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Threshold effects of renewable energy consumption on economic growth under energy transformation

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ABSTRACT
China proposed that non-fossil energy consumption account for 20% in total energy consumption. EU increased the target of renewable energy consumption share from 27% to 35% in 2030. Energy transformation and increasing renewable energy consumption are important energy strategies for all countries at present. Then, is the impact of renewable energy consumption on economic growth positive or negative? Are there any differences in the direction or magnitude of the impact among countries or regions, and what are the determinants behind them? We apply panel threshold effect model to test threshold effects of renewable energy consumption on economic growth of EU. Empirical result shows: first, the impact of renewable energy consumption on economic growth is negative. Second, renewable energy consumption has significant threshold effects on economic growth. Third, now, energy consumption intensity and GDP per capita of most EU members are in the appropriate threshold regimes. In contrast, more and more EU members are in the high-subsidy group. Fourth, the average annual growth rates of renewable energy consumption showed no significant difference between high-subsidy and low-subsidy countries from 1990 to 2014. Therefore, subsidy with high economic cost is not the onlyeffective means to increase renewable energy consumption.

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KEYWORDS
Renewable energy consumption; economic growth; panel threshold effect; renewable energy subsidy

1. Introduction

In recent years, there has been a new trend in global energy consumption structure that renewable energy consumption is increasing quickly. According to *International Energy Outlook 2016* released by International Energy Agency (hereafter called IEA), global renewable energy power generation will account for 60% in 2040. Taking European Union (hereafter called EU) for example, total energy consumption gradually decreased in the period of 1990–2015, and the average annual growth rate is −0.1%. However, average annual growth rate of renewable energy consumption is 4.37%. The proportion of renewable energy consumption increased from 4.33% to 12.91%, and the proportion of renewable energy power generation increased from 12.63% to 29.86%. The most important two reasons why renewable energy consumption increased rapidly are listed as follows. First, high volatility in international oil price because of oil supply bottleneck, unstable partial oil producing countries and oil output adjustment, brings challenges to energy security. Second, the problems of climate change, environmental damage, and economic losses caused by fossil fuel consumption have attracted worldwide attention. In Paris climate conference (COP21), China proposed that CO_2 emission peak around 2030 and non-fossil energy consumption account for 20% in total energy consumption. And EU increased the target of renewable energy consumption share from 27% to 35% in 2030 recently. Energy transformation and increasing renewable energy consumption are important energy strategies for all countries at present. According to *BP World Energy Statistics Yearbook*, China's renewable energy power generation increments ranked first in the world, and China surpassed the United States becoming the largest renewable energy producer in 2016. Then, has energy transformation sacrificed economic growth? Is the impact of renewable energy consumption on economic growth positive or negative? Are there any differences in the direction or magnitude of the impact among countries or regions, and what are the determinants behind them? Answering these questions can provide scientific policy basis for China to better develop renewable energy, optimize energy structure and achieve the goal of renewable energy consumption share in 2030 with the lowest economic cost.

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2. Literature review

Economists have been devoted to exploring the source of economic growth. Therefore, the relationship between energy consumption and economic growth is a basic proposition of economics. The results show that there are regional differences (Lee and Chang 2007; Huang et al. 2008a) and nonlinear relationship (Zhao and Fan 2007; Huang et al. 2008b) between energy consumption and economic growth. At present, articles about impact of renewable energy consumption on economic growth mainly use linear and grouping methods from the perspective of different mechanisms. However, the results are not consistent.

First, most scholars regarded renewable energy as a factor of production and applied into production function (Apergis and Payne 2012; Salim et al. 2014; Inglesi-Lotz 2016). They found that the substitution of renewable energy for part of nonrenewable energy was conducive to climate mitigation and energy diversification, namely, renewable energy consumption promotes economic growth like other production factors. Inglesi-Lotz (2016) found that the influence of renewable energy consumption to GDP and GDP per capita was positive and statistically significant in OECD countries. Namely, energy transition can improve both environment and economy. Based on co-integration and Granger causality test, Wang (2008) found that there was co-integration relationship between China's renewable energy consumption and economic growth, and renewable energy consumption is the one-way Granger cause of economic growth. Second, some scholars believed that developing renewable energy didn't have technical and cost advantages compared with traditional energy. So, the expansion of renewable energy consumption driven by government policy had certain economic cost (Qi and Li 2017). Based on autoregressive distributed lag model (ARDL), Ocal and Aslan (2013) found that if renewable energy consumption increased 1%, GDP would decrease 0.3%. Third, some scholars pointed out that renewable energy consumption had no significant impact on economic growth. Based on Toda-Yamamoto test method, Payne (2009) found that there was no Grainger causality between U.S. renewable energy consumption and real GDP. Using random effects model, Menegaki (2011) found that there was no Grainger causality between renewable energy consumption and real GDP in 27 European countries because European renewable energy development was insufficient and uneven. Finally, in recent years, some scholars found that the impact of renewable energy consumption on economic growth (or employment) had regional differences. Al-Mulali et al. (2013) found that the higher the income level, the positive impact of renewable energy consumption on economic growth is more sustained and significant. Markandya et al. (2016) hold the same opinion. Apergis and Salim (2015) also found the impact of renewable energy consumption on employment was heterogeneous in different regions.

Literature listed above mainly used linear and grouping methods to analyze the impact of renewable energy consumption on economic growth and its regional differences. However, (1) the relationship between renewable energy consumption and economic growth may be nonlinear due to a variety of influence mechanisms (Qi and Li 2017). So traditional linear method is not accurate, resulting in inconsistent conclusions. (2)The biggest problem of grouping method is that choice of group standard is always subjective and optional, not based on mathematical statistics. And, we cannot test whether the differences of regression results from different samples are significant or not. So the validity and reliability of parameter estimation is easy to be questioned. Therefore, considering data availability and integrity, this paper explores nonlinear threshold effects of renewable energy consumption on economic growth of EU, which is the leader in renewable energy and has complete statistics. Marginal contributions are listed as follows. First, nonlinear threshold test method is used to identify various factors leading to nonlinear effect of renewable energy consumption on economic growth, and to estimate specific threshold values robustly. Second, we analyze the mechanism of each variable threshold thoroughly, and put forward the deadweight loss and crowd-out effect of renewable energy subsidy policy, path dependence effect of energy consumption and technical basis effect of economic level on renewable energy consumption. Third, based on economic theory and classic literature, we improve measuring indicators of production factors in production function to make the conclusion more accurate and robust. Labor stock is adjusted by human capital index considering heterogeneity of labor, capital is stock index not flow index (e.g. fixed capital formation), technology is total factor productivity. Total renewable energy consumption and total nonrenewable energy consumption are used, respectively, which include energy consumed not only in power generation but also in other sectors.

3. Threshold effect mechanism

Based on literature review above, there may be nonlinear effect of renewable energy consumption on economic growth, the direction or degree of which may change as some important variables reach a certain level or threshold value. While panel threshold regression model is a nonlinear econometric model (Zhu and Lu 2017), we can regard threshold value as an unknown variable and apply it into empirical model to construct piecewise function of explanatory variable, estimate threshold value endogenously and estimate parameters of different threshold regimes. Therefore, we apply panel threshold regression model into the study of nonlinear effects of renewable energy consumption on economic growth. According to economic theory and classic literature, the reasons and theoretical mechanisms of threshold effects are analyzed as follows.

3.1. Renewable energy subsidy

Subsidy is generally used to develop renewable energy in most of countries, so the amount of renewable energy subsidy reflects the strength of government's renewable energy policy to some extent. If one country boosts renewable energy consumption by high subsidy, economic cost of promoting renewable energy consumption will increase when renewable energy subsidy is higher than threshold. Namely, economic cost of increasing renewable energy consumption is greater for countries with high subsidy. The reasons are explained as follows. Compared with fossil energy, renewable energy consumption is not cost effective, so there must be economic cost to promote renewable energy consumption through subsidy. First, from the perspective of social welfare, under government subsidy policy, market does not operate in the optimal state and net social welfare losses. Government subsidy cannot be completely transformed into social welfare and this part of loss is called deadweight loss. Second, the expense sharing mechanisms of renewable energy subsidy are different, so the expense is borne by power consumers (e.g. Austria), by the government(e.g. Netherlands), or by both power grid corporations and power consumers (e.g. France, Denmark), and so on (Batlle 2011). EU is in financial trouble now. Huge renewable energy subsidy has seriously increased government's financial burden and crowded out government other investment and consumption. At the same time, renewable energy subsidy will pass on to power consumers through electricity price or other forms, bringing cost burdens to power companies and individuals. Taking China for example. China has levied from electricity selling price for renewable energy development fund since 2006. The levy standard increases from 0.1 cents per Kwh to 1.9 cents per Kwh. Apergis and Salim (2015) believed that high cost of renewable energy lead to a reduction in government and private budgets, so investment and consumption decreased, which was detrimental to employment and economic growth. Dachis and Carr (2011) found that renewable energy feed-in tariff caused increase of 310 US dollars in annual electricity price per capita, which was not conducive to economic growth.

> Hypothesis 1: There is nonlinear impact of renewable energy consumption on economic growth. Economic cost of promoting renewable energy consumption will increase when renewable energy subsidy is higher than threshold. Namely, economic cost of increasing renewable energy consumption is greater for countries with high subsidy.

3.2. Energy consumption intensity

Energy consumption intensity (hereafter called energy intensity) is the ratio of total energy consumption to domestic GDP, reflecting the dependence of economic growth on energy and nonrenewable energy consumption. When energy intensity reaches a certain level, dependence of economic growth on energy consumption and nonrenewable energy consumption is higher, path dependence and lock-in effect of energy consumption are greater, so economic cost of energy transformation and increasing renewable energy consumption is greater. That is, economic cost of increasing renewable energy consumption is greater for countries with strong energy intensity. Path dependence effect of energy consumption is applying path dependence theory into the field of energy (David 1988; Arthur 1994). Self enhancement mechanisms, such as economy of scale, learning effect, cooperation effect and adaptive expectation, increase marginal return of nonrenewable energy consumption, which drive economic development highly dependent on nonrenewable energy in the aspects of technology, cognition, industry structure, and system. As a result, there are serious path dependence and lock-in effect of economic development on nonrenewable energy consumption, which hinder renewable energy technology innovation and energy transformation. Based on technology and system dependence, and increasing marginal returns, Unruh (2000) proposed that industrial economy had been locked in fossil energy system, which hindered policies and market forces in promoting emission reduction technology diffusion. Unruh (2000) took large technology system – power generation, distribution and terminal use as an example. He believed that it had been embedded in the social background, and was difficult to change the path of technology infrastructure and the corresponding institutions and systems.

> Hypothesis 2: There is nonlinear impact of renewable energy consumption on economic growth. Economic cost of promoting renewable energy consumption will increase when energy intensity is stronger than threshold. Namely, economic cost of increasing renewable energy consumption is greater for countries with strong energy intensity.

3.3. Level of economic development

GDP per capita is used to measure the level of economic development (hereafter called economic level). When economic development reaches a certain level, developing renewable energy is more advantageous in technology, capital and high-tech personnel and so on, so the economic cost of increasing renewable energy consumption is relatively smaller. That is, economic cost of increasing renewable energy consumption is smaller for countries with high economic level. Economic level determines the "hardware" (e.g. scientific researcher, research fund and infrastructure equipment) and "software" (e.g. professional knowledge, environmental protection concept and green demand), static and dynamic foundation of renewable energy technology innovation. Scientific researchers, educational funds and scientific research inputs are more adequate, professional knowledge is more abundant, and environmental protection concept and green demand are more advanced in countries with relatively high economic level. Moreover, these countries are easier to attract capital, technology and high-tech personnel to flow in, which is so-called agglomeration effect. Therefore, the foundation of renewable energy technology innovation is more advantageous. This means economic cost of increasing renewable energy consumption is relatively smaller. Huang et al. (2008a) divided 82 countries into groups according to economic level, and discovered that the relationship between energy consumption and real GDP were different among different groups. Lee and Chang (2007) also proposed similar conclusion. Al-Mulali et al. (2013) divided 108 countries into four groups according to economic level, such as high income, upper middle income, lower middle income, and high income countries, and proved that the positive impact of renewable energy consumption on economic growth is more persistent and significant in countries with higher economic level. Xu et al. (2013) found that regional advantages are more obvious, scientific research ability is stronger, and green technology innovation level is higher in countries with higher economic level. Thus, when economic level is higher than the threshold, the impact of renewable energy consumption on economic growth may mutate.

> Hypothesis 3: There is nonlinear impact of renewable energy consumption on economic growth. Economic cost of promoting renewable energy consumption will decrease when economic level is higher than threshold. Namely, economic cost of increasing renewable energy consumption is smaller for countries with high economic level.

Therefore, we apply panel threshold regression model into the study of nonlinear effects of renewable energy consumption on economic growth, taking renewable energy subsidy, energy intensity, and GDP per capita as threshold variables.

4. Econometric model and variable description

4.1. Econometric model

In recent years, under the background of climate change and low carbon transformation, scholars have begun to focus on the important role of renewable energy in economic growth. So, they subdivide energy consumption, treat renewable energy consumption as a production factor and apply it into the extended production function (Arbex and Perobelli 2010; Salim et al. 2014; Inglesi-Lotz 2016). Extended production function can be expressed as follows:

$$Y = fA, K, L, R, N = AK^{\alpha}L^{\beta}R^{\rho}N^{\delta}\ (0<,<1). \tag{1}$$

In this model, Y, A, K, L, R and N stand for real total output, technology, capital stock, labor stock, renewable energy consumption and nonrenewable energy consumption, respectively. And α, β, ρandδ stand for output elastic coefficients of capital, labor, renewable energy consumption and nonrenewable energy consumption respectively.

In order to avoid the error brought by man-made grouping and accurately identify factors that influence the direction and size of the impact of renewable energy consumption on economic growth, we use panel threshold regression model proposed by Hansen (1999). So we can study the heterogeneous impact of renewable energy consumption on economic growth among different groups divided according to the characteristics of data itself endogenously. Single threshold regression model can be expressed as:

$$\begin{aligned} Y_{it} = \mu_i + \boldsymbol{\beta}_0 \boldsymbol{z_{it}} + \beta_1 R_{it} I(q_{it} \leq \gamma) \\ + \beta_2 R_{it} I(q_{it} > \gamma) + \varepsilon_{it} \end{aligned} \tag{2}$$

In this model, subscript i indexes the country and subscript t indexes time. Explained variable Y_{it} stands for real total output of t year i country. q_{it} is threshold variable, and R_{it} is the core explanatory variable affected by threshold variables, namely renewable energy consumption. $\boldsymbol{z_{it}}$ is a set of variables other than renewable energy consumption that has a significant impact on real total output, including technology, capital stock, labor stock and nonrenewable energy consumption. $\boldsymbol{\beta_0}$, β_1 β_2 are corresponding coefficients, and γ is threshold value. $I(\cdot)$ is indicator function which is 1 when condition in corresponding bracket holds otherwise is 0. μ_i reflects unobservable individual effects of country, and ε_{it} *–iid* $N(0,\delta^2)$ is a random disturbance term. There may be multiple thresholds in practice which will be validated in this paper. The software used is STATA 13, and the panel threshold regression program used is "xthreg" written by Wang Qunyong in Nankai University.

4.2. Variable description

Year 1990 was the base year for most climate action targets in EU, such as 2020, 2030 and 2050 climate policy goals. So considering data availability and policy background, we select annual data of 1990–2014 in 28 EU members as panel data sample. Data is available from Euro stat, WDI database of World Bank, Penn World Tables (PWT 9.0) under United Nations International Comparison Project (ICP), OECD Statistics database and IEA energy data statistics.

Explained variable (Y, unit: million dollar) is real GDP of each country. Explanatory variables are various input factors, including, (1) renewable energy consumption (RE, unit: million toe). According to Renewables Information 2016 released by IEA, only 32.5% of renewable energy are used for electricity production and heat production globally, while 48.5% are used in the residential, commercial and public sectors in 2014. Considering that electricity consumption is only part of energy consumption, we use total renewable energy consumption, including renewable energy consumed not only in power generation but also in other sectors. (2)Nonrenewable energy consumption (NRE, unit: million toe). We use total nonrenewable energy consumption. (3)Labor stock (L, unit: million). There is huge human capital gap in different countries because labor productivity is heterogeneous among people received different education. So, employment can only reflect the number of labor stock but ignore the quality, and cannot fully represent labor stock. Therefore, labor stock is adjusted by human capital index considering heterogeneity of labor (Feng et al. 2012; Lu and Cai 2014), and this data is available from Penn World Tables (PWT 9.0). $L_{it} = EMP_{it} \cdot h_{it} \cdots$. $L_{it} \cdots$ is labor stock, $EMP_{it} \cdots$ is employment number, and $h_{it} \cdots$ is human capital index, which is constructed based on average years of education from Barro and Lee(http://www.barrolee.com/) and return rates of education(Barro and Lee 2013). $h_{it} = e^{\emptyset(s_{it})} \cdots$ is the function of national average education years(s_{it}). $\emptyset(s_{it})$ is a piecewise linear function reflecting different education return rates of different education years. (4) Capital stock (K, unit: million dollar). Capital formation is flow index which is not accurate to represent capital stock. So, we use capital stock data calculated by perpetual inventory method (Guo 2006; Lu and Cai 2014) from the Penn World Tables (PWT 9.0). $K_{it} = 1 - \delta_{it} K_{it-1} + I_{it} \cdots$. In this model, $\delta_{it} \cdots$ is depreciation rate, and $I_{it} \cdots$ is investment. (5) Technology($A \cdots$). We use total factor productivity (Solow 1957; Lu and Cai 2014), which indicates the contribution of technological progress to economic growth besides the input of various factors. Threshold variables include renewable energy subsidy (RD), energy intensity (INT, units: t/million dollar) and GDP per capita (gdp, unit: dollar). Among them, renewable energy public RD&D subsidy of 19 EU members from OECD Statistics database is used to represent the renewable energy subsidy (RD). Considering RD&D subsidy is only one kind of renewable energy subsidies, we use other proxy variables of renewable energy subsidy in robustness tests. In order to reduce the possible heteroscedasticity of the data, explained variable and explanatory variables are processed by logarithm, and then the letter "L" before the names of each variables is added.

5. Empirical results and analysis

In this section, panel threshold model is used to test the existence of threshold effect. If there is threshold effect, threshold value is determined, and parameters in different threshold regimes are estimated. Finally, we compare the condition of each country with threshold value to clarify which threshold regime each country is.

5.1. Results of threshold model

The test statistic F value and P-value can be calculated after 500 times of bootstrap (see Table 1). The results show that all threshold variables are significant at 5% level in single threshold model and not significant at 5% level in double threshold model. Relatively small confidence interval means threshold estimation is

Table 1. Results of threshold effect test.

	Single threshold model		Double threshold model			
Threshold variable	Fstat	Prob	Fstat	Prob	Threshold	[95% conf. interval]
RD	23.43**	0.048	9.59	0.310	3	[1.5, 4]
INT	101.22**	0.014	46.73	0.228	328.14	[313.73, 341.30]
gdp	101.19**	0.036	82.73*	0.052	5833.08	[5544.20, 6154.13]

** and * denote the level of significance at 5% and 10%, respectively.

basically accurate. Therefore, the following analysis will be based on single threshold model (see Table 2).

(1) On the whole, the impact of renewable energy consumption on economic growth is negative. That is, promoting renewable energy consumption as energy transformation strategy in EU has certain economic cost. Based on linear fixed effect model and three nonlinear threshold models, the results are robust. There are mainly two reasons. First, compared with fossil energy, renewable energy consumption is not advantageous in technology and cost. At present, renewable energy consumption expansion is mainly driven by government subsidy policy which brings deadweight loss, crowds out government other expenses, and brings cost burdens to power companies and individuals. Second, some countries are highly dependent on nonrenewable energy consumption which hinders renewable energy technology innovation and energy transformation. However, with the development of renewable energy technology innovation, decrease of renewable energy cost, dynamic scale economy and learning by doing effect and so on, the negative impact will be positive in the long run.

(2) Renewable energy consumption has significant threshold effects on real GDP. Specifically, (1) when renewable energy subsidy (*RD*) is higher than threshold, the negative impact of renewable energy consumption on real GDP is greater. When renewable energy subsidy (*RD*) is below threshold value ($RD = 3$), real GDP decreases around 0.04% with the increase of 1% in renewable energy consumption. When renewable energy subsidy (*RD*) surpasses threshold value, real GDP decreases around 0.048% with the increase of 1% in renewable energy consumption. Therefore, if one country boosts renewable energy consumption by high subsidies, economic cost of promoting renewable energy consumption will increase as renewable energy subsidy surpasses the threshold. Because high subsidy brings more deadweight loss, crowds out other government expenditures, and transfers to power consumers through electricity price or other forms, bringing cost burdens to power companies and individuals. As a result, economic cost of increasing renewable energy consumption is greater for countries with high subsidy. (2)When energy intensity is higher than the threshold, negative impact of renewable energy consumption on real GDP is greater. When energy intensity (*INT*) is less than 328.14 t/million US dollors, real GDP decreases around 0.038% with the increase of 1% in renewable energy consumption. When energy intensity (*INT*) is higher than 328.14 t/million US dollars, dependence of economic growth on energy consumption and nonrenewable energy consumption is higher. As a result, there are serious path dependence and inherent inertia of economic development on

Table 2. Threshold model regression results.

		Threshold model		
	Fixed effect model	Threshold variable: *RD*	Threshold variable: *INT*	Threshold variable: *gdp*
LRE	−0.037***	−0.040***($q \le 3$)	−0.038***($q \le 328.14$)	−0.121***($q \le 5\,833.08$)
	(0.008)	(0.006)	(0.007)	(0.011)
		−0.048***($q > 3$)	−0.104***($q > 328.14$)	−0.042***($q > 5\,833.08$)
		(0.006)	(0.010)	(0.007)
LNRE	−0.001	−0.089***	0.015	−0.004
	(0.018)	(0.016)	(0.016)	(0.016)
LK	0.501***	0.460***	0.494***	0.480***
	(0.010)	(0.012)	(0.009)	(0.009)
LL	0.478***	0.609***	0.503***	0.538***
	(0.025)	(0.022)	(0.024)	(0.024)
La	2.404***	2.139***	2.271***	2.338***
	(0.036)	(0.033)	(0.037)	(0.035)
Constant	2.588***	3.398***	2.662***	2.781***
	(0.108)	(0.122)	(0.101)	(0.103)
Obs.	700	437	700	700
R^2-within	0.974	0.990	0.977	0.977

Threshold regimes are in right parentheses. Standard errors are in bottom parentheses. *** denotes the level of significance at 1%. The linear model is estimated by fixed effect model based on Hausman test.

nonrenewable energy, which hinder renewable energy technology innovation and energy transformation. At this time, as renewable energy consumption increases 1%, real GDP decreases significantly around 0.104%. Therefore, economic cost of increasing renewable energy consumption is greater for countries with strong energy intensity. (3) When GDP per capita(*gdp*) surpasses the threshold, negative impact of renewable energy consumption on real GDP is smaller. When GDP per capita (*gdp*) is less than 5833.08 US dollars, real GDP decreases around 0.121% with the increase of 1% in renewable energy consumption. However, when GDP per capita (*gdp*) increases and is higher than 5833.08 US dollars, the negative impact of renewable energy consumption on real GDP decreases. As renewable energy consumption increases 1%, real GDP decreases 0.042%.Because scientific researchers, educational funds and scientific research inputs are more adequate, professional knowledge is more abundant, and environmental protection concept and green demand are more advanced in countries with relatively high economic level. Moreover, these countries are easier to attract capital, technology and high-tech personnel to flow in. As a result, the foundation of renewable energy technology innovation is more advantageous and negative impact of renewable energy consumption on real GDP is smaller. That is, economic cost of increasing renewable energy consumption is smaller for countries with high economic level.

Therefore, the above three hypotheses have been well tested. And these models are fitted well. For other explanatory variables, impact of nonrenewable energy consumption on real GDP is negative or not significant, namely, the approximate decoupling between economic growth and fossil energy consumption, which confirms environmental Kuznets curve between economic growth and fossil energy consumption. The influence of capital stock, labor stock and technology on economic growth is positive, among which technology contributes most to economic growth.

5.2. Number changes of countries in threshed regimes

In this section, the sample is divided into different regimes according to threshold value, and the number of countries in each threshold regime is calculated (see Table 3). Results are listed as follows. (1) For threshold variable of energy intensity, there were seven member countries in the high-intensity regime in 1990. However, at most one country (Bulgaria) was in the high-intensity regime since 2005. And energy intensity of Bulgaria dropped from 772.10 t/million US dollars in 1990 to 339.27 t/million US dollars in 2014, close to the threshold. Obviously, energy intensity of most EU members is lower than threshold value, so path dependence effect of energy consumption is small. (2) For threshold variable of GDP per capita, there were only Bulgaria and Romania in the regime of low economic level. However, GDP per capita of all members were higher than threshold value since 2010. That is, there are certain advantages in renewable energy technology innovation. Thus, at present, large-scale promotion of renewable energy consumption and energy transformation in EU are under the appropriate energy intensity and economic level conditions.

(3) For threshold variable of renewable energy subsidy (see Tables 3 and 4), first, there was only one country (Netherlands) in the high-subsidy regime in 1990. As the amount of renewable energy subsidy in EU is larger and larger, more and more countries came to the high-subsidy regime. There were seven member countries in the high-subsidy regime in 2012, including Denmark, Germany, Netherlands, Austria, Slovakia, Finland, and Sweden. This explains why the impact of renewable energy consumption on economic growth is negative in EU. Right now, the expansion of renewable energy consumption is mainly driven by high subsidy, which brings more deadweight loss, crowds out other government expenditures, and transfers to power consumers, sacrificing economic growth to some extent. This is a big challenge for EU, which is now in financial trouble and economically and politically unstable. Second, comparing the two groups of countries with high subsidy and low subsidy, the average annual growth rates of renewable energy consumption showed no significant difference between the two groups from 1990 to 2014. The average annual growth rates of renewable energy consumption in Britain and Belgium rank first and second, but the subsidies of both countries have never

Table 3. Description of number changes among countries in different threshold ranges.

Threshed regime	1990	1995	2000	2005	2010	2011	2012	2013	2014
Low subsidy($RD \leq 3$)	18	18	17	18	15	12	12	–	–
High subsidy($RD > 3$)	1	1	2	1	4	7	7	–	–
Low intensity($INTEN \leq 328.14$)	21	21	24	27	27	27	27	28	27
High intensity($INTEN > 328.14$)	7	7	4	1	1	1	1	0	1
Low economic level ($gdp \leq 5833.08$)	2	4	2	1	0	0	0	0	0
High economic level ($gdp > 5833.08$)	26	24	26	27	28	28	28	28	28

Table 4. Growth rates of renewable energy consumption between high and low subsidy groups.

Year 1990		Year 2012	
Low subsidy	High subsidy	Low subsidy	High subsidy
Belgium, Czech Republic, Denmark, Germany, Ireland, Greece, Spain, France, Italy, Hungary, Austria, Poland, Portugal, Slovenia, Slovakia, Finland, Sweden, the United Kingdom	Netherlands	Belgium(8.49%), Czech Republic(5.55%), Ireland(7.54%), Greece(3.36%), Spain(4.48%), France(1.42%), Italy(6.05%), Hungary(3.94%), Poland(7.32%), Portugal(2.19%), Slovenia(3.54%), the United Kingdom(10.91%)	Denmark(6.30%), Germany(8.22%), Netherlands(6.45%), Austria(2.72%), Slovakia(6.30%), Finland(2.66%), Sweden(1.71%)

Average annual growth rate of renewable energy consumption is in parentheses.

crossed the threshold. The average annual growth rate of renewable energy consumption in Netherlands, which has always been in the high-subsidy group, is smaller than that in Belgium, Ireland, Poland and the United Kingdom which have always been in the low-subsidy group. Therefore, subsidy with high economic cost is not the only effective means to develop renewable energy.

6. Robustness test

We test robustness of the above conclusions from three perspectives. First, we adjust the sample to deal with possible error caused by outliers. Second, we adjust the empirical method and compare regression results of different methods to deal with possible error caused by single method. Third, we adjust the proxy variable. Considering RD&D subsidy is only one kind of renewable energy subsidies, we use other proxy variables of renewable energy subsidy in robustness tests.

(1) Adjust the sample. We remove in order the countries which is the most and least 1%, 5%, and 10% of the sample countries according to the proportion of national renewable energy consumption to total renewable energy consumption in EU. Therefore, we test the sample of 26, 24, and 22 EU members respectively through three panel threshold models and the results are similar. That is, when renewable energy subsidy is higher than threshold, energy consumption intensity is stronger than threshold, and GDP per capita is lower than threshold, the economic cost of increasing renewable energy consumption rises. So, the conclusions are consistent with the above estimates and robust. As space is limited, relevant tables are available on request.

(2) Adjust the empirical method. We divide EU members into low-subsidy group and high-subsidy group according to the threshold of renewable energy subsidy (see Table 3) to analyze whether the impact of renewable energy consumption on economic growth is heterogeneous between the two groups. For other threshold variables, because most EU members are in the same threshold regime, it is difficult to carry out the grouping test. The parameter estimation results of grouping method (see Table 5) are similar with the results of threshold model. Specifically, the impact of renewable energy consumption on real GDP is negative for countries in low-subsidy group. However, the coefficient is very small (−0.010), and not significant. The negative impact of renewable energy consumption on real GDP is greater for countries in high-subsidy group. As renewable energy consumption increases 1%, real GDP decreases around 0.069%.And the result is significant at 1% level. In combination with a more rigorous grouping approach, dummy variable D_i is used. $D_i = 1$ in high-subsidy group and $D_i = 0$ in low-subsidy group. The coefficient of the cross term *LRE*D* is significantly negative (−0.044), indicating that economic cost of promoting renewable energy consumption is greater in high-subsidy group.

(3) Adjust the proxy variable. Because of data availability, we use renewable energy public RD&D subsidy to measure renewable energy subsidy. In fact, renewable energy subsidy includes RD&D subsidy, feed-in tariff, tax credits and concessional loans, and so on. Therefore, first, we use Environmental Policy Stringency Index *(ENVI)* from OECD Statistics, including 14 environmental policy instruments, to indirectly measure renewable energy subsidy. Then we use

Table 5. Regression results of grouping method.

	Low-subsidy group $RD \le 3$	High-subsidy group $RD > 3$	Grouping by dummy
LRE	−0.010	−0.069***	−0.015**
	(0.008)	(0.007)	(0.006)
*LRE*D*	–	–	−0.044***
			(0.006)
LNRE	−0.045**	−0.079***	−0.063***
	(0.020)	(0.018)	(0.014)
LK	0.423***	0.512***	0.441***
	(0.012)	(0.023)	(0.011)
LL	0.602***	0.469***	0.580***
	(0.027)	(0.032)	(0.020)
La	2.187***	2.218***	2.207***
	(0.040)	(0.053)	(0.031)
Constant	3.713***	3.021***	3.602***
	(0.126)	(0.264)	(0.113)
Obs.	300	175	475
R^2-within	0.991	0.992	0.991

Standard errors are in bottom parentheses. *** and ** denote the level of significance at 1% and 5%, respectively.

another kind of renewable energy subsidy, feed-in tariff *(FEED)*, to test the robustness of the conclusions. Empirical results show that when environmental policy stringency index *(ENVI)* and feed-in tariff *(FEED)* are higher than the threshold value of 2.4 and 2.5, respectively, the negative impact of renewable energy consumption on economic growth is significantly enhanced. So the conclusions are verified again and robust. That is, the impact of renewable energy consumption on economic growth is negative and nonlinear. Economic cost of increasing renewable energy consumption is greater for countries with high subsidy. As space is limited, relevant tables are available on request.

7. Conclusions

Based on deadweight loss and crowd-out effect of renewable energy subsidy policy, path dependence effect of energy consumption and technical basis effect of economic level on renewable energy consumption, we apply panel threshold regression model into the study of threshold effects of renewable energy consumption on economic growth in 28 EU members from 1990 to 2014, taking renewable energy subsidy, energy intensity, and GDP per capita as threshold variables. We verify three hypotheses and come to following conclusions. (1) Energy transformation sacrifices economic growth to some extent, namely, the impact of renewable energy consumption on economic growth is negative. For different threshold regimes, the impact of renewable energy consumption on real GDP is always negative, but varies in quantity. (2) Renewable energy consumption has significant threshold effects on economic growth. When renewable energy subsidy is higher than threshold, energy consumption intensity is stronger than threshold, and GDP per capita is lower than threshold, the economic cost of promoting renewable energy consumption is greater. (3) Now, energy consumption intensity and GDP per capita of most EU members are in the appropriate threshold regimes. In contrast, more and more countries in EU are in the high-subsidy group. The expansion of renewable energy consumption is mainly driven by high subsidy which sacrifices economic growth. (4) Subsidy with high economic cost is not the only effective means to promote renewable energy consumption. The average annual growth rates of renewable energy consumption showed no significant difference between high-subsidy and low-subsidy countries from 1990 to 2014.The size of subsidy and growth rate of renewable energy consumption are not necessarily related.

The promotion of renewable energy consumption in China is enlightened by empirical results of EU in two ways. On the one hand, government instruments should be rationally and effectively used to stimulate energy transformation. (1) The ultimate goal of subsidizing is no subsidizing. We should prevent excessive and inefficient subsidizing, gradually reduce renewable energy subsidy, and completely cancel fossil fuel subsidy, to reduce the loss of net social welfare. (2)We should improve the management of renewable energy development fund and adopt appropriate fiscal and tax policy to fill the capital gap of renewable energy subsidy and reduce the crowd-out effect to investment and consumption in both government and private sector. (3) The efficiency of subsidizing should be increased, and the management system and subsidizing procedures should be optimized. On the other hand, different renewable energy policies and targets should be formulated according to regional differences. (1) Preferential policies should be more inclined to regions with higher economic cost of energy transformation, namely regions with stronger energy consumption intensity and lower economic level. (2) Efforts should be made to break through the path dependence of fossil energy consumption and strengthen the infrastructure and system construction for renewable energy transmission and connection to the grid. (3) We should enhance the basic conditions for developing renewable energy and vigorously promote renewable energy technology innovation.

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