The dynamics of CO2 emissions, energy consumption and economic development: Evidence from the top 28 greenhouse gas emitters

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The dynamics of CO_2 emissions, energy consumption and economic development: Evidence from the top 28 greenhouse gas emitters

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Abstract

Previous studies have done more research on the relationship between carbon emission reduction, energy consumption and economic growth in specific countries or regions, which rarely consider the issue of heterogeneity between countries or regions, and also lack the refinement of energy consumption categories. Using panel data from 2000 to 2017,this paper divided the top 28 global carbon emission countries into developed countries and developing countries, and explores cointegration and causality between renewable energy consumption,non-renewable energy consumption, economic growth and carbon emission. Results suggested that there is a two-way causal relationship between carbon emissions and economic growth in all economies. There is a two-way causal relationshipbetween economic growth in developed countries and consumption of renewable and non-renewable energy, while there is no significant relationship between economic growth and energy consumption in developing countries. There is a two-way causal relationship between carbon emissions and renewable energyin all economies, but there are significant differences; there is a two-way causal relationship between carbon emissions in developed countries and non-renewable energy, and only one-way causality exists in developing countries.

Key words: carbon emission; energy consumption; economic growth; dynamics; sustainable development

Introduction

In 2015, 196 countries signed the Paris Agreement at the World Climate Conference. In order to reach the target, signatories have adjusted their energy consumption structure to reduce carbon emissions. In 2020, General Secretary Xi Jinping announced China's carbon peak and carbon neutrality goals at the United Nations General Assembly. Therefore, how to balance the relationship between carbon emission reduction, energy consumption structure and economic growth has become a global urgent problem to be solved. From the perspective of development practice, the main source of global carbon dioxide emissions is fossil energy, and reducing fossil energy consumption and increasing renewable energy consumption are the main ways to reduce emissions (Duan and Yang 2018). However, whether such adjustment will lead to the increase of energy consumption cost and then affect the development of regional economy has not been fully demonstrated, and there are certain controversies. How to change the existing economic development model, coordinate the relationship between economic growth, energy consumption and low-carbon emission reduction, and achieve low-carbon and green development of the global economy is a common problem faced by all countries in the world .

Kraft J and Kraft A were the first to focus their research on energy consumption and economic growth (Kraft 1978) Then Akarca and Long (1980) took The United States as the research object, but the same result as Kraft J and Kraft A could not be obtained by reducing the time range of the study. The Payne (2010), And Ozturk (2010) two scholars have systematically summarized the relationship between energy consumption and economic growth of the four hypothesis, namely growth hypothesis (growth content, one-way causal relationship between energy consumption to economic growth), saving hypothesis (conservation content, one-way causal relationship of economic growth to energy consumption), feedback hypothesis (feedback content, exists bidirectional causality between energy consumption and economic growth) and neutral hypothesis (neutrality content,There is no causal relationship between energy consumption and economic growth). For more than 40 years, scholars have done a lot of empirical research in this field, but no consensus has been reached so far. Apergis and Payne studied six countries in Central America, OPEC countries and 13 countries in the European Union and found a two-way causal relationship between energy consumption and economic growth, supporting the feedback hypothesis (Apergis and Payne 2010; Apergis and Payne 2010; Zhang et al. 2011). Foreign scholars such as Shahbaz (2018) and Gorusand (2019) domestic scholars such as Wang Xuhui (2007), jian-hua Yin (2011) Ayoyo, wisdom (Zhang and Dang 2014), Li Lichun (2017) argue that there is a unidirectional causal relationship between economic growth and energy consumption. However, there are also studies that support the neutral hypothesis, arguing that energy consumption plays a relatively minor role in the economic growth process (Narayan and Doytch 2017; Akhmat and Zaman 2013; Danish et al. 2017)

In the early 21st century, with the intensification of the greenhouse effect of climate change, the research on the action mechanism of Energy, Economy and Environment has become a hot topic in the international community. Scholars collectively refer to Energy, Economy and Environment as the 3Es model. In these studies, more researchers focus on the relationship among carbon emissions, various types of energy consumption and economic growth (Zhang et al. 2015; Pao et al. 2015; Chandran and Tang 2013; Zhang et al. 2014; Xu et al. 2019; Zhu 2018; Yao and Zhang 2019). Due to the differences in measurement methods, research objects, time span and other factors, scholars have different research conclusions, and even different views. Pao (2015) used the Lotka-Volterra model to study the 3Es relationship between the United States and Mexico. Due to geographical differences, the carbon emissions and GDP in the United States are mutually causal, while the GDP growth in Mexico will lead to the increase of carbon emissions, and there is only a one-way causal relationship. Chandran's empirical analysis of five Asian countries is consistent with the findings of Pao's study of Mexico (Chandran and Tang. 2013) Scholars Lin and Moubarak (Zhang. 2014) use ARDL model to study China's carbon emissions and renewable energy, they believe that carbon emissions and economic growth are strong factors driving the use of renewable energy.

Generally speaking, the academic circle has basically reached consensus on the significant correlation between carbon emissions, energy consumption and economic growth. However, due to different time spans and selection methods, research conclusions are not consistent, and further improvement is needed. In terms of research objects, the existing studies are mostly for a country or a region, and have not started from the main responsibility subjects of greenhouse gas emissions. In terms of energy types, more than a decade ago, non-renewable energy occupied the main position, and scholars mostly focused on non-renewable energy or fossil energy. Now, the position of renewable energy is gradually rising, and the relationship between energy types and economic growth and carbon emissions needs to be considered. Based on this, this paper considers the top 28 global greenhouse gas emitters using panel data: Australia, South Korea, Germany, France, Netherlands, Canada, USA, Japan, Spain, Italy, UK, Argentina, Pakistan, Brazil, Poland, Russia, Mexico, South Africa, Nigeria, Saudi Arabia, Thailand, Turkey, Venezuela, Ukraine, Iran, India, Indonesia, China. An empirical analysis of greenhouse gas emitting countries was conducted to reveal the correlation and mechanism of action between energy consumption, economic growth and carbon emissions, and to further compare and contrast these countries into two groups, developed and developing countries, to explore whether there is heterogeneity among countries at different stages of economic development. [①]

Variable data and methods

Variable description and data sources

Based on Apergis and Payne (2012) variable selection, the following six variables are finally selected in combination with the characteristics of this paper, as shown in Table 1. In order to eliminate the influence of price changes, the unit of GDP and capital used in this paper is 2010 constant dollar. The carbon emissions in this article only represent carbon dioxide from the burning of fossil fuels and the manufacture of cement, and do not include the implicit carbon from economic activities.

The top 30 greenhouse gas emitting countries (or regions) in the world were announced at the Copenhagen Climate Conference. Considering the strong economic interaction between Mainland China and Taiwan, this paper combined the two countries as one investigation object. At the same time, as the top 30 greenhouse gas emitters already include 6 EU member states including France, the research object of EU is excluded in this paper to avoid duplication, so there are altogether 28 research objects. Due to the availability and completeness of the data, the time span is only extended to 2000-2017. The data in this paper are from the world Bank online database, BP World Energy Statistical Yearbook, etc. The analysis tools used in this paper are Stata15 and Eviews10.0.

Table 1 Variable symbols, names, and units

Variable categories	symbol	meaning	Metrics and descriptions	unit
The key variables	gdp	Economic growth	Gross domestic product of each country	2010 constant dollar usd
	co_2	Carbon dioxide	Carbon dioxide from burning fossil fuels and making cement (including carbon dioxide from the consumption of solid, liquid and gaseous fuels and from the combustion of gas)	One thousand tons of
	re	Renewable energy consumptio n	Renewable energy generation (including hydro, geothermal, solar, tidal, wind, biomass and biofuels, etc.)	KWH
	nre	Non-renewable energy consumptio n	Non-renewable energy generation (including coal, crude oil, natural gas, oil shale, nuclear energy, etc.)	KWH
Control variables	labor	Labour	Total Labour force (over 15 years old, employed, unemployed but looking for work and first time job seekers)	people
	capital	capital	Gross capital formation, also known as gross domestic investment, consists of new spending on fixed assets plus the net change in inventories	2010 constant dollar usd

Research Methods

Panel unit root test

In order to avoid the pseudo regression problem, the unit root test is performed on the variables first. The conventional ADF (Augmented Dickey -- Fuller) unit root test has a low probability of rejecting the null hypothesis, especially when the data time is short.The panel stationarity test is more convincing than the single time series stationarity test (Zhang et al.2015) LLC, Breitung, IPS, Fisher-ADF and Fisher-PP are used in this paper.The first two belong to the homogeneous unit root test, while the last three belong to the heterogeneous unit root test (Wu et al. 2012).

The unit root test is based on the following model:

$$\Delta y_{it} = \alpha_i + \beta_i y_{i,t-1} + \sum_{j=1}^{p_i} \rho_{ij}\,\Delta y_{i,t-j} + \varepsilon_{it}, i = 1, \ldots\ldots, N; t = 1, \ldots\ldots, T \quad (1)$$

In the formula, y_{it} is the series of country i in the panel data for time period t, ρ_i is the lag term selected in ADF regression, ε_{it} is an independently normally distributed random variable with zero mean and variance σ_i^2 for all i and t.

Panel co-integration test

Co-integration is a statistical description of the long-term equilibrium relationship of non-stationary economic variables (Li.2017). Pedroni (2010) proposed a method to test panel data co-integration, which can be regarded as an extension of Engle and Granger two-step method. The Pedroni test takes into account the heterogeneity of parameters between individuals. Therefore, the alternative hypothesis requires that each individual has a co-integration relationship, and the co-integration relationship parameters of each individual panel may not be the same. Therefore, this paper uses Pedroni's method to test the co-integration relationship in heterogeneous panel data, and considers the following co-integration regression:

$$gdp_{it} = \alpha_i + \delta_{it} + \beta_{1i} co_{2it} + \beta_{2i} re_{it} + \beta_{3i} nre_{it} + \beta_{4i} labor_{it} + \beta_{5i} capital_{it} + \varepsilon_{it}, \quad i = 1, \ldots\ldots, N; t = 1, \ldots\ldots, T \quad (2)$$

I represents each country, T represents year, α is the intercept item, δ_i is the time trend item. The slope coefficients β_{1i}, β_{2i}, β_{3i}, β_{4i} and β_{5i} vary from individual to individual, thus allowing heterogeneity of cointegration variables.

FMOLS estimates the cointegration equation

When there is a co-integration relationship, direct OLS estimation will produce deviation. Phillips and Hansen modified OLS, which was called Fully Modified least squares (FMOLS). This method eliminated sequence correlation and endogeneity problems, and was suitable for small sample data. Asymptotically unbiased estimation coefficients and long-term effective normal distribution standard errors could be obtained(Phillips and Hansen. 1990) This paper draws on the practices of Saidi and Mbarek (2016), the condition of cointegration vector is investigated in the form of multi-equation, so economic growth, carbon dioxide emission, renewable energy consumption and non-renewable energy consumption are the dependent variables in turn.

Granger causality test

The existence of cointegration relationship indicates that there is a long-term causal relationship between variables, but the direction of the causal relationship is unknown (Wu et al. 2008). This problem can be solved by the Granger causality test, which is used to test whether a time series can predict another time series. If there is a cointegration relationship between the two variables in the long run, there must be one-way or bidirectional Granger causality between the two variables (Engle and Granger.1987). If there are unit roots and co-integration relationships between sequences, Vector Error Correction Model (VECM) is used for estimation, and Granger causality test is performed on the premise of VECM.

The vector error correction model (VECM) to test Granger causality is as follows:

$$\Delta gdp_{it} = \sum_{j=1}^{k} \beta_{1j}\, \Delta gdp_{i,t-j} + \sum_{j=1}^{k} \gamma_{1j}\, \Delta co_{2i,t-j} + \sum_{j=1}^{k} \vartheta_{1j}\, \Delta re_{i,t-j} + \sum_{j=1}^{k} \delta_{1j}\, \Delta nre_{i,t-j} + \sum_{j=1}^{k} \rho_{1j}\, \Delta labor_{i,t-j} + \sum_{j=1}^{k} \theta_{1j}\, \Delta capital_{i,t-j} + \lambda_1 ECT_{i,t-1} + \Delta\mu_{1it} \quad (3)$$

Among them, Δ is the first-order difference operator; $\beta_j, \gamma_j, v_j, \delta_j, \theta_j, \rho_j (j = 1,2,3,4,5,6)$ is the estimated parameter;$\mu_{jit} (j = 1,2,3,4,5,6)$, ECT is the error correction term obtained from the estimated residual of the cointegration equation (2). The coefficient of ECT λ_j (j=1,2,3,4,5,6) represents the deviation of the dependent variable from the long-term equilibrium. When the lag order is different, f-statistics are used to judge the significance and determine the short-term Granger causality between variables (Sebri and Abid. 2012) . Only one VECM formula is given here for space reasons.

Empirical Results

Panel unit root test results

In order to avoid the negative impact on the test results caused by the limitations of the test method itself, this paper uses the five panel data unit root test methods mentioned in above for testing, and the results are shown in Table 2. GDP, CO2, RE, NRE, labor and capital have unit roots in most of the five test methods, and their first-order difference terms reject the unit root hypothesis at the significance level of 5%, which means d_GDP and D_co in the panel2, d_re, d_nre, d_ labor and d_capital are first order differential stationary. These results essentially show that most macroeconomic variables are not stationary horizontally, but become stationary after the first difference. Therefore, the variable data is stable in the first-order difference, and this sequence follows a random trend, which can be cointegration test.

Table 2 Panel unit root test

variable	IPS	FISHER_ADF	FISHER_PP	LLC	Breitung
gdp	9. 4079 (1. 0000)	7. 8038 (1. 0000)	8. 8992 (1. 0000)	9. 3707 (1. 0000)	13. 4902 (1. 0000)
d_gdp	-8. 9038***	-7. 2442***	-10. 5417***	-2. 9517***	-4. 7937***

	(0. 0000)	(0. 0000)	(0. 0000)	(0. 0016)	(0. 0000)
co_2	-0. 1338	-1. 6916*	-1. 4654	-0. 4920	-7. 1116
	(0. 4468)	(0. 0454)	(0. 8986)	(0. 3114)	(1. 0000)
d_co_2	-9. 6198***	-5. 183***	-11. 0573***	-2. 9961***	-9. 4982***
	(0. 0000)	(0. 0000)	(0. 0000)	(0. 0014)	(0. 0000)
re	-0. 0402	-1. 0915	-1. 0898	-3. 2204***	-4. 2509
	(0. 4839)	(0. 1375)	(0. 8131)	(0. 0006)	(1. 0000)
d_re	-13. 7391***	-9. 2447***	-17. 9102***	-1. 7601**	-8. 9007***
	(0. 0000)	(0. 0000)	(0. 0000)	(0. 0392)	(0. 0000)
nre	2. 0417	3. 3207	4. 0767	3. 9021***	8. 6588
	(0. 9794)	(0. 9996)	(1. 0000)	(0. 0000)	(1. 0000)
d_nre	-8. 5909***	-10. 7920***	-17. 7759***	-4. 6562***	-12. 8062***
	(0. 0000)	(0. 0000)	(0. 0000)	(0. 0000)	(0. 0000)
labor	1. 8352	2. 2078	0. 4062	3. 2023***	13. 460
	(0. 9668)	(0. 9864)	(0. 3423)	(0. 00007)	(1. 0000)
d_labor	-6. 4396***	-8. 6995***	-5. 0590***	-6. 0659***	-5. 1727***
	(0. 0000)	(0. 0000)	(0. 0000)	(0. 0000)	(0. 0000)
capital	8. 8888	7. 1347	8. 8982	6. 6128	11. 3658
	(1. 0000)	(1. 0000)	(1. 0000)	(1. 0000)	(1. 0000)
d_capital	-6. 1598***	-6. 9929***	-8. 0990***	-4. 3080***	-6. 5391***
	(0. 0000)	(0. 0000)	(0. 0000)	(0. 0000)	(0. 0000)

Note: in the table"***","**","*"Respectively at the significance level of 1%, 5% and 10%, the same as below. Panel unit root tests include intercepts and trends.

Panel co-integration test results

Since the variables are single integer series of the same order, satisfying the cointegration test prerequisites, this paper uses the method proposed by Pedroni to carry out co-integration test, as shown in Table 3.

In small samples, Panel ADF statistic and Group ADF statistic have the best test effect, Panel V-statistic and Group ρ-statistic have the worst test effect, and other samples are in the middle (Pedroni. 2010) According to Table 3, Panel PP-statistic, Panel ADF statistic, Group PP-statistic and Group ADF statistic all reject the null hypothesis and statistically significant, while Panel V-statistic, Panel ρ-statistic and Group ρ-statistic cannot reject the null hypothesis. Considering the number of samples, and four of the seven co-integration statistics significantly reject the null hypothesis, it can be considered that there is panel co-integration relationship among the six variables, that is, there is a long-term co-integration relationship.

Table 3 Panel co-integration test

Panel test statistics:		Group mean panel test statistics:	
Panel v-statistic	17. 502 59	Group ρ-statistic	7. 465 847
Panel ρ-statistic	4. 816 530	Group PP-statistic	-4. 407 253***
Panel PP-statistic	-5. 844 121*	Group ADF statistic	-2. 444 693***
Panel ADF statistic	-2. 2314 074*		

Note: Among the seven tests, the Panel V-statistic statistic is a one-sided test, in which positive numbers with large values reject the null hypothesis without cointegration, while negative numbers with large values of the remaining test statistics reject the null hypothesis without cointegration. The critical value at the significance level of 10% is expressed as"*"; The critical value at the significance level of 5% is expressed as"**"; The critical value at the significance level of 1% is expressed as"***".

FMOLS estimation results

The correlation coefficients of each explanatory variable were examined in this paper. The maximum correlation coefficient was 0.772, and the correlation coefficients between 0.3 and 0.8 were all weakly correlated. Therefore, the FMOLS estimation in the following paper can ignore the multicollinearity problem. At the same time, considering the current situation of unbalanced development among different economies, this paper divides these 28 countries into developed countries (□) and developing countries (□) for independent discussion. The results of the estimated cointegration equation of FMOLS are shown in Table 4.

FMOLS estimation results show that : (1) At the significance level of 1%, carbon emissions in 28 countries have a significant negative impact on economic development; The growth of renewable energy and non-renewable energy in the 28 countries as a whole and in developed countries has a positive impact on economic development. The impact of renewable energy is stronger, and the impact of developed countries is more significant. (2) At the significance level of 1%, the economic development of 28 countries can reduce carbon emissions, but the impact coefficient is very insignificant; The growth of non-renewable energy will lead to the increase of carbon emissions, but the impact coefficient is not obvious. The impact of renewables on carbon emissions in the 28 countries is significant at the 10% level and extremely weak. (3) At the significance level of 1%, the economic development of 28 countries has a positive impact on the consumption growth of both renewable and non-renewable energy, and has a significant impact on non-renewable energy. However, the impact on renewable energy is significant in developed countries, but not in developing countries. (4) The growth of carbon emissions in developing countries will lead to the rapid growth of renewable energy consumption, but it is only significant at the level of 5% and 10% in 28 countries as a whole and developed countries;The growth of carbon emissions in 28 countries has a significant positive impact on non-renewable energy consumption. In developed countries, non-renewable energy and renewable energy have negative impacts on each other, and there is a substitution relationship. In contrast to Ito's study, this paper does not find a substitution relationship between renewable and non-renewable energy sources in developing countries; instead, the two are growing in the same direction. In this paper, it is believed that developed countries have entered the post-industrialization stage with low energy consumption, and the total energy consumption is close to the limit, so the two are decreasing, while developing countries are in the industrialization stage with high energy consumption, and the total energy demand is increasing, so the two are climbing simultaneously. Developed countries such as the United Kingdom (-1.8 percent), Japan (-1. 6 percent), France (-1 percent) have reached a limit with a negative annual growth rate of primary energy consumption (2006-2016), while developing countries such as India (5.7 percent), the Philippines (4.6 percent), and China (4.4 percent) are still in the 4-6 percent range.

② Developed countries: Australia, South Korea, Germany, France, Netherlands, Canada, United States, Japan, Spain, Italy, United Kingdom.

③ Developing countries: Argentina, Pakistan, Brazil, Poland, Russia, Mexico, South Africa, Nigeria, Saudi Arabia, Thailand, Turkey, Venezuela, Ukraine, Iran, India, Indonesia, China.

Table 4 FMOLS estimation results

The dependent variable	The independent variables	The 28 countries	The developed countries	Developing country
gdp	*co2*	-7. 24E+08***	-1. 11E+09***	-1. 04E+08***
	re	0. 9047***	2. 8507***	0. 0542
	nre	0. 1247**	1. 6367***	0. 0318
	labor	14 561. 84***	10 645. 14	8 315. 185***
	capital	2. 32 496***	1. 842229***	1. 877199***
Adjusted R^2		0. 9980	0. 9995	0. 9983
co_2	*gdp*	-7. 44E-10***	-5. 24E-10**	-7. 79E-10***
	re	3. 98E-09*	6. 79E-10	2. 08E-10
	nre	2. 48E-10***	9. 53E-10***	2. 08E-10***
	labor	1. 31E-05***	-1. 75E-05*	1. 32E-05***
	capital	2. 22E-09***	1. 11E-09***	2. 38E-09***
Adjusted R^2		0. 9924	0. 9982	0. 9904
re	*gdp*	0. 0797***	0. 0719***	0. 0155
	co2	43 724 198**	38 512 776*	26 211 149***
	nre	0. 0121	-0. 3064***	0. 0110
	labor	-587. 2057	8 990. 885***	-287. 3959
	capital	0. 0270	-0. 1309***	0. 1765***
Adjusted R^2		0. 969 6	0. 988 0	0. 969 8
nre	*gdp*	0. 256 6***	0. 167 7***	0. 481 5***
	co2	4. 89E+08***	2. 07E+08***	4. 64E+08***
	re	0. 2156	-1. 4147***	0. 2211***
	labor	-462. 1875	16 765. 16***	-1 979. 753***
	capital	-0. 3176	-0. 2444***	-0. 6900***
Adjusted R^2		0. 9687	0. 9991	0. 9492

Note: in the table"***","**","*"Respectively at the significance level of 1%, 5% and 10%. The P value in parentheses and the statistical value above parentheses are the same below.

Granger causality test results

The short-term Granger causality test results based on the error correction model are shown in Table 5. The first column shows the causal relationship between GDP and other variables, and so on to the last column. It can be seen from Table 5 that the GDP of 28 countries and developed countries and energy consumption (including renewable energy consumption and non-renewable energy consumption) are Granger causes for each other, supporting the feedback hypothesis. The GDP of developing countries is the Granger cause of renewable energy consumption, supporting the conservation hypothesis. There is no Granger causality between GDP and non-renewable energy consumption in developing countries, which supports the neutral hypothesis. The detailed Granger causality among 28 variables is shown in the fifth part of the results discussion.

Table 5 Granger causality test based on VECM model

countries	variable	*d_gdp*	*d_co$_2$*	*d_re*	*d_nre*	*d_labor*	*d_capital*
28 countries	d_gdp	-	73.7427***	12.5378***	6.0654**	3.8600	27.7028***
	d_co$_2$	55.4827***	-	6.9485**	0.4215	3.2138	39.9389***
	d_re	10.5456***	5.3060**	-	13.0376***	0.2757	6.1120**
	d_nre	5.2809*	34.7017***	1.4811	-	0.0881	9.0495**
	d_labor	9.8907***	1.8397	2.0759	2.5218	-	9.5766***
	d_capital	5.5635*	17.4600***	5.4754*	5.6679*	1.2995	-
Developed countries	d_gdp	-	152.4647***	8.9114**	11.6980***	7.6285*	7.9335**
	d_co$_2$	6.8439*	-	21.7079***	17.6032***	5.5118	4.7644
	d_re	15.2778***	8.8730**	-	5.7362	2.4429	25.4618***
	d_nre	9.4474**	44.6336***	14.4627***	-	6.2739*	21.0456***
	d_labor	2.1645	36.7506***	2.6278	10.2709**	-	10.0020**
	d_capital	18.4622***	128.0891***	15.5904***	14.7475***	14.5340***	-
Developing	d_gdp	-	58.5394***	1.9813	1.4641	7.3315	23.0657***

Countries	d_co2	35. 5878***	-	14. 9938**	8. 2328	2. 3027	16. 7182***
	d_re	19. 4280***	31. 8926***	-	5. 1722	11. 8615**	61. 6105***
	d_nre	6. 9920	18. 1480***	11. 8022**	-	4. 2664	11. 0512*
	d_labor	11. 5777**	9. 0904	3. 5225	11. 0522*	-	22. 1807***
	d_capital	32. 3718***	19. 0729**	1. 9138	2. 1663	9. 3892*	-

Note: in the table"***","**","*"Respectively at the significance level of 1%, 5% and 10%. The P value in parentheses and the statistical value above parentheses are the same below.

Analysis and discussion of measurement results

Based on the results of FMOLS estimation (Table 4) and Granger causality test (Table 5), this paper constructed the causal graph of 28 countries and distributed the corresponding causal graph to developed countries and developing countries (see Figure 1). It found that:

(1) With Gorus (2019), Wang (2016), The difference is that there is a bidirectional Granger causality between carbon dioxide emissions and GDP, whether viewed from the overall situation of 28 countries or from the perspective of developed and developing countries. The first two scholars believe that there is no Granger causality between carbon dioxide emissions and GDP. In contrast, this paper thinks that this may be related to the selection of different research objects and research methods. On the one hand, carbon emissions have a negative impact on the economic development of all kinds of economies, which indicates that the growth of carbon emissions not only causes environmental pollution but also has a significant inhibitory effect on economic development, hindering the sustainable development of the global economy, on the other hand, The development of various economies also has a negative impact on carbon emissions, but the effect is very weak, This shows that the efforts made by countries to achieve green and low-carbon development have achieved initial results, just effect is not significant, countries in the process of economic development still need to further increase the intensity of emission reduction, to ensure global emissions reduction targets.

(2) There is a bidirectional Granger causality between the GDP of 28 countries as a whole and that of developed countries and renewable energy consumption Lin (2014)、Saidi (2016)、Apergis (2012)，the results were consistent. There is only one-way Granger causality between GDP in developing

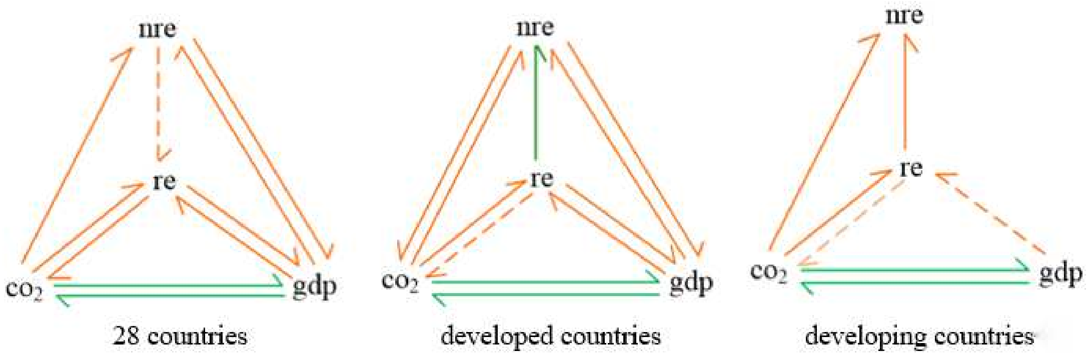
countries and renewable energy consumption. In terms of direction and intensity of impact, renewable energy consumption has a significant positive impact on economic growth in both the 28 countries as a whole and developed countries. Economic growth also has a positive impact on renewable energy consumption in all countries, but the impact of renewable energy in developing countries is not significant. The result shows that the overall economic growth and mutually reinforcing relationship between renewable energy consumption, economic development will be to a certain extent, promoting renewable energy consumption growth, the growth of the renewable energy consumption at the same time also promoted the economic development, but developing countries due to the different economic development stage, renewable energy consumption is limited, only non renewable energy supplement, its growth is not obvious lead to economic growth.

(3) There is a bidirectional Granger causality between the GDP of 28 countries as a whole and that of developed countries and non-renewable energy consumption, This is consistent with the results of Narayan (2017) And Apergis (2012). In terms of direction and intensity of impact, non-renewable energy consumption in 28 countries as a whole and developed countries has a significant positive impact on economic growth. This result shows that the economic development of developed countries still needs to rely on the consumption of non-renewable energy. Renewable energy is only a beneficial supplement to their economic development, but it cannot replace the dominant position of non-renewable energy at present, but its impact intensity is higher than that of non-renewable energy. There is also a problem found in the study that there is no Granger causality between economic development and non-renewable energy in developing countries, and FMOIS estimation is not significant, which is related to Ito (2017). Ito believes that non-renewable energy has a negative impact on economic growth. Further empirical analysis is needed to solve this problem.

(4) No matter from the overall situation of 28 countries or from the distinction between developed and developing countries, there was a two-way Granger causality between carbon dioxide emissions and renewable energy consumption, which is consistent with the research results of Danish (2017). The result shows that the increase of carbon emissions leads to the increase of renewable energy consumption, but the significance is different, the most significant in developing countries, developed countries only meet the significance of 10%. The increase in renewable energy consumption will also lead to an increase in carbon emissions, but not significantly. This result shows that the increase of total carbon emissions leads to the increase of relatively clean renewable energy consumption, especially in developing countries due to environmental pressure and low cost of technology replication. However, the result also shows that the increase of renewable energy does not necessarily lead to the reduction of total carbon emissions.

(5) There is an one-way Granger causality relationship between carbon dioxide emissions and non-renewable energy in 28 countries as a whole and in developing countries, and it has a significant positive impact. And a two-way Granger causality

relationship between carbon dioxide emissions and non-renewable energy in developed countries, which is also a significant positive influence. This result suggests that non-renewable energy is a major contributor to carbon emissions, and that the growth of carbon emissions, if unchecked, will further stimulate non-renewable energy consumption.



(a) (b) (c)

Figure 1 gdp-co2-re-nre indicates the relationship between re-nres

Note: A→B indicates that A is B's Granger cause. If there is no arrow, there is no causality. The solid line indicates that the coefficients estimated by FMOLS are statistically significant, and the dotted line indicates that the coefficients estimated by FMOLS are statistically insignificant. "Orange" indicates positive influence, and "green" indicates negative influence; re、nre、co_2、gdp represent renewable energy consumption, non-renewable energy consumption, carbon dioxide emissions, and GDP in that order.

Conclusions and policy recommendations

In this paper, we divide the top 28 countries of carbon emissions into developed and developing countries, and use the data from 2000-2017 to test the cointegration and causality between carbon emissions, renewable energy consumption, non-renewable energy consumption and economic growth, and obtain the following main conclusions:

(1) From the perspective of all economies, the growth of carbon emissions leads to environmental pollution and also has a significant negative impact on economic development, hindering the sustainable development of global society and economy. (2) The growth of renewable and non-renewable energy consumption in developed countries is the direct driving force of economic growth, in which renewable energy has a stronger influence. Meanwhile, economic growth in turn further increases the demand for energy consumption. The results support the feedback hypothesis. (3) There is no significant role relationship between economic growth and energy consumption growth in developing countries, and there is only a weak causal relationship between economic growth and renewable energy consumption, indicating that the growth of energy consumption does not necessarily drive economic growth in developing countries, which is directly related to the stage of economic development they are in, and the results of the study support the neutral hypothesis. (4) From the perspective of all

economies, non-renewable energy is the main factor of carbon emissions, and the consumption of renewable energy will also lead to an increase in carbon emissions, but the impact is weaker, indicating that the growth of carbon emissions must be controlled artificially, otherwise environmental pollution and energy consumption will form a vicious circle, which in turn will affect the sustainable socio-economic development.

Based on the main conclusions above, this paper gives the following proposals for the development of the macro policy level: (1) Countries around the world should collaborate to increase the control of carbon emissions, developed and developing countries should clarify the timeline for carbon peaking and carbon neutrality according to their own economic development level, and gradually reduce or completely replace the consumption of fossil energy through the adjustment of energy consumption structure. (2) Developed and developing countries should improve the transfer mechanism of energy conservation and emission reduction technologies within the framework of the Paris Agreement, so as to ensure that developed countries get appropriate benefits from technology transfer and reduce the cost of renewable energy development and utilization for developing countries. (3) Developing countries should optimize their industrial structure, step up efforts to eliminate backward industries such as those with high energy consumption, high pollution and high emissions, and strictly screen new industries to avoid repeating the old path of "pollution first, treatment later" and reduce trial and error costs. (4) In the process of industrial transfer, developed countries should provide appropriate carbon compensation to the target countries according to the carbon emissions of the transferred industries, so as to avoid transferring the responsibility of carbon emissions to developing countries through industrial transfer and increasing their environmental governance costs.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication Not applicable.

Availability of data and materials If there is a reasonable request, it can be obtained from the corresponding author.

Competing interests The authors declare no competing interests.

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Authors' contributions Jin Lei contributed to the conception of the study, most of the systemic review and edited the final manuscript. Chang Yuan-hua contributed to inclusion and exclusion criteria, data management and statistical analysis. Wang Meng and Zheng Xin-zhu contributed to manuscript draft preparation. Yang Jian-Xun and Gu Jin contributed to data collection. All authors read and approved the final manuscript.

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