# How does hydrogen-renewable energy change with economic development? Empirical evidence from 32 countries

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## Abstract

The hydrogen-based renewable energy resource base is sufficient to meet several times the present world energy demand. This paper analyzes the drivers promoting hydrogen-based renewable energy utilization, focusing on a group of 32 countries by applying panel data techniques. The pooled ordinary least square estimator and fixed effect estimator are employed for comparison. Grey relational analysis is used to explore the relationships at a national level between renewable energy development and its influencing factors. The main results over our time span indicate that: (1) GDP per capita is a significantly positive contributor to renewable energy consumption, while oil price does not present a strong relationship in the use of renewables; (2) social awareness about climate change and concerns for energy security is not enough to motivate the switch from traditional to renewable energy sources; (3) the role of urbanization in renewable energy consumption relies on different stages of the urbanization process, resulting in opposite trends in renewable energy development between developing and developed countries. The results show that the market mechanism is not entirely responsible for encouraging the use of renewables and the role of climate change and energy security concerns in renewables use should be enhanced. By analyzing the results, policy implications are provided for the sustainable development of renewable energy.

**Key words**: hydrogen-based renewable energy; carbon emission; income elasticity; Grey relational analysis

## 1. Introduction

Renewable energy (hereafter RE), especially hydrogen-based renewables, which can be considered as a substitute for fossil fuels, is vital for social development from the aspects of environmental benefits, energy security, climate change and clean production [1, 2, 3, 4]. As is well documented, energy consumption in emerging countries is growing very rapidly, while that of developed countries is at a balanced level. The world's huge energy demand has promoted the utilization of renewables and the transition to hydrogen economy over the past decades, especially the first decades of the 21st century, and has surpassed all expectations. The Renewables Global Status Report points out that RE accounted for an estimated 19.2% of the world's primary energy use in 2014, and 173 countries defined their renewable targets in 2015 [5]. Further, the achievement of the Millennium Development Goals and the sustainability of clean production require the development of hydrogen-based renewable energy system [6, 7]. None of the Millennium Development Goals can be met without major improvements in the quality and quantity of energy services in developing countries. It is suggested that hydrogen-based renewables can play a vital role in this path, assisting developing countries in expediting their economic development and alleviating rural poverty [8].

Analysis on the drivers of RE development is central to sustainable development [9]. A future hydrogen-based renewable energy system needs technical change and the infrastructure building. The world needs to move faster and more decisively if we are serious about ensuring access to clean and sustainable energy for all people by 2030 [10]. First, many developing economies are now finding themselves facing an energy security issue similar to that of most developed economies [11,12], such as the relatively higher energy dependency of China and Japan. Hydrogen-based renewable energy systems can enhance energy security and achieve China's CO2 emissions peak through technological diversification and minimizing dependence on foreign imports of energy fuels [4, 13]. For example, China's Blue Book on Hydrogen Energy Infrastructure has been released in October 2016. Hydrogen energy and fuel cell integration are included in Energy Technology Innovation Plan (2016-2030) [14]. Second, RE can help to disentangle the issue of energy poverty, mobilizing national actions to ensure universal access to modern energy services [15]. Bhide and Monroy (2011) analyzed the current status of energy development in India and suggested a sustainable method to eradicate energy poverty there through RE technologies [16]. Last, while fossil-fueled economic growth, through the release of greenhouse gases, is a major contributor to climate change, RE can be an efficient tool to cope with that change. The special report from the Intergovernmental Panel on Climate Change (IPCC) analyzes the challenges and opportunities of RE development in addressing climate change [17]. Sapkota et al. (2014) examined the role of RE technologies in climate change adaptation in rural areas of Nepal through the Long-range Energy

Alternatives Planning model and estimated the potential emissions reduction by the use of different renewable technologies [18].

While the drivers of energy consumption have been well studied, there are relatively few studies on the determinants of RE development. The empirical work has been primarily focused on USA, Europe and the G7 countries generally. Sadorsky (2009) analyzed the relationships between $CO_2$ emissions, GDP, oil prices and RE consumption in G7 countries and concluded that GDP and $CO_2$ are the major drivers for RE consumption [19]. Marques et al. (2010) applied a panel data model to study the drivers of RE in European countries and concluded that energy security was a stimulator for RE use [20]. After examining the role of different energy sources in economic growth, Marques and Fuinhas (2011) pointed out the negative effect of RE in promoting economic growth [21]. Menz and Vachon (2006) developed a regression equation through the OLS method for the wind power sector in 30 American states and discussed the contribution of different policy regimes on wind power development [22]. However, there is a lack of empirical research on the determinants of RE in developing countries [23]. Although Europe and the USA have taken a leading role in the RE market, China and Brazil has become emerging contributors to the world's RE consumption. The internal mechanisms of RE development in developing countries and their comparison with that of developed economies are relevant to further understand the determinants that have promoted or hampered RE development in the world.

Based on the previous studies, this paper chooses various countries that are deploying RE and applies panel data techniques to explore the influencing factors governing RE development. Due to the differences in economic development levels and situations surrounding energy use, these 32 countries have been classified either as developing countries or developed countries for comparison purposes. Twenty-one countries facing energy security issues out of the original 32 have been selected as the sample to research the role of energy security concerns in RE development, and Grey relational analysis is utilized to explore the relationships between RE consumption and its impact factors. Thus, this paper will help to identify challenges and opportunities for RE use and shed some light on future world RE policies. Most importantly, given the increasingly important role of emerging economies in the RE market, this analysis fills in gaps in the RE research on developing nations.

The remainder of this paper is structured as follows. In Section 2, the theoretical framework and data resources supporting the Panel Data model and Grey relational analysis used are explained, while the results and discussion are presented in Section 3. Finally, Section 4 presents policy implications and the concluding remarks. This last part also highlights the contributions that the present study seeks to make as well as the future direction of this research.

## 2 Methodologies

### *2.1. Conceptual framework for the determinant analysis of renewable energy development*

Figure 1 depicts the framework for the impact factor analysis of renewable energy development. The 32 chosen countries are divided into developing and developed countries based on classification from the International Monetary Fund. Two panel data estimators are applied to study the underlying drivers governing RE consumption. The comparison on impact factors of RE between developed and developing countries will be helpful for the sustainable development of renewable energy in the world. Further, 21 countries facing energy security issues from the original 32 countries are selected to study the influence of energy security on renewable energy deployment. Grey relational analysis is utilized to explore the relationships between RE consumption and its impact factors. By analyzing the results, this study puts forward some recommendations for the world's renewable energy development.

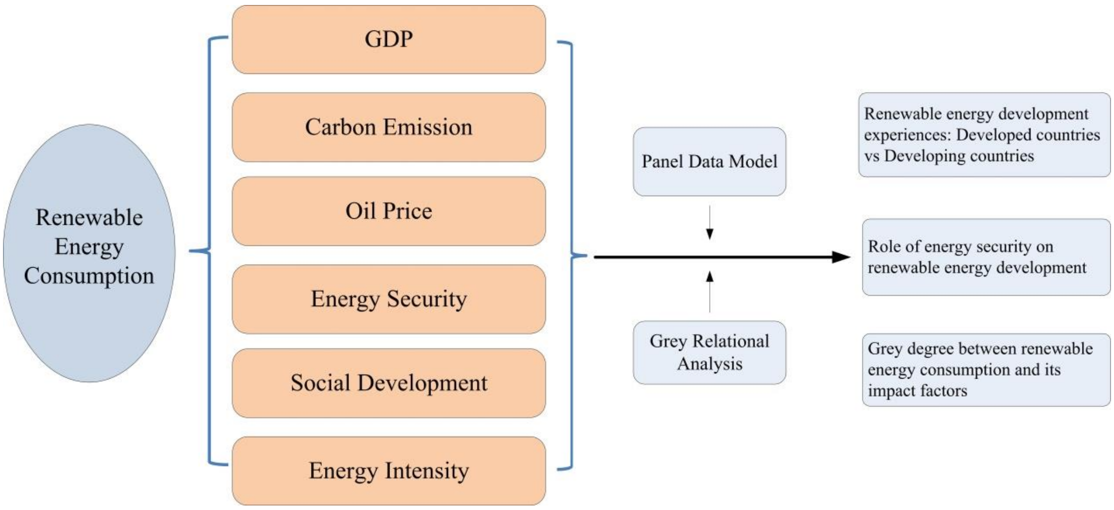


**Fig. 1.** Framework for Impact factors analysis of renewable energy development.

## *2.2. Panel estimators for renewable energy development*

The panel data model, with its wide application in energy policy research [21, 24], is employed in this study. There are many panel estimators and transformed panel data models, such as the group-means fully modified OLS estimator, parametric dynamic OLS estimator and the fixed effects vector decomposition model. In our model, two general estimators (pooled OLS and fixed effect OLS) are presented. The use of two different estimators allows for a comparison to evaluate whether the estimated regression parameters are sensitive to the estimation technique.

In this paper the variables are chosen in accordance with economic theory and data availability. As is standard in energy development models, income [25] is measured by per capita real GDP. With the growing public concern about climate change [26, 27], per capita $CO_2$ emissions is an important incentive for RE consumption. Hydrogen-based RE can be a substitute for fossil fuel consumption, and the price of oil, natural gas and coal should be considered among the drivers of renewable energy development. Traditionally, the price of energy generated from fossil fuels is lower than the price of energy generated from renewables. Changes in the price of traditional energy sources will influence the use of renewable energy through the competitiveness of renewable energy in the energy market. However, due to lack of data availability for energy prices in these 32 countries, this paper only considers the effect of oil price on renewable energy utilization. Hydrogen-based renewable energy consumption is measured by per capita renewable electricity generation, and a linear relationship between the natural logarithm of renewable energy consumption per capita (RE) and its impact factors is postulated as follows equation (1).

$$RE_{it} = \alpha_{0i} + \alpha_{1i} GDP_{it} + \alpha_{2i} CO2_{it} + \alpha_{3i} OP_{it} + h(v_{1,it}, v_{2,it}, \cdots) + \varepsilon_{it} \quad (1)$$

Where $i = 1, 2, \cdots, 32$ denotes the country and $t = 1980, 1981, \cdots, 2011$ denotes the time period. $RE_{it}$, $GDP_{it}$, $CO2_{it}$ and $OP_{it}$ represent the natural logarithms of renewable energy consumption per capita and per capita $CO_2$ emission, per capita real GDP of country $i$ in year $t$, while $v_{k\square}$ represents controlling variables we employed to examine the contribution of other indicators for RE consumption (these variables include socio-economic development, energy demand, energy security and the time variable), and $\varepsilon_{it}$ is assumed to be independent and identically distributed with a zero mean and constant variance. More details about the variables will be discussed in Section 2.4. The panel data model is run with the software EViews 7.

*2.3. Grey relational degree between renewable energy consumption and its drivers*

The Grey system theory was first presented by [28], and is a good tool to handle problems with poor information. Nowadays, this theory is applied to study energy and environmental issues [29, 30]. For example, Feng et al. (2011) studied the influence of residents' consumption in China on the energy use and carbon dioxide emissions by means of Grey relational analysis and consumer lifestyle theory, and not only found that the indirect effects were greater but also revealed the effects on the income of the residents as well as the impacts on different income levels [31]. The Grey forecasting model is applied in [32] to study the vulnerability of hydropower generation to climate change, and noted increasing hydropower vulnerability in the poorest regions in China. A brief description of the Grey relational analysis is given below.

$X_i$ ($X_i = (x_i(1), x_i(2), \cdots, x_i(n)),$) is the original renewable energy data series of a given country, and $n$ represents the time period. The original sequence is normalized based on the initial annihilation operator $X_i D$, shown as Equation (2). Thus, the concept $s_i = \int_1^n (X_i - x_i(1))\mathrm{d}t$ is obtained for the next step.

$$X_i D = \left(x_i(1)d, x_i(2)d, \cdots, x_i(n)d\right), \quad x_i(k)d = x_i(k) - x_i(1), \quad (k = 1, 2, \cdots, n) \quad (2)$$

The RE consumption data series ($X_i$) and GDP data series ($X_j$) of a given country are $X_i = \left(x_i(1), x_i(2), \cdots, x_i(n)\right)$, $X_j = \left(x_j(1), x_j(2), \cdots, x_j(n)\right)$, which have the initial annihilation image of $X_i D$ and $X_j D$, namely $X_i^0 = \left(x_i^0(1), x_i^0(2), \cdots, x_i^0(n)\right)$ and $X_j^0 = \left(x_j^0(1), x_j^0(2), \cdots, x_j^0(n)\right)$, respectively.

If $s_i - s_j = \int_1^n (X_i^0 - X_j^0)\mathrm{d}t$, $\varepsilon_{ij} = \frac{1+|s_i|+|s_j|}{1+|s_i|+|s_j|+|s_i - s_j|}$, the ratio $\varepsilon_{ij}$ is the absolute degree of Grey incidence between RE use and GDP for the targeted country. The higher the Grey relational degree is, the closer the relationship between RE consumption and the driver.

The current research uses the Grey Theory Modeling Software (GTMS) 3.0 for calculation. The results from the Grey relational analysis can act as checks to gain robust results on the panel estimator results.

*2.4. Data descriptions and data sources*

From the renewable electricity generation data from U.S. Energy Information Administration, this study collected annual data for 32 countries (Canada, Brazil, Norway, Russia, Japan, China, India, Sweden, Venezuela, Denmark, Spain, Italy, France, Portugal, Germany, Indonesia, Vietnam, Pakistan, Australia, Switzerland, Turkey, Finland, Austria, Peru, Paraguay, Chile, Colombia, Argentina, Mexico, New Zealand, United Kingdom, and the United States) that accounted for at least 22 billion kWh in renewable electricity consumption. Figure 2 denotes the RE utilization in these 32 countries. Numerous studies about the drivers of renewable energy development, such as [19, 20], have only considered developed countries. However, recent decades have witnessed the rapid growth of renewable energy utilization in emerging economies such as China, Brazil, India, etc. The experience from developing countries will help to promote RE deployment in the most underdeveloped regions of the world, which may result in poverty alleviation. This paper not only analyzes the drivers of RE consumption at different levels, but also gives special emphasis to researching the role of energy security issues in promoting RE utilization.

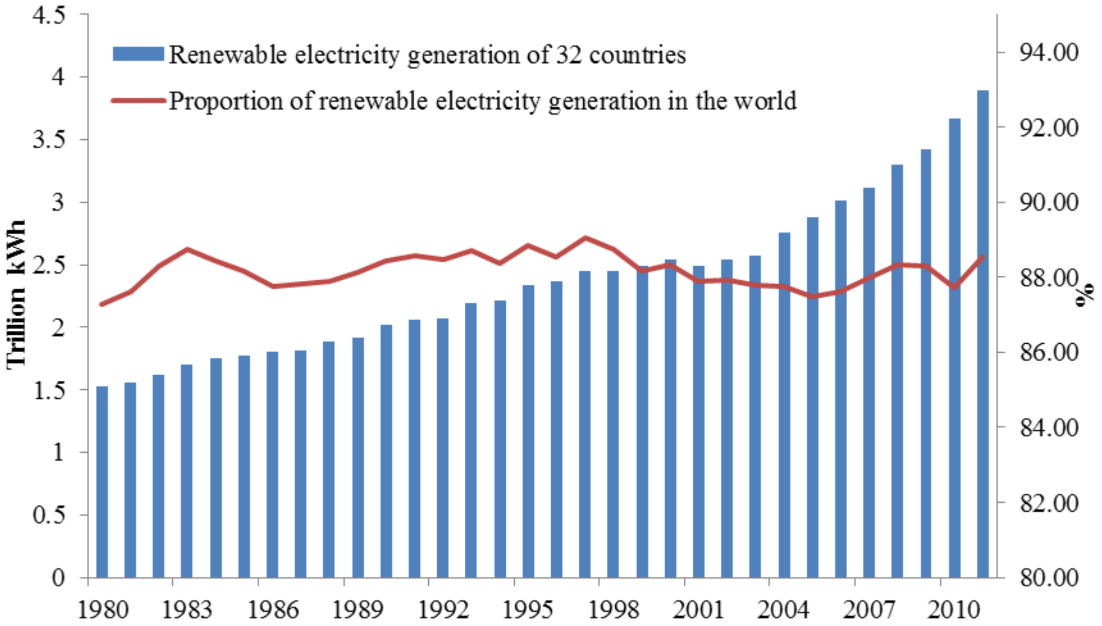


**Fig. 2.** Proportion of renewable electricity generation in 32 countries (1980-2011)

From the data sets, the years 1980-2011 are used in this paper. The German data from before reunification are formed by merging the data from East Germany with the data from West Germany. The Russian data from 1980 to 1989 are estimated from the data of the Union of Soviet Socialist Republics and the percentage of each indicator for Russia. The hydrogen-based renewable energy consumption in billions of kilowatt-hours is measured as net geothermal, solar, wind, wood, and waste electric power consumption, which are sourced from U.S. Energy Information Administration. Net consumption does not include the energy consumed by the generating units. Hydrogen energy is an important aspect for future sustainable energy system. However, its utilization is at the initial stage of industrialization. Furthermore, because of the shortage of historic data, hydrogen energy is not considered in our study. As the three biggest standard crude oil price ratings, WTI, Brent, and Dubai represent the oil price changes in North America, Europe and Asia, respectively. Due to the difference in densities and sulfur content, their prices are different. To avoid the interference of different markets and different crude oil prices, this paper adopts the average spot price of international crude oil calculated from WTI, Brent, and Dubai prices. The data for WTI, Brent, and Dubai crude oil prices come from British Petroleum [33]. The data on population are from the U.S. Energy Information Administration.

**Table 1**

Definition of the variables used in panel data model.

| Variables | Description | Source | Unit |
|---|---|---|---|
| Hydrogen-based renewable energy | Total renewable electricity consumption | US EIA[1] | Billion kWh |
| Population | Population | US EIA[1] | Million |
| Energy security | Net energy imports | World Bank | % of energy use |
| Industrialization | Industry value added | World Bank | % of GDP |
| Urbanization | Rural population | World Bank | % of total population |
| Income | GDP per capita | United Nations Statistics Division[2] | Equivalent 2005 prices in US dollars per capita |
| Climate change | $CO_2$ emissions per capita | World Bank | Kiloton |
| Energy consumption | Energy use per capita | World Bank | kg of oil equivalent per capita |
| Energy intensity | GDP per unit of energy use | World Bank | Equivalent 2011 US dollars per kg of oil equivalent |

Table 1 shows the definition and sources of data used in this paper. Apart from the variables (GDP, $CO_2$ and oil price) discussed in Section 2.2, other variables have

[1] http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm

[2] http://unstats.un.org/unsd/snaama/dnlList.asp

been selected according to data availability and through literature review. The social development process represented by urbanization [34] and industrialization [35], energy security concern, the effect of lobbying for fossil energy use [36], and technology innovation (energy intensity) are the control variables we employed to examine the contributions of other indicators to RE consumption [37]. Apart from the variables of energy security, lobbying effects, and energy intensity, the reason we chose urbanization and industrialization as the control variables is that: (1) when the urbanization process promotes energy demand, the pursuit of green, low-carbon development may enhance the renewable penetration rate; (2) because the industrialization process involves huge energy consumption, energy shortages resulting from this process will facilitate the adoption of renewable energy. Thus, the social development indicators will reflect how the social process influences the development of renewable energy industries.

## 3. Results and discussion

### *3.1. Impacts of economic development and carbon emissions on renewable energy consumption*

The specification test in this paper is done to check whether the results are fragile when other relevant factors are included in our model. Because our main purpose is to find the factors governing RE consumption, this paper applies 5 models, as listed in Table 2. Model 1 considers the impacts of economic development, global warming, and the price of fossil fuel on RE development [19]. Based on Model 1, Models 2, 3, 4, and 5 correspond to the effects of energy security, energy intensity, social development, and the effect of lobbying for traditional energy use.

**Table 2**

Model specifications for robustness check on renewable energy consumption

| Model | Variables included |
|---|---|
| M1 | GDP per capita (IN), $CO_2$ per capita (IN), Oil price (IN) |
| M2 | GDP per capita (IN), $CO_2$ per capita (IN), Oil price (IN), Energy security |
| M3 | GDP per capita (IN), $CO_2$ per capita (IN), Oil price (IN), Energy intensity |
| M4 | GDP per capita (IN), $CO_2$ per capita (IN), Oil price (IN), Social development |
| M5 | GDP per capita (IN), $CO_2$ per capita (IN), Oil price (IN), Energy use per capita (IN) |

*Note*: the dependent variables are natural log per capita RE consumption. The IN in bracket represents the natural log of these variables.

The pooled least squares (PLS) and fixed effect (FE) ordinary least squares (OLS) estimators of these 5 models are listed in the corresponding columns of Table 3, from which several conclusions can be derived. The emphasis is on the robustness of RE-income, $CO_2$, oil price relationships, and other factors' impacts on RE development.

Income level is significantly and positively related to renewable electricity generation in all models, which implies that RE development relies on economic development. Carbon emissions have a negative effect on RE development in most of these models. The role of climate change on RE use suggests that the current levels of $CO_2$ are not enough incentive to switch to renewables. Social pressure seems to have been insufficient to stimulate the use of renewables, and international agreements should be more ambitious in coping with climate change. Economic theory generally postulates that the price of traditional fossil energy sources should encourage renewable energy consumption. Even though oil price is positively related to RE development, in almost all cases it is not a major factor in explaining the use of renewables. The theoretical support of the price mechanism on renewables may be more complex than the simple direct mechanism of high prices of fossil fuel in making renewables more attractive. During the timespan in our study, the roles of IEA and OPEC in the setting of oil prices may result in mixed results.

**Table 3**

Empirical results of the 5 models under PLS and FE OLS estimation

| | M1 | | M2 | | M3 | | M4 | | M5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | PLS | FE | PLS | FE | PLS | FE | PLS | FE | PLS | FE |
| GDP | 0.815*** | 1.036*** | 1.083*** | 1.256*** | 3.077*** | 0.514*** | 0.888*** | 0.904*** | 0.375*** | 1.319*** |
| $CO_2$ | -0.305*** | -0.050 | -0.924*** | -0.428*** | -2.156*** | 0.368** | -0.609*** | -0.156 | -2.156*** | 0.368** |
| Oil Price | 0.086 | 0.019 | 0.117 | 0.069* | 0.139* | -0.015 | 0.088 | -0.032 | 0.139* | -0.015 |
| Energy Security | | | -0.001 | -0.020*** | | | | | | |
| Energy intensity | | | | | -2.702*** | 0.805*** | | | | |
| Urbanizat-ion | | | | | | | -0.016*** | -0.029*** | | |
| Industriali-zation | | | | | | | 0.050*** | 0.006 | | |
| Energy use | | | | | | | | | 2.702*** | -0.804*** |
| Constant | 1.730*** | -2.191*** | 4.100*** | -0.764 | 37.793*** | -13.136*** | 2.493*** | 0.802 | 0.463 | -2.020*** |
| R2 | 0.375 | 0.915 | 0.428 | 0.937 | 0.548 | 0.917 | 0.439 | 0.918 | 0.548 | 0.917 |
| Obs. | 1024 | 1024 | 672 | 672 | 1024 | 1024 | 1024 | 1024 | 1024 | 1024 |

*Note*:*p<0.05, **p<0.01, ***p<0.001

In addition to other drivers of RE development, urbanization and industrialization have positive relationships to RE development, while the results for energy intensity and energy use are inconsistent in these two indicators. The urbanization and industrialization processes stimulate energy consumption, and the results suggest that these additional energy needs could also stimulate production from RE sources and not just from traditional ones. The varying results about energy intensity and energy use reveal that they are not conclusive for the development of renewables over the study period.

*3.2. Concern of energy security and renewable energy development*

Energy security is a major driver of national energy policies [38, 39], and for countries with larger energy dependency, it would induce higher investment in their own renewable sources [40]. Based on energy import rate, this analysis considers 21 countries (Austria, Brazil, Switzerland, Chile, China, Germany, Denmark, Spain, Finland, France, United Kingdom, Italy, Japan, India, Pakistan, Peru, Portugal, Sweden, Turkey, United States, New Zealand) from the above 32 countries which faced energy security issues during the research period, shown in Figure 3.

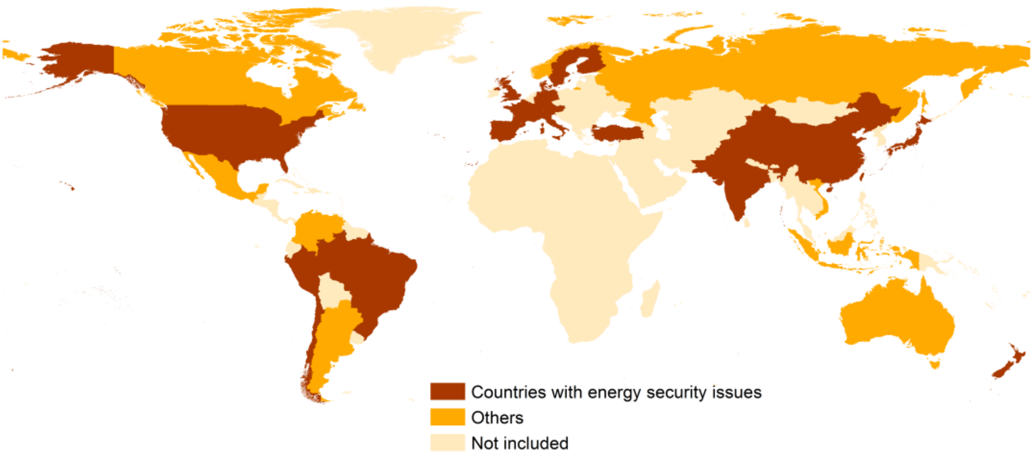


**Fig. 3.** Data for renewable electricity generation research in 32 countries (including 21 countries with energy security issues)

As shown in Table 3, Model 2 tests the role of energy security in RE use, and the results indicate that energy security is slightly but negatively correlated to the use of RE. The effect of energy dependency on RE use suggested in some of the literature, such as [21] and [41], is inconsistent. Our results point out the shortage of renewable technology in an uninterrupted electricity supply. The countries which rely heavily on energy imports will have a higher commitment to a stable energy supply, while renewables are not adequate in providing continuous production and avoiding idle capacity excess.

*3.3. Comparison between developing and developed countries*

Based on the classifications from the International Monetary Fund [42], this paper divides the 32 countries into two categories: developed and developing. Analysis of these two samples can help in making a further analysis which considers the states of economic development. While most previous studies have focused on developed countries, studying the experiences of RE development from developing countries, such as China, Brazil, and India, could provide lessons for the rest of the world.

Table 4 shows that the pooled least squares estimator is more robust than the FE estimator. GDP and industrialization are positively and significantly related to the use of RE. Unlike the results from Table 3, urbanization has a different effect on RE development in developed and developing countries. It has a positive relationship with RE consumption in developed countries, while a negative connection occurs in developing nations. This fact reflects the different energy needs of the urbanization process in developed and developing economies. Generally speaking, the urbanization process in developed countries is relatively more advanced than in developing countries. In the advanced phases of urbanization, the demand for renewable energy may be higher than in other stages with lower urbanization rates.

**Table 4**

Results from models targeted on developed and developing countries

| | Developed countries | | Developing countries | |
|---|---|---|---|---|
| | PLS | FE | PLS | FE |
| GDP | 4.503*** | 1.547*** | 2.191*** | -0.216 |
| CO2 | -3.281*** | -0.729** | -1.691*** | 0.950*** |
| Oil price | 0.275*** | -0.022 | 0.084 | -0.160*** |
| Energy intensity | -4.429*** | 0.830** | -2.134*** | 0.196 |
| Urbanization | 0.042*** | 0.020* | -0.038*** | -0.047*** |
| Industrialization | 0.056*** | 0.020** | 0.009* | 0.008* |
| $R^2$ | 0.550 | 0.894 | 0.708 | 0.944 |
| Obs. | 544 | 544 | 480 | 480 |

Note: Developed countries include Australia, Austria, Canada, Switzerland, Germany, Denmark, Spain, Finland, France, United Kingdom, Italy, Japan, Norway, Portugal, Sweden, United States and New Zealand, whilst Argentina, Brazil, Chile, China, Colombia, Indonesia, India, Mexico, Pakistan, Peru, Paraguay, Russian, Turkey, Venezuela, and Vietnam are considered developing countries.

*p<0.10, **p<0.05, ***p<0.01

### *3.4. Relational analysis between renewable energy consumption and its impact factors*

According to the method presented in Section 2.3, the connections between renewable energy consumption and its impact factors among 32 nations are listed in Table 5. First, the results for the average relational degrees for all countries (last column) suggest that the relationships between renewable energy consumption and GDP, $CO_2$, energy intensity, and energy use are much closer than those of energy security, urbanization and industrialization, which indicates that concerns about energy security and social development did not act as important incentives for RE use. This result further verifies the weak connection between social development and RE use (shown in Table 3) and the validity of the conclusion in Section 3.2.

Comparison of the Grey relational degrees between developing and developed countries indicates that renewable energy consumption has closer relationships with GDP, energy security, and industrialization in developing nations than that in advanced economies, and that there are big gaps in the Grey degrees between $CO_2$, energy intensity, and industrialization between developing and developed nations. Depending on the relational degree, the stimulus effects of energy security and sustainable urbanization process have more potential for improvement. Special concern about the results of China suggests that energy intensity and GDP have closer relational degrees than that of urbanization, energy security. Public acceptance of renewable technology should be the priority for government.

**Table 5**

Grey relational degrees between RE use and the impact factors

| | GDP | $CO_2$ | EI | ES | EC | URB | IND |
|---|---|---|---|---|---|---|---|
| Argentina | 0.5803 | 0.6346 | 0.7674 | 0.5036 | 0.7387 | 0.5109 | 0.5140 |
| Australia | 0.5706 | 0.6675 | 0.6029 | 0.5003 | 0.6922 | 0.5222 | 0.5029 |
| Austria | 0.8348 | 0.8308 | 0.9628 | 0.6576 | 0.8228 | 0.6579 | 0.5221 |
| Brazil | 0.5640 | 0.5960 | 0.6086 | 0.5091 | 0.6520 | 0.5170 | 0.5212 |
| Canada | 0.7214 | 0.9503 | 0.7135 | 0.5016 | 0.6213 | 0.5203 | 0.5104 |
| Switzerland | 0.6419 | 0.6917 | 0.7855 | 0.5025 | 0.7359 | 0.5017 | 0.5044 |
| Chile | 0.8465 | 0.7242 | 0.5175 | 0.5215 | 0.8501 | 0.5784 | 0.8462 |
| China | 0.8963 | 0.8077 | 0.9318 | 0.6845 | 0.7069 | 0.5383 | 0.6812 |
| Colombia | 0.7521 | 0.5572 | 0.7005 | 0.5017 | 0.5703 | 0.5275 | 0.7521 |
| Germany | 0.7197 | 0.9014 | 0.8164 | 0.5217 | 0.9127 | 0.8367 | 0.5154 |
| Denmark | 0.5402 | 0.5221 | 0.5452 | 0.5232 | 0.5070 | 0.6832 | 0.7403 |
| Spain | 0.6892 | 0.8533 | 0.6200 | 0.5096 | 0.6979 | 0.5228 | 0.5141 |
| Finland | 0.8000 | 0.6224 | 0.6617 | 0.5175 | 0.6531 | 0.5331 | 0.5566 |
| France | 0.7647 | 0.6816 | 0.9908 | 0.5030 | 0.9839 | 0.5172 | 0.5094 |
| UK | 0.7422 | 0.5703 | 0.7320 | 0.5571 | 0.5203 | 0.5979 | 0.5375 |
| Indonesia | 0.7468 | 0.7328 | 0.5480 | 0.5120 | 0.7055 | 0.5414 | 0.7311 |
| India | 0.6668 | 0.6494 | 0.8798 | 0.5186 | 0.7838 | 0.5262 | 0.5470 |
| Italy | 0.5894 | 0.8713 | 0.6844 | 0.5122 | 0.6557 | 0.5464 | 0.5031 |
| Japan | 0.6029 | 0.9057 | 0.7051 | 0.5073 | 0.6914 | 0.5099 | 0.5070 |
| Mexico | 0.6107 | 0.5456 | 0.5307 | 0.5643 | 0.6153 | 0.5233 | 0.9412 |
| Norway | 0.8402 | 0.5386 | 0.8912 | 0.5004 | 0.8745 | 0.5338 | 0.6120 |
| Pakistan | 0.9946 | 0.8476 | 0.6146 | 0.5284 | 0.9134 | 0.5451 | 0.6256 |
| Peru | 0.6389 | 0.7825 | 0.7956 | 0.5058 | 0.9103 | 0.5253 | 0.5524 |
| Portugal | 0.8828 | 0.7857 | 0.8644 | 0.5699 | 0.7525 | 0.5165 | 0.5769 |
| Paraguay | 0.5101 | 0.5457 | 0.5087 | 0.5229 | 0.5161 | 0.6411 | 0.5924 |
| Russia | 0.8806 | 0.8791 | 0.5306 | 0.5334 | 0.8934 | 0.6413 | 0.5633 |
| Sweden | 0.7708 | 0.7177 | 0.9940 | 0.5034 | 0.9719 | 0.6033 | 0.5250 |
| Turkey | 0.8402 | 0.9423 | 0.5326 | 0.5232 | 0.8218 | 0.5167 | 0.5445 |
| USA | 0.6045 | 0.8769 | 0.5939 | 0.5060 | 0.8871 | 0.5089 | 0.5045 |
| Venezuela | 0.5984 | 0.5418 | 0.6024 | 0.5075 | 0.5143 | 0.5493 | 0.6061 |
| Vietnam | 0.7286 | 0.6965 | 0.6439 | 0.5311 | 0.5900 | 0.6879 | 0.7328 |
| NZL | 0.6604 | 0.6322 | 0.9999 | 0.5018 | 0.6275 | 0.5247 | 0.5066 |
| Developing | 0.7237 | 0.6989 | 0.6475 | 0.5312 | 0.7188 | 0.5580 | 0.6501 |
| Developed | 0.7045 | 0.7423 | 0.7743 | 0.5232 | 0.7416 | 0.5669 | 0.5381 |
| All | 0.7135 | 0.7220 | 0.7149 | 0.5270 | 0.7309 | 0.5627 | 0.5906 |

Note: EI, ES, EC, URB, and IND are the abbreviations of energy intensity, energy security, energy consumption, urbanization, and industrialization, respectively.

# 4. Conclusions and policy implications

*4.1. Conclusions*

This paper analyzes the drivers for the use of renewables for a set of 32 countries for the years 1980 to 2011. The use of dynamic estimators proved to be appropriate. From the analysis conducted in this study, the following conclusions can be drawn.

(1) Economic development provides the basis for the use of renewable energy, while concern about climate change is insufficient to stimulate the use of renewables. The results show that income is a positive contributor to RE consumption, and the prices of fossil-based fuels (e.g., oil prices) were not decisive for the development of renewables over the analyzed period. Therefore, it was not entirely the market forces that encouraged renewables, but other factors as well. Scarcity of fossil fuel and the competitiveness of renewable technology were not enough to promote RE consumption during the study period, and social awareness about climate change mitigation and $CO_2$ reduction was not a sufficient incentive to motivate a switch from traditional to renewables.

(2) The analysis of other drivers of RE development shows that sociological processes (urbanization and industrialization) promote RE consumption slightly, while concern about energy security discouraged the use of RE over the analyzed timeframe. The weak but positive relationship between RE consumption and social development processes reveals the huge potential of social development in promoting RE use. This study did not find any evidence of the stimulus effect of energy security on RE use for our timespan. This fact may relate to the role of the International Energy Agency in securing energy supply and the shortage of RE in uninterrupted energy supply. As for energy intensity and energy use, their role in RE development is an issue that deserves further research.

(3) The determinants of RE development in the developed and developing world are in substantial agreement, and the only difference occurs in the effect of urbanization on RE use. The results point out the positive role of urbanization in motivating RE use in developed nations. There is, however, a negative relationship between RE consumption and urbanization in developing economies. The reason may lie in the different demands for RE in different stages of urbanization. The results from the Grey relation analysis coincide with the outcomes from the panel data model, and there is much potential for stimulating the roles of energy security and a sustainable urbanization process in RE development.

*4.2 Policy implications*

Based on the results of the panel data model and the Grey relational analysis on the impact factors, some important implications for RE development in the world are presented below.

(1) It is wise to develop a mix of renewables that will ensure stable electricity production and avoid an excess of idle capacity, which increases the energy costs of a

country. This suggestion may promote RE use from at least two aspects. First, the improvement in RE production, especially the stability of renewable energy production, can eliminate an obstacle for higher-energy-importing countries in introducing RE technology. Only in this way can the concern about energy security promote renewables. Second, the reduction of renewable electricity prices will improve the competitiveness of RE in the energy market.

(2) Policies for RE development in developing and developed countries should be different. Economic development provides an important base for RE development, but developing nations should focus more on economic development before attempting sustainable energy development. Public awareness about climate change mitigation and $CO_2$ reduction ought to be the impetus for RE use, and should be paid attention to. Renewables could be a wise choice for countries with energy security issues, and indicates that renewable energy development should be considered in their national energy policy.

(3) The way to hydrogen-based renewable energy system for a sustainable development needs the Chinese government to coordinate the economic development, social change and energy evolution. As the largest energy consumer with a coal-dominated energy structure, China is ready to make a transition to hydrogen economy for a more sustainable future. The increase of public acceptance about hydrogen energy technology or fuel cell could be a strategy for promoting its development.

The panel estimators and Grey relational analysis on RE development allow us to: (i) explore the commitment to renewables as a time series; (ii) analyze the drivers for RE development; (iii) summarize experiences from both developing and developed nations; (iv) figure out the relational degrees between RE use and its drivers. However, there are some limitations in this research. Although the authors used two panel estimators for comparison, other panel estimators could also be used, For example, the Least Squares Dummy Variable Corrected estimator suggested by [43] could be complementary. Additionally, Grey relational analysis provides preliminary pathways for RE development, and the feedback effect of its drivers, such as the dual influence between climate change and RE use [44, 45] and how to bridge the gap towards the hydrogen economy [46], should be considered. Also, the authors only considered oil prices when considering the price of substitute RE and did not identify the influence of price mechanisms in RE use, which deserves attention for further research. Public acceptance about energy transition and common but differentiated responsibilities for the general public [47-49] is also a factor to facilitate action towards a rapid global transition to renewable energy, which should be considered in further study.

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