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The Impacts of Technology Shocks on Sustainable Development from the Perspective of Energy Structure—A DSGE Model Approach

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Abstract: Considering that the effect of different types of energy on sustainable development differs, the optimization of energy structure is commonly seen as a decisive factor for sustainable development. In this study, we focus on energy structure and construct a dynamic stochastic general equilibrium (DSGE) analysis framework including the environment, society, and the economy. Furthermore, we analyze the effect of different technology shocks on sustainable development when the proportion of clean energy is separately set at 10%, 20%, and 40%. To demonstrate the conclusions of the DSGE analysis framework, we construct the sustainability index and measure the relationship between the sustainability index scores and the proportion of clean energy of 68 countries in 2017, and the R^2 of the linear relationship between the sustainability index score and the proportion of clean energy was 0.30. Results show that the technology shock of clean energy exhibits more benefits for sustainable development than that of non-clean energy. Moreover, we find that the optimization of the energy structure can be helpful for the enhancement of sustainable development capacity. This study is helpful to expand the DSGE analysis framework from the perspective of energy structure. This study also provides effective ways and reference suggestions for local governments to optimize energy structure and improve sustainable development capability.

Keywords: energy structure; sustainable development; DSGE model; energy technology shock

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Citation: Sun, D.; Wang, F.; Chen, N.; Chen, J. The Impacts of Technology Shocks on Sustainable Development from the Perspective of Energy Structure—A DSGE Model Approach. *Sustainability* **2021**, *13*, 8665. https://doi.org/10.3390/su13158665

Academic Editors: Domingo Ribeiro-Soriano and Andrea Rey-Martí

Received: 10 June 2021
Accepted: 30 July 2021
Published: 3 August 2021

1. Introduction

The concept of "sustainable development" is an important consideration in economic development and policy implementation. In "Our Common Future" published by the World Environment and Development Commission (WECD) in 1987, sustainable development is defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [1]. The United Nations General Assembly has proposed a set of global Sustainable Development Goals (SDGs), which included 17 goals and 169 targets. In addition, 330 indicators were introduced in March 2015 [2]. The SDGs place greater value and demands on the scientific community than the Millennium Development Goals. The former considers various factors, in which socially, economically, and environmentally are the core [3,4].

According to the existing literature, we concluded that sustainable development can be regarded as a combination of economic growth, social development, and environmental protection. As a decisive factor of production and the source of pollution emissions, energy has an important effect on economic growth, social development, and environmental protection [5–9]. Edenhofer [10] pointed out that research on energy issues would help to promote the understanding of sustainable development capacity. In an economic growth, energy not only can be regarded as an intermediate input in the production process but also plays the role of value creation in the production process. Jorgenson [11] analyzed the economic growth and productivity of the United States after World War II using the KLEM database, which takes energy and other raw materials as intermediate inputs and introduces them into the production function together with capital and labor. In social development, energy consumption plays an important role in all aspects of society, such as transportation, food, housing, and infrastructure. Based on the sampling data evaluation, Ntanos et al. [12] found that the use of renewable energy is conducive to improving the quality of life of residents. In environmental protection, awareness of the negative effect of a large amount of carbon dioxide, nitrogen oxides, and chlorofluorocarbons on the environment is increasing [13].

The utilization and pollution degrees of different types of energy including the effect on the environment and economy have significant differences. Energy can be divided into traditional and new energy according to the degree of utilization. Alternatively, energy can be divided into renewable and non-renewable energy or be divided into non-clean and clean energy based on the pollution degree. Among energy sources, coal, oil, and natural gas are widely used, non-renewable, and contaminated, whereas solar, wind, and marine energy are developing, renewable, and pollution-free. It is inevitable for the energy structure to change along with the renewable energy development. Therefore, the energy structure should be considered in the study of sustainable development. At present, most studies considering the energy structure mainly analyze the trend of energy structure change or how to effectively improve the energy structure from a policy perspective. For example, Wang et al. [14] built a model based on the analysis of the balance of energy supply and demand to predict the trend of the energy structure change. Ozturk [15] took Turkey as an example and mentioned that the development of new energy and the optimization of energy structure is demanded due to the further development of the economy and the restriction of traditional energy.

According to the existing studies, it can be found that most researchers concern about the energy use in sustainable development or the optimization of energy structure. In-depth research on the relationship between energy structure and sustainable development capacity is limited. With the restrictions on energy exploitation and the pollution causing low quality of lives, the development of new energy and the sustainable development have become global issues, it is meaningful to research in the effect of energy structure on the sustainable development. Thus, the present study chooses to investigate the influence of energy technology shocks on sustainable development capacity from the perspective of energy structure.

The remainder of this paper is structured in the following sections. Section 1 reviews the related literature. Section 2 constructs the dynamic stochastic general equilibrium (DSGE) model considering the energy structure. Section 3 estimates the parameters. Section 4 analyzes the impulse response of different technology shocks and energy structures. Section 5 constructs the sustainability index and compares sustainability index scores and the proportion of clean energy of 68 countries in 2017 to demonstrate the conclusions of the DSGE analysis framework. Section 5 concludes the study.

2. Literature Review

2.1. Sustainable Development

In the description of the concept of sustainable development, early scholars mainly emphasized that the environmental and ecological factors should be included in the analysis of economic growth. Dasgupta pointed out that after introducing consumption and ecological or environmental factors into the representative "dynasty" welfare utility function, the model can be the best theoretical framework for analyzing sustainable development [16]. As the concept of sustainable development receives increasing attention, the understanding of sustainable development tends to be mature and perfect. Scholars associate the connotation of sustainable development with the dimensions of economy, society and environment, and apply this connotation to a wide range of research. For example, Živković et al. [17], Cambero and Sowlati [18], and Kamali [19], respectively, analyzed the influence of biodiesel production and use, supply chain construction of forest biomass energy, and performance and problems of agricultural planting system from the perspectives of sustainable development, namely, economy, society, and environment. Moreover, relevant United Nations agencies believe that sustainable development should include economic, social, and environmental aspects, which are not only different but also interrelated [20]. In the 2030 Agenda for Sustainable Development, a pattern of society, economy, and environment has been formed. This finding emphasizes that sustainable development means the realization of economic growth, social harmony, and sustainable coordinated development of the environment.

With the maturity and development of the concept of sustainable development, scholars gradually turn to researches in the issues and challenges in the sustainable development process. Pirouz et al. [21] investigated the challenge of COVID-19 (new version of Coronavirus) as one of the epidemic diseases in the sustainable development process. Mainali et al. [22] evaluated synergies and trade-offs among sustainable development goals (SDGs) to explore the appropriate development path. Researchers also pointed out that innovation is an important issue in the sustainable development process [23–26], Silvestre and Ţîrcă [27] reviewed the literatures on innovation for sustainable development and found that sustainable innovation improves entities' sustainability trajectories and performance. Apart from this, the concept of sustainable development has an intersection with various branches of economics. For example, theories related to the concept of sustainable development in circular and ecological economics exist [28]. Moreover, sustainable development theory not only applies to national macroeconomic development goals but is also introduced into the enterprise strategic management as a theory. In this regard, Pieroni [29] summarized 92 methods for the company to apply sustainable development theory and circular economics to strategic management.

According to the existing literature, it shows that the theory about sustainable development has become mature and systematic. Therefore, this study constructs the sustainability index on the basis of the concept of sustainable development.

2.2. DSGE Method in Sustainable Development and Energy Research

This study uses DSGE to analyze the relationship between energy structure and sustainable development. The DSGE model can be traced back to the real business cycle model proposed by Kyland and Prescott [30]. Compared with other macroeconomic frameworks, DSGE is helpful to analyze the dynamics of the inter-temporal behavior of economic actors in macro-economy [31–33]. After an energy technology shock, the DSGE analysis framework is helpful to describe the dynamic characteristics of the relationship between macroeconomic variables under different energy structures. The DSGE model has been applied to the study of sustainable development and energy structure. For example, Alaminos et al. [34] constructed a DSGE-VAR model to analyze the transmission connection between the tourism industry and sustainable economic growth in the empirical scenario of international countries. Chan [35] constructed an environmental dynamic stochastic general equilibrium (E-DSGE) model to study in the impact of uncertainty (second-moment) shocks on the carbon emissions, abatement investment, and output. Niu et al. [36] used the DSGE model to study sustainable development and found that environmental tax is helpful to the optimization of energy structure. Xiao et al. [37] pointed out that emissions' intensity shock will exert greater effects than environmental tax rate shock on macroeconomic fluctuations in a DSGE approach.

Apart from the study of sustainable development, the DSGE model is also used widely in the study of energy shocks. Argentiero et al. [38] used a DSGE model for renewable energy sources and fossil fuels in the perspective of energy policy which including a carbon tax and renewable energy sources price subsidy. Balke and Brown [39] used a medium-sized DSGE model of the U.S. economy to evaluate how U.S. real GDP responds to oil price movements that originate from global oil supply shocks.

According to the existing literature, it can be found that though scholars had considered shocks of energy price, energy tax and energy supply in the DSGE model, the consideration of energy structure is still in lack. As a result, this study explores the impact of different energy technology shocks on sustainable development by DSGE analysis framework considering the situation of energy structure.

2.3. Innovations

The current study establishes a DSGE model to study the effect of energy technology shocks on the macro-economy under different energy structures. The innovations of this article are as follows: (1) At present, scholars introduce energy factors into the DSGE framework mostly from the perspective of energy price shocks. They do not fully consider the effect of energy structure changes on the consequences of technological shocks. In building the DSGE model, this study analyzes the effect of energy technology shocks under different energy structures from the perspective of energy structure, taking energy technology and energy pollution into account. (2) The application of the DSGE method is usually faced with the limitations including the difficulty of unobservable to exogenous variables and the over identification problem of the parameters and so on. For the above limitations, the studies that used the DSGE framework to analyze problems usually take the impulse response results as the conclusion, given the limited empirical test. Furthermore, the present study constructs the sustainability index and makes an empirical test on the relationship between sustainable development capability and energy structure. The conclusions help verify and supplement the impulse response results.

3. DSGE Model Method

This study makes the following extensions based on the traditional DSGE model. First, in constructing the DSGE model, energy is regarded as a coal factor in the production function, and the influence of energy structure is fully considered. Secondly, the environmental sector is introduced to greatly describe sustainable development. In the environmental sector, the use of energy will produce pollution and have a negative effect on the environment. Moreover, the government will take a certain proportion of output as the expenditure for pollution control.

In this study, we construct a closed multi-sector DSGE model with three main departments, namely, households, manufacturers, and the environment. In households department, labor is provided by households and wages are obtained for consumption. In manufacturers department, capital, employed labor, and energy are accumulated to produce final products and form total social income. In environment department, environmental pollution is affected by different factors. On one hand, the environment can be polluted by the energy emission originated from manufacturers. On the other hand, it has self-purification ability and the government takes a certain proportion of the total social income as the expenditure for pollution control. The shocks introduced by the model include two kinds of technology shocks, namely, the non-clean and clean energy technology shocks.

3.1. Households

The utility function of representative households is given by

$$U(C_t, L_t) = \frac{{C_t}^{1-\sigma} - 1}{1-\sigma} - \theta \frac{{L_t}^{1+\omega}}{1+\omega} \quad (\sigma > 0,\ \omega > 0) \tag{1}$$

Households' utility depends on current consumption C_t and labor supply L_t. θ is the coefficient of labor contribution to utility and is greater than 0; σ is the reciprocal of consumption substitution elasticity, and ω is the reciprocal of labor supply elasticity.

The representative households maximize the expected utility, and β denotes the discount factor.

$$E_0 \sum_{t=0}^{\infty} \beta^t U(C_t, L_t) \tag{2}$$

Under the first-order condition, the equation for optimal consumption and labor supply is given by

$$\theta L_t^{\omega} = C_t{}^{-\sigma} w_t \tag{3}$$

3.2. Manufacturers

The production function is a three-factor production function including capital K, labor L, and energy N. α_1, α_2, and α_3 represent the output elasticity of the three factors in the production process. The aggregate production function is given by

$$Y_t = K_t{}^{\alpha_1} L_t{}^{\alpha_2} N_t{}^{\alpha_3} \tag{4}$$

The first-order condition of capital K is given by

$$\lambda_t^1 = \beta \lambda_t^1 (R_t + 1 - \delta) \tag{5}$$

The rate of return can be obtained by deriving capital, and the equation is given by

$$R_t = \alpha_1 K_t{}^{\alpha_1 - 1} L_t{}^{\alpha_2} N_t{}^{\alpha_3} \tag{6}$$

The wage equation can be obtained by deriving labor, and the equation is given by

$$w_t = \alpha_2 K_t{}^{\alpha_1} L_t{}^{\alpha_2 - 1} N_t{}^{\alpha_3} \tag{7}$$

The capital accumulation equation is given by

$$K_t = I_t + (1 - \delta) K_t \tag{8}$$

According to the classification of energy based on the degree of environmental pollution, the production process is assumed to have two types of energy, namely, non-clean (a) and clean (b). The use of technologies for non-clean energy (a) is relatively mature, and the pollution level is high. By contrast, the use of technologies for clean energy (b) is still under development, and the pollution level is low. The total amount of energy is n, and the utilization ratio of the two types of energy is p_a and p_b, $p_a + p_b = 1$ The utilization degree of the two kinds of energy is determined by e_a and e_b. Therefore, the actual input of the two types of energy is $e_a p_a N$ and $e_b p_b N$. If the total amount of energy remains unchanged, then the actual input of energy factors is mainly affected by the energy structure and efficiency. The equation of energy use is given by

$$N_t = N(e_a p_a + e_b p_b) \tag{9}$$

3.3. Economic Constraints

The aggregate output equals the sum of consumption and investment, and the equation is given by

$$Y_t = C_t + I_t \tag{10}$$

3.4. Environment

The pollution equation is given by

$$Pu = \omega (p_a N)^{\varepsilon_a} (p_b N)^{\varepsilon_b} \tag{11}$$

In Equation (11), Pu is the total amount of pollution emitted by the two types of energy. When the total amount of energy remains unchanged, the amount of pollution emissions depends on the energy structure. Among them, ε_a and ε_b are the elasticity of the pollution caused by the two types of energy. Then, ω is the proportional coefficient of dimensional adjustment between energy consumption and the amount of pollution (i.e., "pollution coefficient"). The pollution caused by the use of non-clean energy a is often greater than that of clean energy, that is, $\varepsilon_a > \varepsilon_b$.

The environmental motion equation is given by

$$E_{t+1} - E_t = Pu - \varphi\tau Y_t - \gamma E_t \tag{12}$$

Environmental pollution E_t can describe the state of the environment. The left side of the equation represents the change in environmental pollution from period t to $t + 1$. The right side of the equation can be divided into three parts: pollution caused by energy use Pu, pollution control by government expenditure $\varphi\tau Y_t$, and the environmental self-purification γE_t. Pu is directly linked to the energy structure, and when the energy structure changes, the amount of pollution changes accordingly. $\varphi\tau Y_t + \gamma E_t$ denotes the amount of environmental purification, and $\varphi\tau Y_t$ denotes the government pollution control. Moreover, φ denotes the proportion of government expenditure on pollution control in total output, and τ denotes pollution control ability. The self-purification of each period is denoted by γE_t. γ denotes the self-purification capacity of the environment, and the environment will purify itself based on the amounts of pollution.

3.5. Energy Technology Shock

Common exogenous shocks follow the first-order autoregressive process: $loge_t = \rho loge_{t-1} + \epsilon_t$. The function shows that when technology shock occurs, the fluctuation of the follow-up technology is affected by the positive shock and the fluctuation level of the previous state. However, the technological progress in this study is reflected in the improvement of energy efficiency, where higher output can be obtained by the same energy input. The proportion and type of energy will have an influence on the advancement of efficiency. Therefore, we consider the characteristics of the energy structure and set the energy technology shocks accordingly.

(1) As the proportion increases, the rate of technological progress increases. The energy with high proportion is used more generally than the energy with low proportion, thus the possibility of technological improvement in the process of using this kind of energy is higher. Technical improvement is mainly manifested in the way of "learning by doing." In the production process, the proficiency of workers will be improved, which will reduce energy consumption. Moreover, skilled workers will improve energy efficiency in the production process to obtain technical progress.

(2) As the level of development increases, the probability of positive technology shock decreases. When the history of energy development is long and the relevant technology is relatively mature, its efficiency will face bottlenecks. For example, although thermal power generation can reduce pollution and improve efficiency through refined coal use, its progress space is lower than that of clean energy. Therefore, when the energy-related technology is in the preliminary stage, the possibility of positive technology shock is high, and the external technological change likely promotes the improvement of the energy use efficiency. When the technical use of energy has been improved, the external technological change will promote the progress of energy technology with less possibility.

$$loge_t^a = \rho^{e^{p_a-1}} loge_{t-1}^a + \epsilon_t^a \tag{13}$$

$$loge_t^b = \rho^{e^{p_b-1}} loge_{t-1}^b + \epsilon_t^b \tag{14}$$

Considering the above two factors, this study describes the process of technological progress from the perspective of energy structure. The following equations can be obtained:

The technology shock equations given by Equations (13) and (14) have the following two characteristics: (1) If the proportion of energy (p_i) is high, then the energy efficiency is fast, which means high $\rho^{e^{p_i-1}}$. (2) If the level of technological development of energy is mature, then the potentiality of energy efficiency advancement is low, and ϵ_t^i is low. As a result, external technology shock promotes little extent to the efficiency of this energy.

Non-clean energy (a) mainly includes coal, oil, and other traditional energy, with a long history, relatively high proportion, mature use technology, and high pollution. On the contrary, clean energy (b) includes solar, wind, and marine energy, with a short history and a relatively low proportion. The development of technology is still in the initial stage, and the pollution is low.

According to the two characteristics of the technology shock equation, the improvement rate of the non-clean energy efficiency is higher than that of clean energy efficiency. By contrast, the improvement potential of non-clean energy efficiency is lower than that of clean energy efficiency.

In summary, 13 variables are included in this DSGE model: C_t, L_t, K_t, N_t, Y_t, I_t, r_t, w_t, e_t^a, e_t^b, E_t and two exogenous shocks. Three departments, households, manufactures and environment are considered and have correlation with each other in this model. In the following part, we will simulate the impulse response of 11 variables under clean energy technology shock and non-clean energy technology shock. The result is helpful to understand the impact of energy technology shocks on sustainable development under different energy structures.

4. Calibration Parameters and Simulation Results

On the basis of the constructed model, we can finally evaluate concretely the systematical and structured influence of long-term energy technology shocks over the entire dynamic economy, especially on sustainable development. In this part, we first calibrated the parameters inferring in the DSGE model, and then perform several simulation experiments to assess the energy technology shocks in the perspective of energy structure. In the basic experiment, we consider two simulations which differ in the kind of energy technology shock. In the following simulation, we furthermore consider the difference in energy structure. We set the proportion of clean energy desperately at 10%, 20%, and 40%, and then compare the impulse responses under different energy structures.

4.1. Calibration Parameters

In this study, the values of various parameters are calibrated by referring to previous literature and actual economic data. We apply the "calibration" method for the following two reasons. First, "calibration" is more convenient and rapid but less accurate than "estimation." This study aims to compare the differences in economic output and environment under different energy structures, rather than accurately simulate the real economy. Second, the policy mechanism and effect displayed by the DSGE model mainly depend on the setting of the initial model rather than the slight difference of parameter values, thus "calibration" is more applicable.

Referring to most studies, the range of subjective discount factor is 0.95–0.99, and the commonly used quarterly depreciation rate is 0.025. Therefore, this study sets the subjective discount factor β as 0.99, and the annual depreciation rate δ to 0.1. α_1, α_2, and α_3 represent the elasticity coefficient of capital, labor force, and energy, respectively. Following Sun and Jiang [40], the three values are calibrated to 40%, 45%, and 15%, respectively. σ and ω denote the elasticity coefficients of consumption and labor for residents, and from the estimation results of Chen [41], they were calibrated to 0.77 and 2.50, respectively. φ denotes the proportion of government spending on environmental protection. The ratio of environmental protection expenditure to GDP in developing countries is often less than 1%, whereas that in developed countries is approximately 3%. This study sets the proportion to 0.01. This study refers to the estimation of the normal decomposition rate of the ecological environment to carbon emissions to measure environmental self-purification capacity. Angelopoulos et al. [42] set such capacity to 0.1 after calibration. τ denotes pollution control ability. We calibrate the parameter as 1.16 based on the calibration result of Wu [43]. As mentioned, the characteristics of different energy technology shocks vary. Therefore, we impose a 1% positive shock on non-clean energy technology, and a 10% positive shock is applied to clean energy technology. Table 1 shows the specific parameter calibration table.

Table 1. Calibrated Parameters.

Parameter	Description	Value
β	Household's discount factor	0.99
σ	Personal preference for consumption	0.77
ω	Personal preference for labor	2.50
δ	Depreciation rate of physical capital	0.025
α_1	Output elasticity of capital in the production function	40%
α_2	Output elasticity of labor in the production function	45%
α_3	Output elasticity of energy in the production function	15%
ω	Pollution coefficient	1
ε_a	Elasticity of pollution caused by non-clean energy	0.95
ε_b	Elasticity of pollution caused by clean energy	0.05
φ	Proportion of pollution control expenditure in total output	0.01
τ	Pollution control ability	1.16
γ	Environmental self-purification ability	0.1
ρ	Autoregressive coefficient of technology shock	0.8
ϵ_t^a	Non-clean energy technology shock	0.01
ϵ_t^b	Clean energy technology shock	0.1

4.2. IR Analysis

We use MATLAB to simulate the impact of energy technology shocks and comparatively analyze the impact of energy technology shocks on various variables under different energy structures. In this section, we initially set the proportion of non-clean energy to 90% and analyze the effect of the two types of energy technology shocks on various economic variables. Then, we compare the characteristics of impulse response results under different energy structures.

4.2.1. IR under Different Energy Technology Shocks

In this part, the impulse response function is used to simulate the effect of the two kinds of energy technology shocks on the economic system.

Shock1: Clean energy technology shock

Figure 1 shows the impulse response after a 10% increase in clean energy technology. In Figure 1, the vertical axes mean the change ratio of the variable and the horizontal axes mean the periods after the shock. The increase in clean energy utilization will directly lead to an increase in energy input (N), deviating from the equilibrium state by approximately 1%. Moreover, the capital (K) and labor supply (L) are positively deviated from their equilibrium state by approximately 0.05%, and the range of change was lower than other variables. Over time, the capital stock (K) reached its maximum value in the 10th period, deviating from its equilibrium state by 0.15%, which was three times higher than its initial fluctuation. Investment (I) initially deviated positively by approximately 0.4% of its equilibrium state and has the highest deviation compared with other variables. The technological shock of clean energy will rapidly drive a substantial increase in investment levels, which is consistent with the situation in reality. Driven by the increase in investment level and energy input, the output (Y) has a positive deviation, which initially deviates from its equilibrium state by approximately 0.19%.

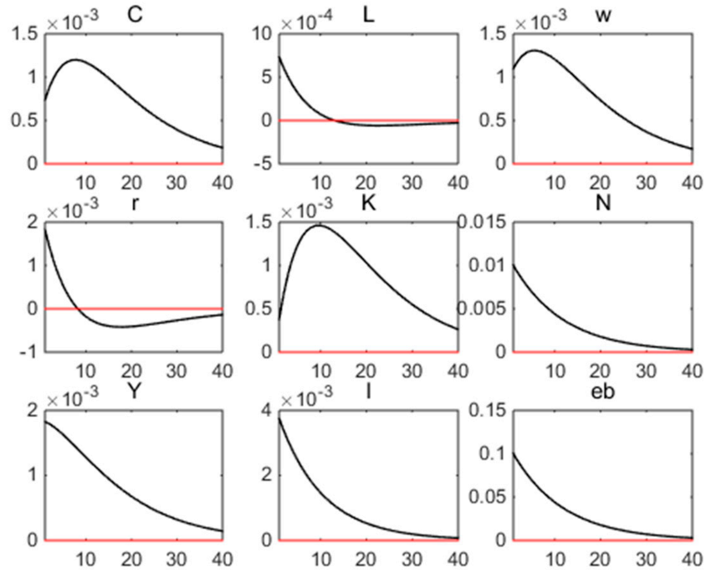

Figure 1. Impulse response of variables under clean energy technology shock.

By analyzing the variation characteristics of impulse response results, the following conclusions can be concluded:

(1) The technology shock of clean energy will promote macroeconomic growth. According to the results in Figure 1, the effect of energy technology shocks on energy use is the most direct, and that on investment is the most lasting. Under the co-promoting effect of increasing energy use and rising investment, energy technology shocks will eventually have a positive effect on economic output.

(2) In the fifth, seventh, and tenth periods, wage (w), consumption (C), and capital stock (K) deviate from the steady-state value farthest, reaching the highest level of fluctuation. Under the energy technology shock, the rise of energy use will promote additional output under the same labor input, and thence, the wage level of workers will be further improved. Furthermore, the increase of wages will promote the rise of consumption and savings and then promote the rise of capital through investment. Therefore, wages, consumption, and capital stock reach the highest fluctuation orderly.

(3) The impact of clean energy technology shock is conducive to improving the utility of residents and promoting the transformation of society to sustainability. By analyzing the changes in the rate of return on investment (r), wage (w), and labor time (L), their change ratios reach the bottom in the 14th period, and the deviation degree is always lower than the steady-state value. Moreover, the salary reached the highest level of positive deviation from the steady-state value in the fifth period, and the positive deviation has been maintained since then. Furthermore, the labor time reached the bottom at approximately the 22nd period, and a negative deviation was maintained since then. This changing trend means that in the early stage after the energy technology shock, the improvement of energy use efficiency promoted additional output per unit of capital and unit labor, thereby increasing capital return and wage. However, with the improvement of residents' consumption level and savings, capital increases rapidly, and thus, return on capital decreases to an even lower level than that before the energy technology shock, while the residents' wage level can remain on a positive growth trend. In the long run, the improvement of energy efficiency is conducive not only to economic development but also to the transfer of output value from the capital to the labor force and the improvement of employment rate and the overall living standard of society. Moreover, the labor supply (L) eventually declined compared with the initial one. Residents can obtain additional consumption with less labor, and thence, the residents' utility will increase significantly. The conclusion fully demonstrates that energy technology shock is conducive to the transformation of society

into sustainability, the improvement of residents' living standards, and the harmonious development of society.

In addition to the common macroeconomic variables, this study considers the change in the environmental pollution in the construction process of the DSGE model. Figure 2 depicts the impulse response of environmental pollution (E) after the clean energy technology shock.

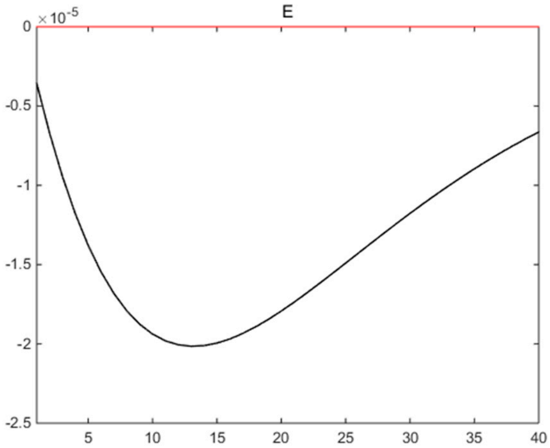

Figure 2. Impulse response of environmental pollution under clean energy technology shock.

Figure 2 shows that the improvement of energy use efficiency is significantly conducive to the reduction of environmental pollution, and the impact is lasting. The decline in pollution reached a peak in the 13th period, and a long-lasting negative trend was maintained after the 40th period.

Shock 2: Non-clean energy technology shock

When the economic system is affected by a 1% increase of non-clean energy technology, the characteristics of impulse response results in Figure 3 are similar to that of impulse response under shock 1. However, significant differences were observed in specific fluctuation amplitude and duration.

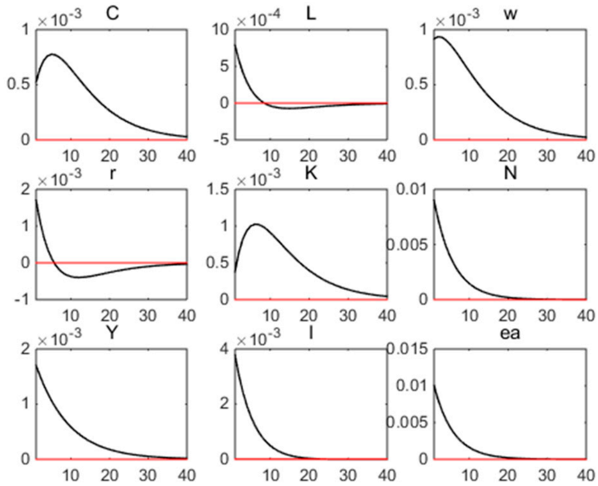

Figure 3. Impulse response of variables under non-clean energy technology shock.

From the amplitude of fluctuations, under shock 1, the range of economic variables deviating from the steady value is greater than that of shock 2. Taking the capital (K) as an example, the deviation of capital from the steady-state value reaches the maximum value of 0.15% in the 10th period, which is three times higher than its initial fluctuation. In the case of shock 2, the deviation of the capital stock reaches the maximum value in the seventh period, which is only approximately two times higher than its initial fluctuation.

From the duration of fluctuations, the variables tend to stabilize faster and the duration of fluctuations is relatively short under the shock of non-clean energy technology compared with the situation of clean energy technology shocks. For example, in the case of shock 2, the rate of return on investment (r) tends to be stable in the 36th period, and the investment (I) tends to be stable in the 18th period. While in the case of shock 1, these variables still maintain a certain degree of fluctuation deviating from their steady-state values in the 40th period.

Figure 4 shows the impulse response result of environmental pollution (E). It can be found that Figures 2 and 4 have similarities and differences in characteristics. In terms of similarities, technology shocks of both energies have a negative effect on the amount of environmental pollution. After a certain period of time, the negative deviation of environmental pollution from the steady-state value reaches the maximum.

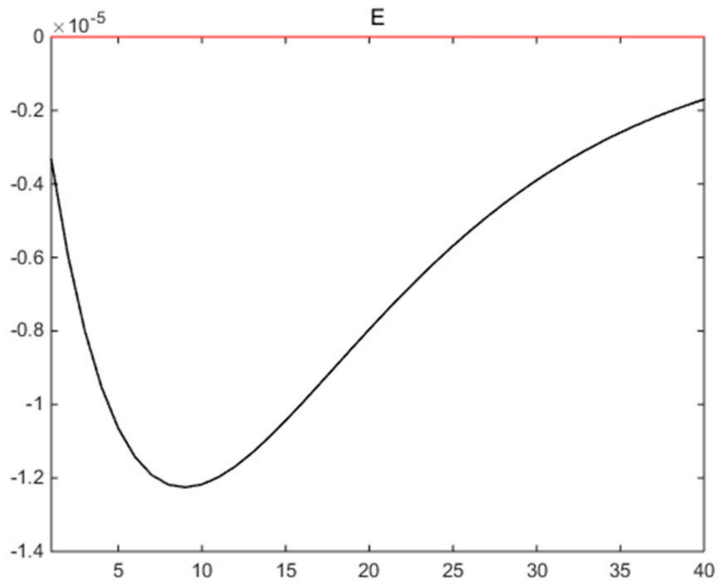

Figure 4. Impulse response of environmental pollution under non-clean energy technology shock.

The difference is that the negative effect of clean energy technology shock on environmental pollution is greatly lasting and significant. The maximum value of deviation from steady-state amplitude was reached in phase 7 in Figure 4, and it was reached in period 13 in Figure 2. This means the effect of clean energy technology shock on environmental pollution is comparatively enduring. Moreover, in the 40th period, the negative effect caused by non-clean energy technology shock was lower than the amplitude of deviation from the steady state in the initial period. While the negative deviation degree of environmental pollution after clean energy technology shock in the 40th period was still higher than the initial state.

4.2.2. IR under Different Energy Structures

In this section, the proportion of clean energy is set at 10%, 20%, and 40%. Under different energy structures, energy technology impact is applied to the variable output (Y) and environment pollution (E), which are concerned with the economy and environment. Figures 5 and 6 show the results.

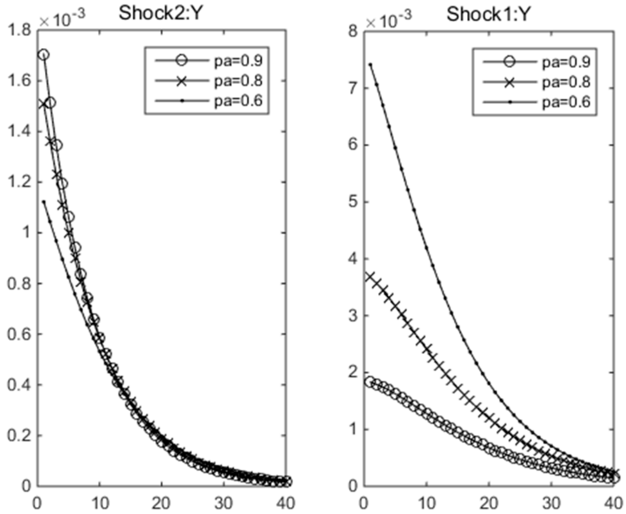

Figure 5. Impulse response of output under different energy structures.

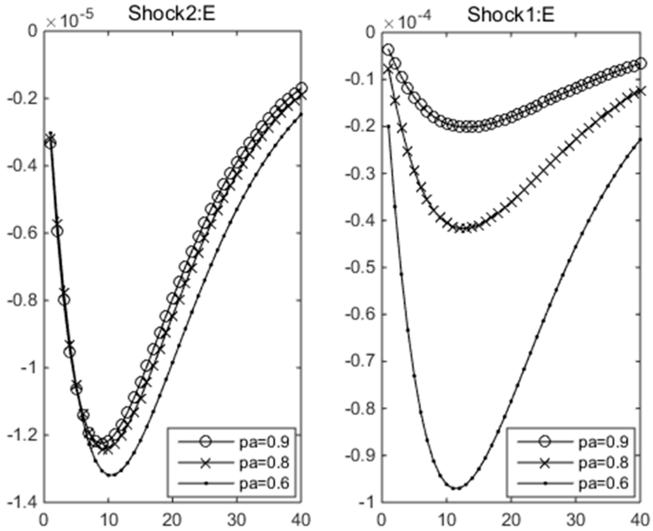

Figure 6. Impulse response of environmental pollution under different energy structures.

Comparing the impulse response results of two types of energy technology shocks to output (Y) in Figure 5, the impact of energy technology shocks on output significantly varies under different energy structures.

When shock2, namely, a non-clean energy technology shock occurs, the impulse response analysis of the output under different energy structures can be obtained. At the initial stage after the technology shock, significant differences in output changes are observed. In the early stage after the technology shock of non-clean energy, the change in output increased with the increase in the proportion of non-clean energy. This result is consistent with the expectation that the influence of a high proportion of energy on the economy will be greatly significant. In the mid-to-late period after the technology shock of non-clean energy, the range of output changes under different energy structures gradually approached and even turned upside down. After the 20th period, in the case of non-clean energy accounting for 90%, the positive deviation of output has been lower than that in the other two situations. This result means that when non-clean energy accounts for a relatively high proportion (90%), although non-clean energy technology can positively affect economic growth, in the long run, such effects are extremely limited.

When shock1, namely, a clean energy technology shock occurs, the impulse response analysis of the output can be obtained. At the initial stage after the clean energy technology shock, as the proportion of clean energy increases from 10% to 40%, the positive promotion effect of clean energy technology shock on economic growth is significantly increased. On the contrary, in the mid-to-late period of technology shocks, when the proportion of clean energy is 40%, the positive deviation range of output can still maintain a high range. In addition, this deviation range of output is higher than that when the proportion of clean energy is low.

Comparing the impulse response results of two types of energy technology shocks to environmental pollution (E) in Figure 6, the effect of energy technology shocks on environmental pollution significantly varies under different energy structures.

When shock2, namely, a non-clean energy technology shock occurs, the impulse response analysis of the output under different energy structures can be obtained. At the initial stage after the non-clean energy technology shock, the changes in the environmental pollution in different energy structure situations are very close, with almost no difference. In the mid-to-late period after the non-clean energy technology shock, when non-clean energy accounts for 60%, the decline in environmental pollution is lower than that in the other two situations. This result means that the technological advancement of non-clean energy is conducive to the growth of total output (Y) and thus promotes the rise of pollution control expenditures. However, the negative effect of high pollution emissions caused by the use of non-clean energy on the environment is greatly evident. Therefore, the efficient management of environmental pollution requires the optimization of energy structure, and blindly pursuing the progress of energy technology is not feasible.

When shock1, namely, a clean energy technological shock occurs, in the entire period after the occurrence of a technology shock, the negative deviation degree of environmental pollution increases significantly corresponding with the decrease of the proportion of non-clean energy. Furthermore, in the early stage after the technology shock, under different energy structures, the gap of negative deviation degree of environmental pollution increased with time and reached the maximum value in the 12th period.

Based on the comparative analysis of the above impulse response results, this study summarizes the following conclusions on how the energy structure affects sustainable development capability.

(1) The effect of non-clean energy technology shock is highly conducive to sustainable development. Compared with non-clean energy, the effect of clean energy technology shock on economic growth and overall social living standard is more significant and lasting.

(2) The optimization of energy structure is conducive to the enhancement of sustainable development capability. From the perspective of output growth, when the proportion of non-clean energy is high, non-clean energy technology shock can positively affect economic growth, whereas, in the long run, this effect is extremely limited. From the perspective of pollution, regardless of whether non-clean or clean energy technology shock, when the proportion of non-clean energy is 40%, the degree of negative deviation of environmental pollution is greater than the other two cases. Therefore, the influence of energy technology shocks on the environment depends on the energy structure rather than the type of technology shocks.

5. Empirical Analysis and Discussion of Results

The impulse response results of the DSGE model show that the effect of clean energy technology is greatly conducive to sustainable development. Then, the optimization of the energy structure is conducive to the enhancement of sustainable development capability. Furthermore, this study verifies the above conclusion from the perspective of data validation.

5.1. Sustainability Index

Considering that there is no clear index existing to describe sustainable development capability. Therefore, for the concept of sustainable development capability, this study needs to build a sustainability index to measure sustainability development capability.

5.1.1. Establishment of a Sustainability Index

The sustainability index mainly includes three elements; namely, economically, socially, and environmentally sustainable development. Among them, economic sustainable development mainly considers economic development and technological progress, and socially sustainable development includes social and population elements. Finally, the first-level indicators are established as economy, society, environment, population, and technology. The ability of macroeconomic sustainable growth is comprehensively measured through these five indexes. The sustainability index constructed in this study includes 29 tertiary indicators, 10 secondary indicators, and 5 primary indicators, as shown in Figure 7.

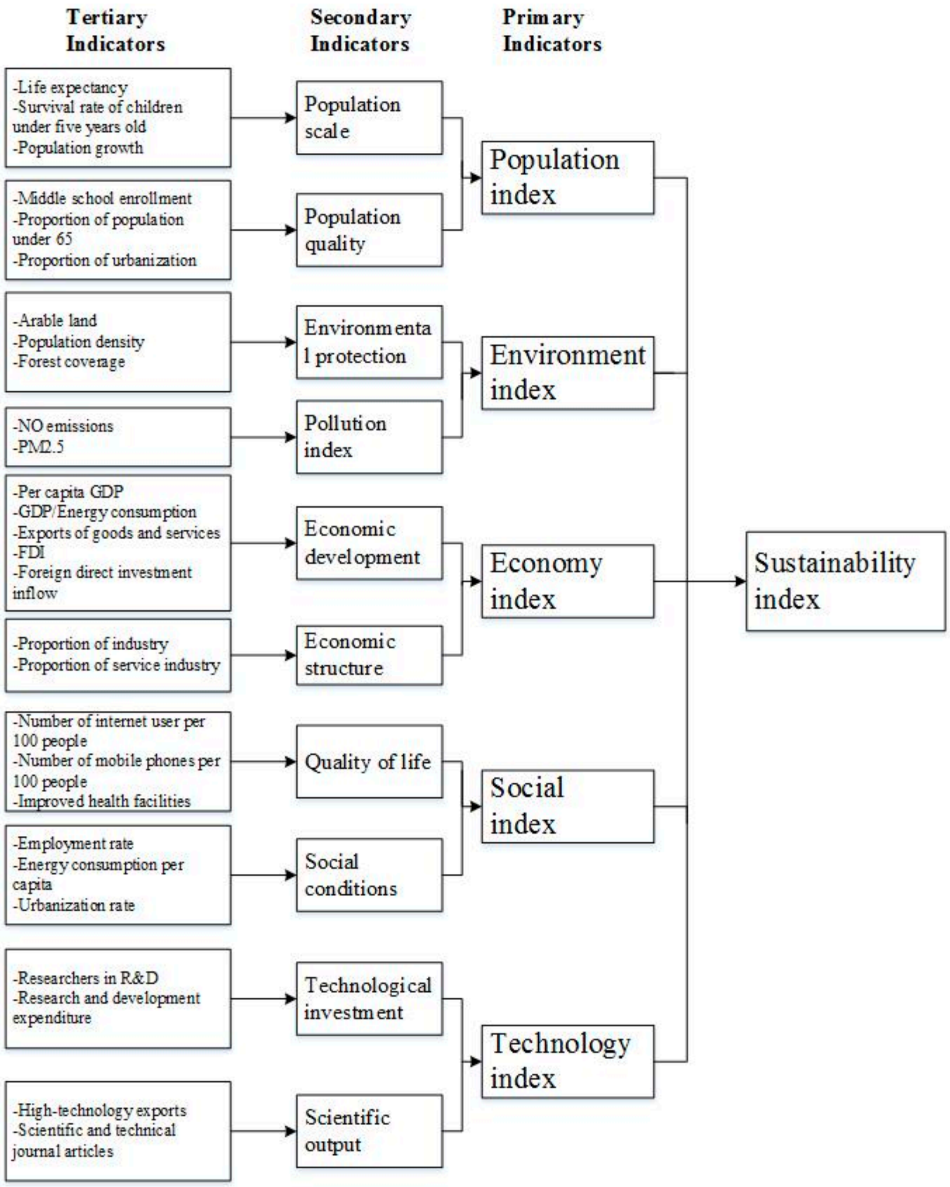

Figure 7. Establishment of a sustainability index.

5.1.2. Calculation of Sustainability Index Scores

The calculation of sustainability index scores is based on the data of 29 tertiary indicators. The data used in the calculation in this study all can be obtained from World Bank Database and WIND database. Open data is essential to promote open science practices, and create an effective science-policy interaction [44]. World Bank offers free and open access to global development data which is commonly used in similar studies [45]. As a result, it is feasible for readers who are interested in the sustainability index scores calculated in this paper to replicate the calculation results. Considering the integrity and representativeness of the data, this study takes the data of 68 countries in 2017 as the sample data. Furthermore, the sustainability index is applied to calculate 68 countries' sustainability index scores in 2017.

In the calculation process, considering the difference of index dimensions, this study adopts the normalization method to deal with the data dimensionless, so that each index value is comparable. The tertiary indexes selected in this study are mostly benefit index, which can be treated by Formula (15), whereas the cost index, such as nitric oxide emissions and PM2.5, can be treated by Formula (16).

$$x_{ij}^* = \frac{x_{ij} - minx_j}{maxx_j - minx_j} \tag{15}$$

$$x_{ij}^* = \frac{maxx_j - x_{ij}}{maxx_j - minx_j} \tag{16}$$

In the process of determining the weight, this study uses the objective weighting method, combined with the entropy method and coefficient of variation method to estimate the weight of all levels of indexes. The variation coefficient method is suitable for the determination of the internal indexes of each factor but does not pay enough attention to the specific economic significance of the indexes. The limitation of the entropy method is that this method is too sensitive to abnormal data, which leads to the impractical comprehensive weight. Therefore, when we weight the tertiary indicators, the coefficient of variation method is used to provide a great weight to the indexes with a large standard dispersion degree and a low weight to the indexes with a low standard dispersion degree. Equations (17) and (18) show how to calculate the coefficient of variation cv_{ij} and the weight w_j.

$$cv_{ij} = \frac{\sigma_i}{\overline{x_j}} \tag{17}$$

$$w_j = \frac{cv_{ij}}{\sum_{j=1}^{n} cv} \tag{18}$$

After obtaining the weight of the tertiary index, the corresponding index value of the secondary index is obtained based on the normalized result and the weight obtained by the coefficient of variation method. At this time, the entropy value method is used to weight the secondary indicators. The entropy value method can measure the information content provided by the index value. If the entropy of an index is great, then the degree of variation in the index value is low, and the information content is less. The calculation steps are as follows: The first step is to calculate the proportion p_{ij} of the index value of the country i under the index j. Equation (19) shows the calculation formula, where r_{ij} is the index value corresponding to country i under the index j. The second step is to calculate the entropy value e_j of the indicator j, as shown in Equation (20). In $k = 1/lnm$, m is the number of countries participating in the evaluation. The third step is to calculate the weight w_j of the index j as shown in Equation (21), where n is the number of indexes.

$$p_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}} \tag{19}$$

$$e_j = -k \sum_{i=1}^{m} p_{ij} ln p_{ij} \tag{20}$$

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{n} 1 - e_j} \tag{21}$$

Furthermore, the secondary index values are normalized and weighted, and the corresponding index values of the primary index are calculated through the weighted arithmetic average method. After obtaining the index value, the entropy method is again used to weight the primary indicators, and the sustainability index scores of 68 countries in 2017 are finally calculated. Table 2 shows the sustainability index scores and ranking of 68 countries.

Table 2. Sustainability index scores and rankings of 68 countries in 2017.

Rank	Country	Sustainability Index	Rank	Country	Sustainability Index
1	Iceland	0.845	35	Serbia	0.280
2	Sweden	0.776	36	Oman	0.272
3	Denmark	0.762	37	Turkey	0.265
4	Norway	0.703	38	Kuwait	0.258
5	Finland	0.696	39	Argentina	0.256
6	Canada	0.639	40	Costa Rica	0.255
7	Netherlands	0.608	41	Tunisia	0.253
8	Austria	0.597	42	Romania	0.249
9	United States	0.595	43	Chile	0.241
10	Germany	0.594	44	Uruguay	0.236
11	Japan	0.581	45	Ukraine	0.221
12	Belgium	0.573	46	South Africa	0.214
13	France	0.542	47	Montenegro	0.211
14	Malaysia	0.527	48	Colombia	0.207
15	Luxembourg	0.527	49	Morocco	0.196
16	United Kingdom	0.514	50	Jordan	0.193
17	Ireland	0.504	51	Algeria	0.191
18	Slovenia	0.500	52	Angola	0.182
19	Estonia	0.476	53	Indonesia	0.176
20	Portugal	0.416	54	North Macedonia	0.174
21	Spain	0.402	55	Mauritius	0.173
22	Malta	0.398	56	Paraguay	0.169
23	Hungary	0.391	57	Moldova	0.167
24	China	0.380	58	Georgia	0.166
25	Greece	0.373	59	Iraq	0.161
26	Italy	0.369	60	El Salvador	0.145
27	Poland	0.365	61	Sri Lanka	0.141
28	Latvia	0.331	62	Guatemala	0.122
29	Cyprus	0.321	63	Uzbekistan	0.120
30	Thailand	0.321	64	Honduras	0.116
31	Kazakhstan	0.306	65	Myanmar	0.116
32	Croatia	0.294	66	Pakistan	0.099
33	Vietnam	0.291	67	Togo	0.092
34	Bulgaria	0.280	68	Ethiopia	0.080

5.2. Empirical Test

After calculating the sustainability index score of each country, we selected the proportion of clean energy and the national sustainability index scores of 68 countries in 2017 to draw a scatter diagram, as shown in Figure 8.

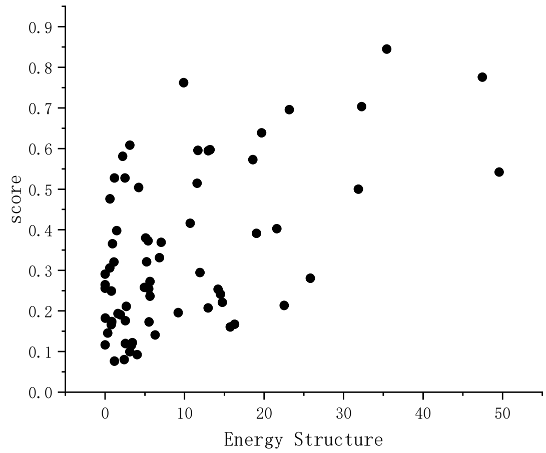

Figure 8. Scatter diagram of energy structure and sustainability index scores.

The scatter distribution in Figure 8 shows the significant positive correlation between energy structure and sustainability index scores. A linear regression equation $y_t = \beta_0 + \beta_1 x_t + \varepsilon_t$ was constructed to measure this relationship accurately. y_t is the sustainability index score, and x_t is the proportion of clean energy. The fitting result is $y_t = 0.2469 + 0.0097 x_t$. Each coefficient passed the significance test of 1%, and R^2 was 0.30, which means a high correlation between energy structure and sustainable development capability. The results show that countries with a high proportion of clean energy tend to have high sustainable development capability, which is consistent with the conclusion of the DSGE model.

According to the classification of energy structure in impulse response analysis, the proportion of clean energy can be divided into three ranges: $\leq$10%/10–20%/$\geq$20%. Among the 68 countries in the sample, 44 countries (64.7%) with clean energy are at less than 10%, 15 countries (22.1%) with clean energy are at 10–20%, and 9 countries (13.2%) with clean energy are at more than 20%. We analyze the five primary index scores in the three ranges to further compare the differences in sustainable development capability under different energy structures, and Figure 9 is obtained.

Figure 9. Comparison of primary index scores under different energy structures.

Figure 9 shows the following: (1) From the overall scores of sustainable development capability, when the proportion of clean energy is higher than 20%, the overall score of its sustainable development capability is significantly higher than that when the proportion of clean energy is lower than 20%. (2) In terms of various primary indexes of sustainable development capability, countries with a clean energy proportion of less than 10% have higher scores in the economic index, but the gap is extremely limited compared with the other two categories. For the environmental, technology, and social indexes, countries with a clean energy proportion of less than 10% obtained significantly low scores.

The comparison results of primary index scores show that the results of the data are consistent with the impulse response results of the DSGE model. Although the use of non-clean energy is conducive to economic growth, the positive effect is extremely limited in the long term. Relatively, for the environment and society, the high proportion of clean energy has a significant role in promoting them. Therefore, the optimization of the energy structure is conducive to the enhancement of sustainable development capability.

6. Conclusions

This study aims to explore the relationship between energy structure and sustainable development capacity. First, this study incorporates energy into the DSGE framework, which helps consider the energy structure, energy pollution, and energy technology. Second, based on the DSGE model, impulse response analysis is carried out from two dimensions: one is to analyze IRFs under different energy technology shocks, and the other is to compare IRFs of output (Y) and environmental pollution (E) under different energy structures (the proportion of clean energy is set to 10%, 20%, and 40%). Finally, this study constructs the sustainability index and compares sustainability index scores and the proportion of clean energy of 68 countries in 2017 to demonstrate the conclusions of the DSGE analysis framework. The main conclusions are as follows:

(1) The positive shock of clean energy technology is highly conducive to sustainable development, but differences exist in economic, social, and environmental performance. From the perspective of the economy, compared with the shock of non-clean energy technology, the positive technology shock of clean energy on economic growth does not have significant advantages at the initial stage. However, from the perspectives of society and the environment, the positive shock of clean energy technology is significantly conducive to the harmonious development of society and the sustainability of environmental ecology. This effect is also a relatively long term.

(2) The optimization of energy structure is conducive to the enhancement of sustainable development capability. From the economic perspective, when the proportion of non-clean energy is relatively high, non-clean energy technology can positively affect economic growth, but in the long run, this effect is extremely limited. From a social perspective, countries with a high proportion of clean energy tend to rapidly develop. From the environmental perspective, the effect of energy technology shocks on the environment depends on the energy structure and not the type of energy technology shocks.

The policy implications of the above conclusions include the following:

(1) For countries with a high proportion of non-clean energy (most of which are developing countries), when their policy objective is short-term economic growth, they can focus on improving the efficiency of non-clean energy. Moreover, when their policy objective is long-term sustainable economic growth, they should pay attention to optimizing the energy structure and promoting clean energy efficiency.

(2) For countries with a high proportion of clean energy (most of which are developed countries), their policy objectives often focus on the coordinated development of economy, environment, and society. Therefore, these countries should adopt reasonable energy policies to promote the optimization of energy structure. It would be significant for developed countries to push forward the exploration of clean energy storage technology and grid connected technology. The optimization of energy structure is conducive to promoting sustainable development from the social and environmental aspects. The positive effect of energy technology shocks on society and the environment depends on the energy structure rather than the type of energy technology shocks.

Author Contributions: Conceptualization, D.S. and N.C.; methodology, D.S.; software, D.S.; validation, D.S., F.W. and J.C.; formal analysis, N.C.; investigation, J.C.; resources, F.W.; data curation, J.C.; writing—original draft preparation, D.S.; writing—review and editing, F.W.; visualization, F.W.;

supervision, N.C.; project administration, N.C.; funding acquisition, N.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Fundamental Research Funds for the Central Universities, grant number 21lzujbkyjh012.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Publicly available datasets were analyzed in this study. This data can be found here: [https://data.worldbank.org.cn/indicator, accessed on 9 June 2021]. The data presented in this study had been processed by the authors and they are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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