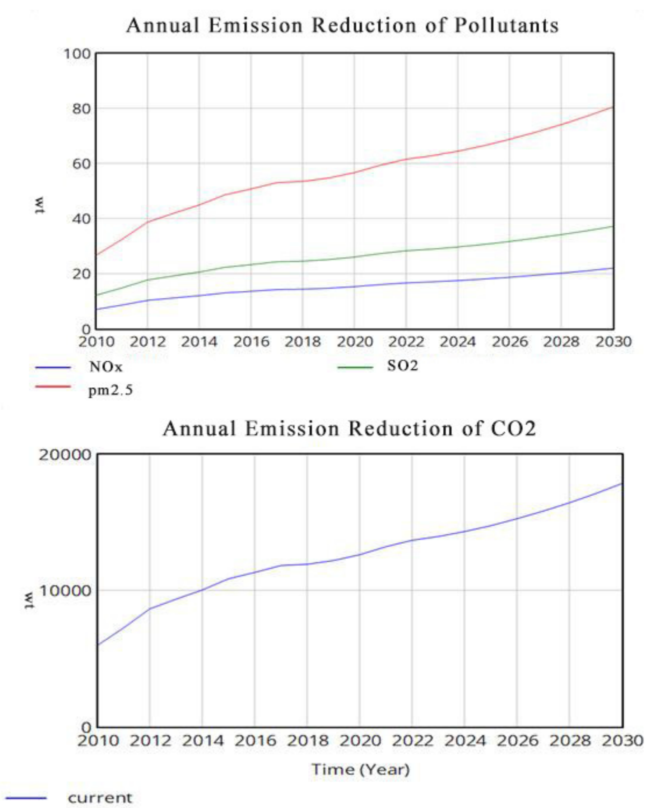

Figure 6. Changes in Environmental Subsystem

3.2. Scenario Analysis

When the rural energy investment is increased by 20% on the original basis, the renewable energy supply can be increased by 1.2578 million tons of standard coal in 2030, and the total annual emission reduction of CO2 will increase by 3.366 million tons, the total annual emission reduction of SO2 will increase by 6833 tons, the total annual emission reduction of NOx will increase by 3947 tons, and the total annual emission reduction of PM2.5 will increase by 14985 tons. At the same time, it can be found that increasing the investment of solar energy heat utilization funds brings more incremental supply of renewable energy than increasing the investment of biogas funds, and the role of replacing traditional energy to reduce CO2 and pollutants is also greater. However, increasing the investment of biogas funds and increasing the development of Biogas resources can provide biogas fertilizer for agricultural production, reduce the use of chemical fertilizer, effectively promote the production of food crops, and effectively deal with agricultural waste, so as to realize the sustainable development of agriculture.

Renewable energy technology innovation can significantly increase the supply of renewable energy in rural areas, increase the proportion of rural renewable energy consumption, effectively improve the energy self-sufficiency rate in rural areas, reduce the dependence on external energy, and enhance the independence and stability of the rural economy. At the same time, the upgrading of renewable energy technology can promote the substitution of traditional energy, accelerate the transformation of rural energy, reduce the emissions of greenhouse gases and harmful substances, and help improve the rural ecological environment. The comparison scheme can be found that improving the solar energy heat utilization technology can bring more renewable energy supply increment than improving the biogas utilization technology. The actual role of improving the solar energy heat utilization technology for the solar energy heat function cannot be underestimated. At the same time, promoting the technological innovation of biogas utilization and improving the efficiency of biogas digesters also play an important role in rural renewable energy. In short, the government's increased support for rural renewable energy technology innovation can effectively promote the transformation of rural energy, increase rural energy supply capacity, and effectively promote the emission reduction of carbon dioxide and polluting gases.

Increasing the proportion of renewable energy power generation can effectively increase the proportion of rural renewable energy consumption, and increase the proportion of renewable energy power generation by 15% on the original basis. It is estimated that the proportion of rural renewable energy consumption can reach 28% in 2030. Under the current scenario, the proportion of rural renewable energy consumption is expected to be 25.8% in 2030.

Renewable energy power generation does not produce greenhouse gases and harmful pollutants. With the increase in the proportion of power generation in the whole society, it will significantly reduce pollution emissions. With the transformation and upgrading of rural power grid, rural infrastructure is gradually improved, rural power consumption is gradually increased, and the proportion of renewable energy power generation is increased, which can indirectly reduce the emissions of greenhouse gases and pollution gases in rural areas, improve the air quality and ecological environment in rural areas, and protect the health of farmers. The proportion of renewable energy power generation will be increased by 15% on the original basis. It is estimated that the total annual emission reduction of CO2, SO2, NOx and PM2.5 will increase by 15.193 million tons, 31834 tons, 18942 tons and 68770 tons in 2030, respectively. Therefore, increasing the proportion of renewable energy generation is also one of the effective ways to promote the transformation of rural energy. However, due to the strong volatility and uncertainty of energy demand in rural areas, improving the stability of power supply and ensuring the stable supply of rural power is a key challenge.

4. Conclusion

This study provides a unified research framework based on SD, and uses the constructed system dynamics model to simulate the changes in energy, social economy and environment brought about by China's rural energy transformation, and makes a predictive evaluation of the results of the system operation. The main findings are as follows: (1) the total energy supply in China's rural areas showed a trend of "first rising and then falling" from 2010 to 2020. It is estimated that the energy demand in China's rural areas will be 267million tons of standard coal by 2030. The energy structure is undergoing major changes. Biogas, solar energy and renewable electricity are gradually replacing traditional energy represented by coal, straw and firewood. It is estimated that the proportion of rural renewable energy consumption will reach 24.94% by 2030, effectively improving the efficiency of rural energy utilization; (2) The substitution of renewable energy for traditional energy has made outstanding contributions to the emission reduction of CO2, SO2, NOx and PM2.5, and can improve the rural ecological environment. The simulation results show that the total cumulative CO2 emission reduction of rural renewable energy that can replace traditional energy is expected to reach 2.642 billion tons, the total annual SO2 emission reduction will reach 5.4614 million tons, the total annual NOx emission reduction will reach 3.296 million tons, and the total annual PM2.5 emission reduction will reach 11.8739 million tons from 2010 to 2030; (3) The development of rural renewable energy can broaden the income channels of rural residents and provide more jobs. It is expected that under the background of rural energy transformation, the per capita income of rural residents will increase by 772.8 yuan. At the same time, the development of biogas can provide high-quality organic fertilizer for agriculture, treat agricultural waste and promote the sustainable development of agriculture in China. The simulation results show that the development of biogas can provide about 1.58 billion tons of biogas fertilizer from 2010 to 2030, which can promote the increase of grain production by about 1.73 million tons, and effectively promote the development of agriculture. By adjusting relevant parameters and design feedback, planners can also simulate and evaluate the impact of relevant policies. The research process and results show that: (1) the construction of rural renewable energy system should adhere to technology-based, and technological progress is the basic support and fundamental power of energy transformation, and is one of the important ways to save energy. (2) Strengthen rural energy infrastructure and provide guarantee for rural energy transformation. The construction of perfect infrastructure plays a protective role for the transformation of rural energy. (3) The state should optimize the allocation and use of renewable energy funds. Governments at all levels should also match the actual use and demand of renewable energy in local rural areas to reduce the waste of funds. In the development of rural energy construction, we should ensure equal treatment of rural energy.

Acknowledgments

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