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Innovation Input, Climate Change, and Energy-Environment-Growth Nexus: Evidence from OECD and Non-OECD Countries

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Abstract: With economic growth and rising incomes, increasing consumption of fossil energy is leading to environmental pollution and climate change, which requires increased innovative inputs to promote the efficiency of renewable energy use. Considering the important impact of innovation input and climate change on renewable energy consumption, greenhouse gas emissions, and green economic growth, this study uses simultaneous equation and sys-GMM model to explore the dynamic nexus of innovation input, climate change, and energy-environment-growth in OECD and non-OECD countries, with panel data covering 2000 to 2019. The empirical results show that renewable energy consumption in non-OECD countries significantly promoted green economic growth, while OECD countries did the opposite. Moreover, renewable energy consumption significantly reduces greenhouse gas emissions caused by climate change, especially for OECD countries. When the level of economic growth exceeds a certain inflection point, greenhouse gas emissions begin to turn from positive to negative, which further verifies the EKC hypothesis. In addition, this study found that innovation input has significantly increased renewable energy consumption, reduced greenhouse gas emissions, and promoted green economic growth in OECD countries. Finally, this study also found that the impact of innovation input in OECD and non-OECD countries on the energy-environment-growth nexus is greater in the short term and more significant in the medium and long term, while the impact of climate change on the energy-environment nexus in OECD and non-OECD countries is more significant in the medium and long term.

Keywords: innovation input; climate change; renewable energy consumption; greenhouse gas emissions; green economic growth; simultaneous equation model

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1. Introduction

Increasing fossil energy consumption aggravates the problems of energy shortage and environmental pollution, resulting in an increase in greenhouse gas emissions [1,2]. While long-term large-scale greenhouse gas emissions are the key reason for extreme weather change [3]. To strengthen the governance of global climate and environment to promote green economic growth, the Paris Climate Agreement clearly puts forward the development of a low-carbon economy [4]. However, the increasing weather events further exacerbate the energy consumption for temperature regulation [5]. Driven by economic growth and increasing income, the energy consumption and greenhouse gas emissions in Organization for Economic Co-operation and Development (OECD) countries tend to be higher than that in non-OECD countries, and then needs to increase innovation input and improve the utilization rate of renewable energy [6]. Therefore, this paper explores the dynamic nexus of innovation input, climate change, and energy-environment-growth in OECD and non-OECD countries, which helps the policymaker to formulate differentiated energy and environmental policies to promote innovation input, increase renewable energy consumption and achieve green economic growth

Most studies have shown that energy consumption in response to temperature change varies greatly among countries in different climate regions [7–9]. Specifically, OECD countries are generally located in high latitudes with huge temperature differences, that is, hot summer and cold winter, while non-OECD countries are on the contrary In addition, according to the Environmental Kuznets Curve (EKC) hypothesis, when the economic income of OECD countries reaches a certain level, they begin to gradually pay attention to the improvement of the ecological environment [10]. With the support of high innovation input, energy efficiency and renewable energy consumption began to improve significantly, and greenhouse gas emissions gradually decreased [11]. In this context, based on the panel data of 35 OECD and 36 non-OECD countries from 2000–2019, this paper further examines the nexus of energy-environment-growth under the differentiated innovation input, which provides theoretical support for the EKC hypothesis.

Compared with the existing literature [12–14], using simultaneous equation and system generalized method of moments (sys-GMM) model is an effective method to explore the dynamic nexus of innovation input, climate change, and energy-environment-growth. As we all know, from the perspective of the production function, the framework of energy-environment-growth includes three important equations: production equation, energy consumption equation, and pollution equation, and each equation provides a reference for further research in this field [15,16]. Moreover, cross-validation shows that the three equations should not be studied separately, which confirms that the simultaneous equations can effectively estimate the dynamic nexus of renewable energy consumption, greenhouse gas emissions, and green economic growth, and help to generate reliable empirical research conclusions [17,18].

This paper is dedicated to exploring the impact of innovative inputs, climate change on renewable energy, consumption of greenhouse gas emissions, and green economic growth. The contributions of this paper are in the following four aspects: First, this paper creatively introduces innovation inputs and climate change into the energy-environment-growth research framework to study their effects on renewable energy consumption, greenhouse gas emissions, and green economic growth. Second, this paper analyzes the differences in the effects caused by the heterogeneity of the sample intervals, and examines the dynamic relationship between innovation inputs, climate change, and energy-environmental growth comprehensively and systematically in the short (2015–2019), medium (2010–2019), and long term (2000–2019), respectively, further confirming the EKC hypothesis. Third, this paper uses frontier simultaneous equations and sys-GMM models to reveal the dynamic relationship among innovation inputs, climate change, and energy-environmental growth, which can better solve the heteroskedasticity, autocorrelation, and endogeneity problems in the model. Fourth, considering the accuracy and comprehensiveness of variable calculation this paper uses principal component analysis to construct the green economic growth index from four dimensions: economic development, resources and environment, globalization, and urban construction (see Table 1). Finally, according to the research results, this paper provides targeted suggestions for the government to develop differentiated energy and environmental policies to promote carbon emission reduction and green economic growth.

Table 1. Indicator system of green economic growth.

Primary Index	Secondary Index	Tertiary Indicators	Symbol	Unit
Green economic growth index	Economic development	Per capita GDP	X1	Dollar
		Final consumption expenditure	X2	Dollar
		Inflation consumer Prices	X3	Dollar
		Taxes on income, profits, and capital gains	X4	
	Resource environment	Per capita energy consumption	X5	kg of oil
		Total natural resources rents in GDP	X6	%
		CO_2 emissions	X7	Kt
		Forest area	X8	Sq.km
	Globalization	Proportion of exports of goods and services in GDP	X9	%
		Proportion of trade in GDP	X10	%
	Urban construction	Agriculture, forestry, and fishing, value added per worker	X11	Dollar
		Population growth	X12	%

2. Literature Review

Energy-environment-growth nexus studies the causality among energy consumption, environmental pollution, and economic growth. Considerable foregoing discussions about this nexus have employed the method of the Granger causality test [19], while the simultaneous equation model is less familiar. To be specific, the granger causality test can only detect whether there is a causal relationship between the concerned variables, but not the relationship sign and sensitivity. However, the simultaneous equation model does not have this limitation. It can not only detect the sign and sensitivity between variables, but also add other essential control variables to avoid missing variables.

In recent decades, the energy-environment-growth nexus has been the subject of a great deal of academic research. There are three branches of research in the literature that deals with the relationships between target variables. The first branch of research focuses on the relationship between economic growth and environmental pollution. Existing literature relies heavily on the Environmental Kuznets Curve (EKC) hypothesis when studying the relationship between the two variables. Stern [20] asserts that the degree of environmental degradation first increased and then decreased with the increase of the GNP per capita. In addition, the degree of environmental degradation is usually measured by air pollution. Some empirical studies verify the EKC hypothesis, such as Naseem et al. studied the relationship between economic development and pollutant gas emissions in OECD and non-OECD countries [21]. And Nasir and Ur-Rehman [22] and Saboori et al. [23] confirmed the existence of the EKC hypothesis by examining the long-term relationship between greenhouse gas emissions (GHGs) and income in Malaysia and Pakistan, respectively.

The second branch investigates the relationship between energy consumption and economic growth. Since the initial study of Kraft [24], the nexus between energy and economy has been the focus of discussion among scholars [25–27]. However, in the existing literature, scholars have several different views on the existence and direction of the causal relationship between these two variables. Soytas and Sari [28] believed that there is no significant causal relationship between energy consumption and economic growth, and supports the neutral hypothesis. Huang et al. [29] pointed out that in middle-income and high-income countries, the economy can affect energy consumption, and supported the conservation hypothesis. In addition, Saidi and Hammami [30] indicated that energy consumption has a significant stimulative effect on economic growth, which supported the feedback hypothesis that there is a two-way causal relationship between the two variables [31,32]. The third branch is related to energy consumption and GHGs. There is a consensus that energy consumption is the main source of GHGs [33–35].

2.1. Climate Change and the Energy-Environment-Growth Nexus

According to the vast majority of literature now available, the energy-environment-growth nexus studies which use the simultaneous equation model have not considered that climate affects energy and the environment in many ways, although extreme temperature changes could distinctly affect energy consumption, and thus GHGs. For example, Considine [36] evaluated the driving factors of GHGs, and the results of the linear logit model indicated the impact of weather changes on GHGs is considerable. That is, the hot summer increases the demand for air conditioning and electricity, which in turn increases energy consumption. While cold winter increases the demand for heating fuel, such as coal, oil, and natural gas. Studies have shown that the consumption of traditional energy sources in both OECD and non-OECD countries will inevitably lead to an increase in greenhouse gases and thus affect economic growth [37].

The environment affects the economy and energy in many ways, and there is heterogeneity in the impact of the environment on economic growth and energy efficiency in OECD and non-OECD countries [38,39]. At the same time, the abnormal temperature will affect the economy in many aspects, causing damage to green economic growth [40,41]. The emergence of extreme temperatures hinders short-term and long-term economic development and affects indicators such as employment and profitability [42,43]. However, the impact of climate change on green economic growth has not been widely studied in the existing literature.

2.2. Innovation Input and the Energy-Environment-Growth Nexus

On the role of innovation input in economic growth, a large amount of literature gives almost the same conclusion. In contrast, there are fewer studies on the impact of innovation input on GHGs and energy consumption, especially the impact of innovation input on the energy-environment-growth nexus. Chen and Lei [44] suggested that technological innovation has played an important role in improving energy efficiency and reducing energy consumption. But technological innovation has a greater impact on countries with higher GHGs than on countries with lower GHGs. Zakari et al. studied the factors influencing green innovation in OECD and non-OECD countries respectively [45]. And Khan et al. [26] examined that technological innovation can reduce GHGs and boost economic growth in BRICS countries. The improvement of innovation input is helpful to develop renewable energy and improve energy efficiency, to ensure energy security and achieve green economic growth.

2.2.1. Innovation Input and Economic Growth

A large number of existing literature believed that innovation input is the pillar of economic growth, a key factor to promote green economic growth, and even the power and source of human social development [46,47]. From the perspective of neoclassical economics, Thompson [48] elaborated his point of view: with the development of an innovation economy, social capital will grow internally with the increase of monopolistic competitors' profits and production. In other words, innovation input and economic growth can promote each other and develop together. Adak [49] cites structural changes in Turkey's economy over the past 35 years as evidence of the impact of technological progress and innovation input on economic growth. In this model, innovation input has become a key endogenous variable of the total production function, and innovation input has brought high productivity and rapid positive growth to the economy.

2.2.2. Innovation Input and Environment Pollution

With regard to innovation input and environment pollution, most scholars believe that the impact of innovation input on GHGs is linear and one-way [50,51]. In a detailed analysis of G20 countries, Erdoğan et al. [52] argue that innovation input in different sectors will have different impacts on GHGs. Increased innovation input in the industrial sector leads to reduced GHGs, while increased innovation input in the construction sector leads to the opposite result. At the same time, a few studies believe that there is a non-linear two-way relationship between them. For instance, Carrión-Flores and Innes [53] pointed out that there is a two-way causal relationship between innovation input and environmental pollution. Innovation input was an important driving force of environmental pollution, and strict pollution control targets will promote the improvement of innovation input.

2.2.3. Innovation Input and Energy Consumption

Sun et al. [54] examined the relationship between innovation input and energy consumption, and testified that innovation input has a positive impact on improving energy efficiency and reducing energy intensity. Wurlod and Noailly [55] analyzed the impact of innovation input on the energy intensity of 14 industrial sectors in 17 OECD countries, and found that innovation input contributed to the decline of energy intensity in most industrial sectors. In conclusion, these studies compelling indicate that climate change and innovation input play a very important role within the energy-environment-growth nexus. Therefore, in the following study on the energy-environment-growth nexus, this paper introduced the two variables of climate change and innovation input.

In general, the existing literature mostly studies the correlation between fossil energy consumption, carbon emissions, and economic growth. It is found that when the economic income level is low, fossil energy consumption and carbon emissions are more, while when the economic income level is high, it is the opposite. The difference is that this paper creatively introduces innovation input and climate change into the framework of renewable energy consumption, carbon emissions, and green economic growth further analyzes the dynamic nexus of innovation input, climate change and energy-environment-growth, and then verifies the EKC hypothesis.

3. Methodology

3.1. Production Function

Many countries are interested in energy-environment-growth nexus, which has gradually become a worldwide problem [56]. In this context, this paper draws on the research results of other scholars and regards energy consumption as a production factor within the nexus [57]. Moreover, innovation input is rarely included in the nexus, which reflects a country's science and technology level. In summary, the augmented Cobb-Douglas production function is as follows:

$$geg = Ak^{\alpha 1}e^{\alpha 2} \tag{1}$$

where *geg* is the green economic growth, which is calculated by the PCA method and consists of twelve indicators as shown in Table 1 [58,59]. *A* is the total factor productivity, *k* is the capital per capita, and *e* is the proportion of renewable energy consumption.

After logging, *i* denotes the country and *t* denotes the time period as follows:

$$geg_{it} = \alpha_{it} + \alpha_1 k_{it} + \alpha_2 e_{it} \tag{2}$$

Assuming that green economic growth depends on innovation input it becomes:

$$a_{it} = \alpha_0 + \alpha_4 ino_{it} + \varepsilon_{1,it} \tag{3}$$

Combining Equations (3) and (4), we can get:

$$geg_{it} = \alpha_0 + \alpha_1 k_{it} + \alpha_2 e_{it} + \alpha_3 ino_{it} + \varepsilon_{1,it} \tag{4}$$

Because capital, renewable energy consumption, and innovation are conducive to green economic growth, they are expected to have a positive impact on green economic growth, indicating that α_1, α_2, and α_3 should be positive. Since pollution is not significant in the estimation and obeys the standard production function theory, we do not introduce pollution as an explanatory variable.

3.2. Energy Consumption Function

Referring to previous literature on the energy-environment-growth nexus [60,61], innovation input and climate change are included in the energy consumption function as follows:

$$e_{it} = \beta_0 + \beta_1 geg_{it} + \beta_2 ind_{it} + \beta_3 ino_{it} + \beta_4 stemp_{it} + \beta_5 wtemp_{it} + \varepsilon_{2,it} \tag{5}$$

where *e* is the proportion of renewable energy consumption, *geg* is green economic growth, *ind* is industrialization, *ino* is innovation input, *stemp* is the average temperature of three months in summer and wtemp is the average temperature of three months in winter, ε_2 is the error term.

3.3. Pollution Function

To update the pollution function [62], innovation input and climate change have been included in the pollution function as follows:

$$pol_{it} = \gamma_0 + \gamma_1 geg_{it} + \gamma_2 geg_{it}^2 + \gamma_3 e_{it} + \gamma_4 ino + \gamma_5 stemp_{it} + \gamma_6 wtemp_{it} + \gamma_7 urb_{it} + \gamma_8 poli + \varepsilon_{3,it} \tag{6}$$

where *pol* denotes greenhouse gas emissions; *geg* denotes green economic growth; geg^2 denotes geg squared; *e* denotes the proportion of renewable energy consumption; *urb* denotes urbanization; *poli* denotes climate policy measured by whether the Kyoto Protocol is signed before 2016 or participation in the Paris Agreement after 2016. If the sample has participated in the above two agreements, we will record it as 1, on the contrary, we will record it as 0. Besides, stemp and wtemp respectively represent the average temperature of three months in summer and winter; and ε is the error term. All variables are logarithmic except stemp and wtemp.

From Equations (4)–(6), A three-dimensional simultaneous equation framework is used to analyze the energy-environment-growth nexus. In conclusion, the structural equations look as follows:

$$\begin{aligned} geg_{it} &= \alpha_0 + \alpha_1 k_{it} + \alpha_2 e_{it} + \alpha_3 ino_{it} + \varepsilon_{1,it} \\ e_{it} &= \beta_0 + \beta_1 geg_{it} + \beta_2 ind_{it} + \beta_3 ino_{it} + \beta_4 stemp_{it} + \beta_5 wtemp_{it} + \varepsilon_{2,it} \\ pol_{it} &= \gamma_0 + \gamma_1 geg_{it} + \gamma_2 geg_{it}^2 + \gamma_3 e_{it} + \gamma_4 ino + \gamma_5 stemp_{it} + \gamma_6 wtemp_{it} + \gamma_7 urb_{it} + \gamma_8 poli + \varepsilon_{3,it} \end{aligned} \tag{7}$$

3.4. The Estimation Method

As shown in Figure 1, based on the theoretical framework, the system estimation is applied to study the nexus of energy-environment-growth.

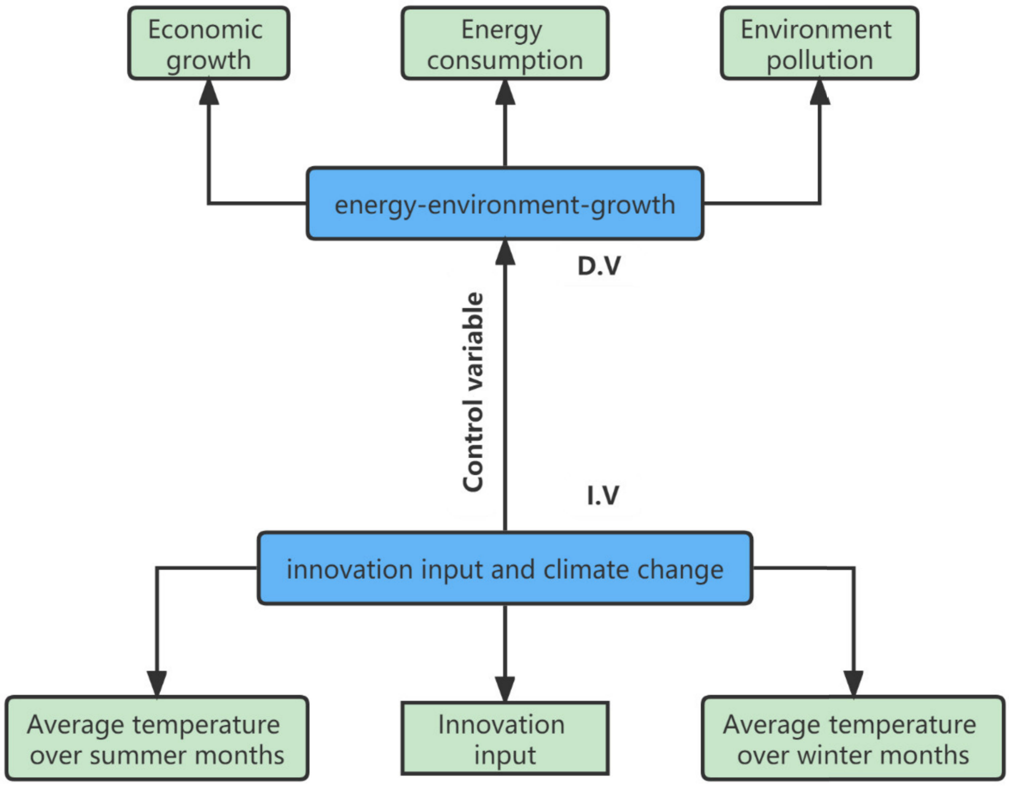

Figure 1. Conceptual framework.

The generalized method of moments (GMM) was first proposed by Hansen and has become one of the most popular measurement methods. Arellano and Bond [63] proposed a first difference GMM (diff-GMM) estimation method. However, Blundell and Bond [64] have found the first-order diff-GMM estimation method is vulnerable to the influence of weak instrumental variables and gets biased estimation results. To overcome the influence of weak instrumental variables, Arellano and Bover [65] and Blundell and Bond [64] proposed another more effective method system GMM (sys-GMM). With the energy-environment-growth nexus, Saidi and Hammami [66] and Sekrafi and Sghaier [67] used diff-GMM in their studies, while Bhattacharya et al. [68] used sys-GMM in the interrelationship of energy-environment-growth. The main advantage of these methods over other methods is that they rely on internal instruments for estimation. However, in the case of a reverse causal relationship, external instruments are the best. However, finding external tools is a difficult task, which varies across units and periods. Fortunately, Farhadi et al. [69] concluded that the internal tools used are different, and sys-GMM is the best choice to control the endogenous nature of explanatory variables.

$$y_{it} = x_{it}\beta + \varphi y_{i,t-1} + c_i + \varepsilon_{it} \tag{8}$$

where t denotes time, and i denotes the cross-section units (countries). It appears that the error terms consist of the fixed individual effects c_i and the idiosyncratic shocks ε_{it}. The properties of fixed individual effects and idiosyncratic shocks are attributed as

$$E(c_i) = E(\varepsilon_{it}) = E(c_i\varepsilon_{it}) = 0 \tag{9}$$

By taking the difference to eliminate the individual effects c_i from Equation (8) resulting in:

$$\Delta y_{it} = (\Delta x)_{it}\beta + \varphi(\Delta y_{i,t-1}) + \Delta\varepsilon_{it} \tag{10}$$

where Δ denotes the first difference operator.

Since Roodman [70] indicated that the diff-GMM and sys-GMM estimator is suitable for data sets with large groups and few periods, the current energy-environment-growth studies do not always follow this rule. However, if groups are too small, the test of cluster robust standard error and sequence correlation becomes inaccurate. Another problem is that the quantity of instruments is quadratic in the periods, which may lead to overfitting the equation because there are too many instruments compared to the sample capacity. To overcome the problem, the quantity of instruments is expected to be less than the groups. To achieve this goal, we can limit the lag of the instruments and collapse the instrument matrix. Table 2 provides the definition and source of the variable. Descriptive statistics are shown in Table 3, which is divided into OECD and non-OECD groups.

Table 2. The definition and source of variables.

Variables	Definition	Source	Calculation by the Author
Dependent variable			
Energy consumption	Renewable energy consumption (% of total)	IEA	
Economic growth	It covers four aspects: Economic development, Resource environment, Globalization, and Urban Construction	Khan et al. (2021) and Zhou et al. (2022)	Calculation by PCA
Environment pollution	Total greenhouse gas emissions (kt of CO2 equivalent)	World Bank's World Development Indicators	
Independent variable			
Innovation input	% Research and development expenditure of total GDP	World Bank's World Development Indicators	
Average temperature over summer months	Average temperatures in June, July, and August for countries with capitals in the Northern Hemisphere, and January, February, and December for countries with capitals in the Southern Hemisphere	World Bank: monthly average temperatures for countries; CIA (2018): latitudes of country capitals	Calculation of average temperatures over summer months based on monthly data
Average temperature over winter months	Average temperatures in January, February, and December for countries with capitals in the Northern Hemisphere, and June, July, and August for countries with capitals in the Southern Hemisphere	World Bank: monthly average temperatures for countries; CIA (2018): latitudes of country capitals	Calculation of average temperatures over winter months based on monthly data
Control variable			
Climate Policy	Signing Kyoto Protocol before 2016 or Joining the Paris Agreement after 2016	Kyoto Protocol and The Paris Agreement	The number 1 represents joining the Paris Agreement or Kyoto Protocol and the number 0 represents no joining
Industrialization	% Value added of industry of total GDP	World Bank's World Development Indicators	Interpolated
Capital	Capital stock at constant 2010 national prices (in mil. 2010USD)	Penn World Table	Divided by population
Urbanization	% Urban population of the total population	Penn World Table	

Table 3. Descriptive statistics.

Variable	Group	Obs	Mean	Std.Dev	Min	Max
pol	OECD	700	11.21	1.852	4.094	13.81
	Non-OECD	720	11.35	1.800	7.534	16.33
geg	OECD	700	1.173	0.575	0.345	3.222
	Non-OECD	720	0.656	0.577	0.211	11.37
k	OECD	700	2.851	1.537	0.860	14.49
	Non-OECD	720	1.288	1.008	−2.232	3.633
e	OECD	700	2.568	0.926	−0.368	4.113
	Non-OECD	720	2.617	1.755	−5.021	4.545
ino	OECD	700	0.277	0.756	−2.040	1.600
	Non-OECD	720	−1.156	1.203	−5.482	0.954
ind	OECD	700	3.249	0.245	2.353	3.856
	Non-OECD	720	3.360	0.287	2.301	4.252
stemp	OECD	700	19.91	3.663	12.86	31.42
	Non-OECD	720	24.62	5.416	8.830	37.01
wtemp	OECD	700	4.326	7.432	−14.19	26.62
	Non-OECD	720	12.60	12.23	−26.85	31.01
urb	OECD	700	4.379	0.593	4.020	8.946
	Non-OECD	720	4.031	0.353	2.901	4.605
poli	OECD	700	0.844	0.363	0	1
	Non-OECD	720	0.850	0.357	0	1

4. Results

4.1. Data Source

For econometric analysis of the proposed models, this paper uses the panel data of 35 OECD and 36 non-OECD countries from 2000 to 2019, which are from the World Bank, Penn World Table, and IEA. In addition, the sample interval is divided into short-term (2015–2019), medium-term (2010–2019), and long-term (2000–2019) for longitudinal comparison. To make the data stable, all variables except temperature are logarithmically transformed.

4.2. The Results of the Production Function

The results of the production functions for the OECD and non-OECD sample groups are shown in Tables 4 and 5. Firstly, in all models, the number of countries is significantly greater than the number of instrumental variables, and the Hansen test presents the instrumental variables are valid at a risk level of 0.05. Furthermore, the results of the Arellano-Bond test indicate that the estimators are consistent. According to the function estimation results, the coefficient of capital per capita is positive in both tables, indicating that capital and wealth are conducive to the development of a green economy in any country and that this effect is more pronounced in non-OECD countries. In contrast, the coefficients on renewable energy consumption are both significant, which is a good indication of the importance of renewable energy for the growth of a green economy. Finally, in agreement with other results in the literature, the coefficients of the innovation input variables are positive and significant, indicating that innovation input has a significant effect on green economic growth in both OECD and non-OECD countries, confirming the importance of innovation input in promoting energy restructuring, increasing the utilization of renewable energy and thus achieving green economic growth. Similar to the effect of the capital per capita variable, the effect of innovation inputs on green economic growth is greater in non-OECD countries due to their lower overall strength than in OECD countries.

Table 4. The production function (OECD).

Variables	**Group (1)**	**Group (2)**	**Group (3)**	**Group (4)**
	Diff-GMM	**Sys-GMM**	**Diff-GMM**	**Sys-GMM**
L.geg	0.925 ***	0.919 ***	0.934 ***	0.910 ***
	(0.00407)	(0.00218)	(0.00574)	(0.00301)
k	0.0251 ***	0.0124 ***	0.0282 ***	0.0104 ***
	(0.00329)	(0.000664)	(0.00499)	(0.000803)
e	−0.0369 ***	−0.0289 ***	−0.0382 ***	−0.0271 ***
	(0.00255)	(0.00170)	(0.00277)	(0.00203)
ino			0.00769 *	0.0184 ***
			(0.00412)	(0.00166)
Constant		0.146 ***		0.150 ***
		(0.00436)		(0.00571)
Observations	630	665	630	665
Sample	35	35	35	35
AR(1)	0.00221	0.00183	0.00223	0.00189
AR(2)	0.785	0.597	0.808	0.598
Hansen test	0.427	0.586	0.381	0.658

Note: Robust standard errors in parentheses, *** $p < 0.01$, * $p < 0.1$.

Table 5. The production function (non-OECD).

Variables	**Group (1)**	**Group (2)**	**Group (3)**	**Group (4)**
	Diff-GMM	**Sys-GMM**	**Diff-GMM**	**Sys-GMM**
L.geg	0.130 ***	0.493 ***	0.185 ***	0.489 ***
	(0.00928)	(0.00724)	(0.0102)	(0.00730)
k	0.249 ***	0.202 ***	0.322 ***	0.178 ***
	(0.00274)	(0.00327)	(0.00372)	(0.00462)
e	0.0471 ***	0.0691 ***	0.0839 ***	0.0595 ***
	(0.00548)	(0.00283)	(0.00586)	(0.00529)
ino			0.124 ***	0.0306 ***
			(0.00298)	(0.00391)
Constant		−0.103 ***		−0.00680
		(0.00524)		(0.0129)
Observations	648	684	648	684
Sample	36	36	36	36
AR(1)	0.248	0.230	0.256	0.228
AR(2)	0.310	0.303	0.306	0.306
Hansen test	0.385	0.527	0.358	0.531

Note: Robust standard errors in parentheses, *** $p < 0.01$.

4.3. The Results of Energy Consumption Function

The results of the estimated energy consumption function are shown in Tables 6 and 7, the results show that these estimates are consistent, and the number of instrumental variables is significantly less than that of all model countries. According to the model estimation results, it can be seen that: firstly, the coefficient of the green economic growth variable shows a positive value in the sample group of OECD countries, indicating that green economic growth can promote renewable energy consumption. In contrast, according to the estimation results for the sample of non-OECD countries, the relationship between green economic growth and the renewable energy consumption is the opposite. Secondly, for the effect of industrialization on renewable energy consumption, industrialization is able to promote renewable energy consumption in OECD countries, while in non-OECD countries, the effect of industrialization on renewable energy is negative. This may be due to the fact that most of the OECD countries are more developed economies and therefore have more developed industries and more diverse and sophisticated energy systems than the non-OECD countries. Whereas the non-OECD countries, most of which are developing countries, are at a stage of industrialization where they are using a lot of fossil fuels. Therefore, industrialization in non-OECD countries is negatively correlated with renewable energy consumption.

Table 6. The energy consumption function (OECD).

Variables	Group (1)	Group (2)	Group (3)	Group (4)	Group (5)	Group (6)	Group (7)	Group (8)
	Diff-GMM	Sys-GMM	Diff-GMM	Sys-GMM	Diff-GMM	Sys-GMM	Diff-GMM	Sys-GMM
L.e	0.835 ***	0.947 ***	0.844 ***	0.939 ***	0.767 ***	0.943 ***	0.774 ***	0.947 ***
	(0.0649)	(0.0187)	(0.0534)	(0.0274)	(0.0820)	(0.0316)	(0.0852)	(0.0288)
geg	0.171 ***	0.117 ***	0.0328	0.0581	0.217 ***	0.0977 ***	0.0791	0.0673
	(0.0482)	(0.0371)	(0.0634)	(0.0460)	(0.0499)	(0.0323)	(0.0691)	(0.0438)
ind	−0.131	0.0472	0.122	0.143 ***	−0.223 *	-2.92×10^{-5}	−0.0136	0.135 **
	(0.0982)	(0.0434)	(0.141)	(0.0523)	(0.118)	(0.0420)	(0.173)	(0.0529)
ino			0.213 ***	0.126 ***			0.186 ***	0.108 **
			(0.0664)	(0.0488)			(0.0696)	(0.0500)
stemp					−0.00681	−0.00893 **	−0.00251	−0.00668 *
					(0.00440)	(0.00444)	(0.00445)	(0.00401)
wtemp					0.00502 *	-9.13×10^{-5}	0.00399	0.000999
					(0.00288)	(0.00292)	(0.00296)	(0.00237)
Constant		−0.138		−0.391 **		0.225		−0.265
		(0.208)		(0.186)		(0.172)		(0.195)
Observations	630	665	630	665	630	665	630	665
Sample	35	35	35	35	35	35	35	35
AR(1)	0.00326	0.00193	0.00108	0.00109	0.00320	0.00189	0.00170	0.00111
AR(2)	0.865	0.816	0.959	0.843	0.915	0.840	0.976	0.850
Hansen test	0.481	0.734	0.696	0.621	0.495	0.676	0.545	0.525

Note: Robust standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 7. The energy consumption function (non-OECD).

Variables	Group (1)	Group (2)	Group (3)	Group (4)	Group (5)	Group (6)	Group (7)	Group (8)
	Diff-GMM	Sys-GMM	Diff-GMM	Sys-GMM	Diff-GMM	Sys-GMM	Diff-GMM	Sys-GMM
L.e	0.672 ***	0.871 ***	0.403 ***	0.873 ***	0.726 ***	0.824 ***	0.409 ***	0.815 ***
	(0.0493)	(0.0318)	(0.0728)	(0.0332)	(0.0570)	(0.0309)	(0.103)	(0.0339)
geg	−0.137 **	−0.0291	−0.0146	−0.0326	−0.101	−0.0954	0.0125	−0.0488
	(0.0665)	(0.0462)	(0.0720)	(0.0499)	(0.0633)	(0.0592)	(0.0884)	(0.0581)
ind	0.0184	−0.259 ***	0.161	−0.246 ***	−0.0459	−0.297 ***	0.272	−0.279 ***
	(0.0845)	(0.0494)	(0.130)	(0.0544)	(0.0882)	(0.0533)	(0.201)	(0.0551)
ino			−0.108 ***	0.00606			−0.146 ***	−0.00251
			(0.0307)	(0.0223)			(0.0509)	(0.0266)
stemp					−0.0185 ***	−0.0337 ***	0.00104	−0.0373 ***
					(0.00691)	(0.00695)	(0.0123)	(0.00831)
wtemp					0.0142 ***	0.00416	0.0264 ***	0.00360
					(0.00432)	(0.00558)	(0.00594)	(0.00652)
Constant		1.231 ***		1.195 ***		2.328 ***		2.352 ***
		(0.244)		(0.251)		(0.286)		(0.287)
Observations	648	684	648	684	648	684	648	684
Sample	36	36	36	36	36	36	36	36
AR(1)	0.273	0.234	0.371	0.234	0.270	0.232	0.345	0.231
AR(2)	0.164	0.149	0.226	0.145	0.192	0.154	0.953	0.160
Hansen test	0.192	0.212	0.349	0.176	0.133	0.106	0.0967	0.0597

Note: Robust standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$.

Compared with similar studies, it is confirmed that innovation input is positive to the renewable energy consumption of OECD countries, and the innovation input is negatively related to the renewable energy consumption of non-OECD countries, which may be due to the fact that compared to developed OECD countries that develop renewable energy technologies, innovation input in non-OECD countries is not reflected in the application of renewable energy. This may be due to the fact that innovation input in non-OECD countries is not reflected in the use of renewable energy compared to R&D in developed OECD countries. Finally, in the results of the estimation of the effect of climate variables on the consumption of renewable energy, the estimates for the OECD and non-OECD country samples are largely consistent, with renewable energy consumption being negatively correlated with summer temperatures and positively correlated with winter temperatures.

4.4. The Results of the Pollution Function

Tables 8 and 9 show the results of the pollution function, these instrumental variables appear to be effective, because the number of instrumental variables is less than that of these countries. According to the model estimation results, first, the estimated results of green economic growth and its squared term coefficient are basically the same in both OECD and non-OECD country samples, both show positive primary squared term coefficient and negative squared term coefficient, indicating an inverted U-shaped relationship between green economic growth and greenhouse gas emissions, which also confirms that renewable energy consumption plays an important role in reducing greenhouse gas emissions. Second, renewable energy consumption is significantly and negatively correlated with greenhouse gas emissions, a result that is undoubtedly consistent with the objective rule.

Table 8. The pollution function (OECD).

Variables	Group (1)	Group (2)	Group (3)	Group (4)	Group (5)	Group (6)	Group (7)	Group (8)	Group (9)	Group (10)
	Diff-GMM	**Sys-GMM**	**Diff-GMM**	**Sys-GMM**	**Diff-GMM**	**Sys-GMM**	**Diff-GMM**	**Sys-GMM**	**Diff-GMM**	**Sys-GMM**
L.pol	0.486 ***	0.932 ***	0.396 ***	0.929 ***	0.434 ***	0.939 ***	0.337 ***	0.933 ***	0.339 ***	0.949 ***
	(0.0190)	(0.0123)	(0.0231)	(0.0212)	(0.0278)	(0.00804)	(0.0382)	(0.00834)	(0.0407)	(0.0121)
geg	0.246 ***	0.0218	0.666 ***	0.186 ***	0.263 ***	0.142 ***	0.577 ***	0.202 ***	0.523 ***	0.170 ***
	(0.0293)	(0.0390)	(0.0777)	(0.0488)	(0.0310)	(0.0283)	(0.0789)	(0.0462)	(0.0971)	(0.0522)
geg2	−0.0591 ***	−0.0283 **	−0.173 ***	−0.0754 ***	−0.0640 ***	−0.0582 ***	−0.146 ***	−0.0753 ***	−0.126 ***	−0.0727 ***
	(0.00847)	(0.0131)	(0.0239)	(0.0165)	(0.00909)	(0.0111)	(0.0277)	(0.0159)	(0.0356)	(0.0138)
e	−0.0750 ***	−0.0211 ***	−0.0844 ***	−0.00393	−0.0864 ***	−0.0114 ***	−0.0873 ***	−0.0115 ***	−0.0772 ***	−0.000620
	(0.00550)	(0.00226)	(0.00746)	(0.00409)	(0.00914)	(0.00208)	(0.0107)	(0.00270)	(0.0105)	(0.00468)
ino			−0.0715 ***	−0.0288 ***			−0.0462 **	−0.00687	−0.0503 **	−0.00740
			(0.0205)	(0.00779)			(0.0208)	(0.00558)	(0.0223)	(0.00756)
stemp					−0.00797 ***	−0.00295 ***	−0.00763 ***	−0.00273 ***	−0.00844 ***	−0.00160
					(0.000931)	(0.000890)	(0.00110)	(0.000725)	(0.00118)	(0.00104)
wtemp					0.000670	0.00482 ***	0.000523	0.00544 ***	0.000498	0.00389 ***
					(0.000535)	(0.000776)	(0.000819)	(0.000740)	(0.000924)	(0.000853)
urb									0.0255 **	0.0282 ***
									(0.0112)	(0.00645)
poli										0.0105 **
										(0.00415)
Constant		0.847 ***		0.720 ***		0.684 ***		0.700 ***		0.374 ***
		(0.139)		(0.230)		(0.0934)		(0.0829)		(0.124)
Observations	630	665	630	665	630	665	630	665	630	665
Sample	35	35	35	35	35	35	35	35	35	35
AR(1)	0.000294	0.000137	0.000385	0.000123	0.000526	0.000150	0.00126	0.000158	0.00188	0.000112
AR(2)	0.597	0.474	0.927	0.522	0.639	0.281	0.939	0.261	0.976	0.392
Hansen test	0.977	0.995	0.985	0.989	0.980	0.998	0.993	0.998	0.993	0.997

Note: Robust standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$.

Table 9. The pollution function (non-OECD).

Variables	Group (1)	Group (2)	Group (3)	Group (4)	Group (5)	Group (6)	Group (7)	Group (8)	Group (9)	Group (10)
	Diff-GMM	**Sys-GMM**	**Diff-GMM**	**Sys-GMM**	**Diff-GMM**	**Sys-GMM**	**Diff-GMM**	**Sys-GMM**	**Diff-GMM**	**Sys-GMM**
L.pol	0.928 ***	1.009 ***	0.914 ***	0.980 ***	0.923 ***	0.995 ***	0.913 ***	1.002 ***	0.785 ***	0.986 ***
	(0.00832)	(0.00982)	(0.0149)	(0.0109)	(0.00801)	(0.00855)	(0.0226)	(0.00978)	(0.0334)	(0.0155)
geg	0.0553 ***	−0.113 ***	0.0641 ***	−0.0139	0.0687 ***	−0.0865 ***	0.0822 ***	−0.0356 **	0.0755 ***	−0.0398 ***
	(0.0137)	(0.0179)	(0.0205)	(0.0149)	(0.0155)	(0.0238)	(0.0270)	(0.0175)	(0.0231)	(0.0129)
geg2	−0.00377 ***	0.00968 ***	−0.00447 **	0.000539	−0.00492 ***	0.00721 ***	−0.00611 ***	0.00294 *	−0.00585 ***	0.00317 ***
	(0.00129)	(0.00176)	(0.00185)	(0.00145)	(0.00147)	(0.00210)	(0.00210)	(0.00158)	(0.00178)	(0.00111)
e	−0.0403 ***	−0.0143 ***	−0.0421 ***	−0.0384 ***	−0.0390 ***	−0.0273 ***	−0.0408 ***	−0.0324 ***	−0.0325 ***	−0.0351 ***
	(0.00229)	(0.00160)	(0.00281)	(0.00360)	(0.00328)	(0.00547)	(0.00238)	(0.00464)	(0.00448)	(0.00574)
ino			0.00475 **	−0.00849 **			0.000567	−0.0100 ***	0.0105	0.00264
			(0.00214)	(0.00368)			(0.00572)	(0.00318)	(0.00685)	(0.00542)
stemp					0.00342 **	−0.00264 *	0.00331	−0.00414 ***	0.000712	−0.00359 **
					(0.00173)	(0.00159)	(0.00220)	(0.000676)	(0.00174)	(0.00143)
wtemp					−0.00223 **	0.00148 ***	−0.000910	0.00217 ***	−0.00149	0.00163 ***
					(0.000971)	(0.000520)	(0.00195)	(0.000287)	(0.00151)	(0.000352)
urb									0.356 ***	−0.0749 ***
									(0.0519)	(0.0281)
poli										0.0121 **
Constant		0.0237		0.342 ***		0.243 ***		0.161		0.655 ***
		(0.103)		(0.129)		(0.0891)		(0.117)		(0.169)
Observations	648	684	648	684	648	684	648	684	648	684
Sample	36	36	36	36	36	36	36	36	36	36
AR(1)	0.000407	0.000177	0.000378	0.000353	0.000253	0.000351	0.000283	0.000522	0.000548	0.000468
AR(2)	0.425	0.482	0.420	0.419	0.341	0.526	0.350	0.551	0.382	0.561
Hansen test	0.971	0.988	0.965	0.997	0.965	0.997	0.967	0.997	0.966	0.997

Note: Robust standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

In addition, innovation input is also negatively correlated with greenhouse gas emissions, suggesting that an increase in innovation input can significantly improve the utilization efficiency of fossil energy and increase the proportion of renewable energy consumption. This is also an important determinant of the reduction of greenhouse gas emissions, such as the stronger the innovation input, the lower the greenhouse gas emissions. Finally, the temperature variable has a significant impact on greenhouse gas emissions, because climate change inevitably increases the consumption of energy for temperature regulation.

4.5. The Heterogeneity of Sample Interval

To analyze the dynamic relationship between climate change, innovation input, and energy-environment-growth in terms of differences between sample zones, the sample was divided into three phases, as shown in Tables 10 and 11. From a green economy growth perspective, innovation investment has a significant contribution to green economy development in both the OECD and non-OECD country samples, and the intensity of the effect decreases gradually depending on the short, medium, and long term of the period. This also suggests that for a green economy to be sustainable, countries need to invest in innovation in the long term. From the perspective of energy consumption, the contribution of innovative input to renewable energy consumption is also significant, with the intensity of the contribution decreasing in the short, medium, and long term.

Table 10. Differences of sample interval (OECD).

Sample Interval	Variables	Production		Energy Consumption		Pollution	
		Diff-GMM	Sys-GMM	Diff-GMM	Sys-GMM	Diff-GMM	Sys-GMM
2015–2019	ino	1.190 ***	−0.0164	0.402 *	0.447 **	−0.582 **	0.0229
		(0.370)	(0.0182)	(0.244)	(0.208)	(0.582)	(0.0154)
	stemp Wt			0.0108	0.0149	0.0173 *	−0.00528
				(0.0126)	(0.0143)	(0.0103)	(0.00387)
	wtemp			−0.00319	−0.00367	0.000773	−0.00652 **
				(0.00414)	(0.00483)	(0.00647)	(0.00264)
2010–2019	ino	0.486 **	−0.00290	0.121	−0.0371	−0.186 **	−0.00415
		(0.197)	(0.0190)	(0.245)	(0.152)	(0.0759)	(0.00392)
	stemp Wt			−0.00888	−0.00320	0.00403	0.00378 ***
				(0.0155)	(0.0128)	(0.00409)	(0.00102)
	wtemp			0.0120 **	0.0171 ***	−0.00161	−0.0021 ***
				(0.00561)	(0.00566)	(0.00115)	(0.00042)
2000–2019	ino	0.00769 *	0.0184 ***	0.186 ***	0.108 **	−0.0503 **	−0.00740
		(0.00412)	(0.00166)	(0.0696)	(0.0500)	(0.0223)	(0.00756)
	stemp Wt			−0.00251	−0.00668 *	−0.00844 ***	−0.00160
				(0.00445)	(0.00401)	(0.00118)	(0.00104)
	wtemp			0.00399	0.000999	0.000498	0.00389 ***
				(0.00296)	(0.00237)	(0.000924)	(0.000853)

Note: Robust standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 11. Differences of sample interval (non-OECD).

Sample Interval	Variables	Production		Energy Consumption		Pollution	
		Diff-GMM	Sys-GMM	Diff-GMM	Sys-GMM	Diff-GMM	Sys-GMM
2015–2019	ino	1.014 *	−0.0358	0.0137 *	−0.00337	0.0131	−0.0206 *
		(1.181)	(0.0355)	(0.0786)	(0.0546)	(0.0602)	(0.0117)
	stemp Wt			−0.00278	0.0103	−0.00128	−0.000340
				(0.0137)	(0.00646)	(0.00662)	(0.00331)
	wtemp			−0.0180	−0.00542	-8.57×10^{-5}	0.00107
				(0.0118)	(0.00447)	(0.0100)	(0.00152)
2010–2019	ino	0.563 ***	0.0882 ***	0.0304	0.0838 *	−0.0961 ***	−0.00994 **
		(0.0976)	(0.0200)	(0.126)	(0.0745)	(0.0260)	(0.00431)
	stemp Wt			−0.0270	−0.0318 *	0.00655 *	0.000566
				(0.0260)	(0.0167)	(0.00362)	(0.000621)
	wtemp			0.0504 **	0.0394 ***	−0.00647 ***	2.57×10^{-5}
				(0.0207)	(0.0116)	(0.00189)	(0.000346)
2000–2019	ino	0.124 ***	0.0306 ***	−0.146 ***	−0.00251	0.0105	0.00264
		(0.00298)	(0.00391)	(0.0509)	(0.0266)	(0.00685)	(0.00542)
	stemp Wt			0.00104	−0.0373 ***	0.000712	−0.00359 **
				(0.0123)	(0.00831)	(0.00174)	(0.00143)
	wtemp			0.0264 ***	0.00360	−0.00149	0.00163 ***
				(0.00594)	(0.00652)	(0.00151)	(0.000352)

Note: Robust standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

In addition, the impact of climate change factors represented by temperature on renewable energy consumption is not significant in the short term and only begins to be significant in the medium to long term, which may make it possible that because climate change is not evident to people in the short term, it is often experienced over a long period of time before significant climate change is manifested, which in turn affects people's energy consumption activities. From the perspective of greenhouse gas emissions, innovation input has a dampening effect on greenhouse gas emissions in OECD countries that diminishes over time. In non-OECD countries, on the other hand, innovation input has a significant dampening effect only in the medium term. The effect of climate variables on GHG emissions in different countries is weaker in the short term than in the medium and long term.

In summary, compared with similar studies, it is confirmed that innovation input and climate change are important variables affecting renewable energy consumption, greenhouse gas emissions, and green economic growth. In contrast to other literature, this paper finds that the effects of industrialization and innovation inputs on energy consumption are significantly different in OECD countries. This should be because OECD countries are mostly developed countries, while non-OECD countries are developing countries, and being an OECD country or not indicates being at different stages of economic development. The different development realities and needs lead to different effects of industrialization and innovation inputs. In addition, the paper finds that the intensity of the impact of innovation inputs on economic growth, energy consumption, and pollution emissions varies over time, which indicates the time lag in the application of technological innovations generated by innovation inputs, and on the other hand the fact that new technology will eventually fall behind over time, which is the reason for the need to constantly innovate inputs and technological innovations.

5. Conclusions and Policy Recommendations

The results of this paper show that: firstly, both renewable energy consumption and innovation inputs have a significant impact on green economic growth, and the impact of innovation inputs is stronger in non-OECD countries. Secondly, green economic development, industrialization, and innovation inputs all boost renewable energy consumption in OECD countries, while the opposite is true for non-OECD countries. Third, while climate change increases energy consumption, renewable energy consumption significantly reduces greenhouse gas emissions in both OECD and non-OECD countries, especially for OECD countries with high renewable energy consumption and high energy efficiency. Fourth, innovation inputs contribute to green economic growth in both OECD and non-OECD countries. Innovative inputs have significantly increased renewable energy consumption and reduced greenhouse gas emissions in OECD countries. Finally, innovation inputs have a large impact on the energy-environment-growth nexus in the short term, while the impact is more significant in the medium to long term. At the same time, the impact of climate change on the energy-environment nexus in OECD and non-OECD countries is more significant in the medium to long term.

Based on the above empirical results, the policy implications are as follows:

(1) Renewable energy consumption promotes green economic growth and vice versa. Therefore, OECD and non-OECD countries should speed up the transformation and upgrading, increase the proportion of new and renewable energy sources, promote the low carbonization of the energy system, fully develop and utilize renewable energy such as solar energy, thermal energy, wind energy, biofuels and nuclear energy, and build an efficient and clean energy consumption system. In addition, OECD countries can also build an industrial chain system for energy storage and then to the application link, realize the coordinated development of the upstream, middle and downstream, and produce high-quality, high-tech, and high-value-added green products, to achieve green economic growth.

(2) Renewable energy consumption reduces greenhouse gas emissions caused by climate change. Therefore, OECD and non-OECD countries should give priority to promoting the development of renewable energy and adjusting the energy structure, gradually increasing the proportion of non-fossil energy consumption, and accelerating the construction of a clean, low-carbon, safe, and efficient energy system. At the same time, non-OECD countries should also strengthen the macro policy guidance and legal

protection functions related to renewable energy development and set sustainable development goals and strategic ideas.

(3) Innovation investment promotes green economy growth in OECD and non-OECD countries. Therefore, OECD and non-OECD countries should pay close attention to the iterative trend of global renewable energy technologies and increase financial support for renewable energy technology R&D, increase support for energy conservation and emission reduction technology R&D through financial allocations, tax exemptions, simplified administrative approvals, and scientific and technological innovation incentives, support the development of high-tech industries, establish and improve the energy conservation and emission reduction technology industrial system, thus achieving continuous innovation and development of technology. In addition, OECD and non-OECD countries should also strengthen the guiding role of financial funds in technology research and development, enrich the construction of research and development mechanisms, open up production, learning, and research channels, and attach importance to the long-term applicability and social effects of renewable technology selection and deployment.

(4) The impact of innovation input on the energy-environment-growth nexus is greater in the short term and more significant in the medium and long term. Therefore, OECD and non-OECD countries should set up a long-term renewable energy development strategy, clarify the long-term goals of renewable energy development and make long-term arrangements for the research and development of key renewable energy technologies such as solar and nuclear energy. At the same time, OECD countries should increase innovation investment, pay attention to renewable energy talent training, research and development, and industrial system construction, establish specialized R&D institutions, support the development of renewable energy scientific research, technology development, and industrial services, and train generations of talents with innovative consciousness, core technologies, and challenging spirit, thus promoting the long-term development of renewable energy technology progress and industrialization.

(5) The impact of climate change on the energy-environment nexus is more significant in the medium and long term. Therefore, OECD and non-OECD countries should formulate long-term sustainable policies to cope with climate change, closely follow the implementation of policy objectives, and give flexibility to dynamic adjustment of policies. OECD countries should pay attention to the binding role of laws, timely study and launch climate law, and "legalize" the medium and long-term emission reduction targets. At the same time, OECD and non-OECD countries should strengthen practical cooperation with countries along the belt and road in the fields of green production capacity cooperation and green financial standards, to build a fair and reasonable global climate governance system with win-win cooperation.

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