

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

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16 **Abstract**

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

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

38

39

40 **1. Introduction**

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

58 Analysis on the drivers of RE development is central to sustainable development
59 [9]. A future hydrogen-based renewable energy system needs technical change and the
60 infrastructure building. The world needs to move faster and more decisively if we are
61 serious about ensuring access to clean and sustainable energy for all people by 2030
62 [10]. First, many developing economies are now finding themselves facing an energy
63 security issue similar to that of most developed economies [11,12], such as the
64 relatively higher energy dependency of China and Japan. Hydrogen-based renewable
65 energy systems can enhance energy security and achieve China's CO2 emissions peak
66 through technological diversification and minimizing dependence on foreign imports
67 of energy fuels [4, 13]. For example, China's Blue Book on Hydrogen Energy
68 Infrastructure has been released in October 2016. Hydrogen energy and fuel cell
69 integration are included in Energy Technology Innovation Plan (2016-2030) [14].
70 Second, RE can help to disentangle the issue of energy poverty, mobilizing national
71 actions to ensure universal access to modern energy services [15]. Bhide and Monroy
72 (2011) analyzed the current status of energy development in India and suggested a
73 sustainable method to eradicate energy poverty there through RE technologies [16].
74 Last, while fossil-fueled economic growth, through the release of greenhouse gases, is
75 a major contributor to climate change, RE can be an efficient tool to cope with that
76 change. The special report from the Intergovernmental Panel on Climate Change
77 (IPCC) analyzes the challenges and opportunities of RE development in addressing
78 climate change [17]. Sapkota et al. (2014) examined the role of RE technologies in
79 climate change adaptation in rural areas of Nepal through the Long-range Energy

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

82 While the drivers of energy consumption have been well studied, there are
83 relatively few studies on the determinants of RE development. The empirical work
84 has been primarily focused on USA, Europe and the G7 countries generally. Sadorsky
85 (2009) analyzed the relationships between CO₂ emissions, GDP, oil prices and RE
86 consumption in G7 countries and concluded that GDP and CO₂ are the major drivers
87 for RE consumption [19]. Marques et al. (2010) applied a panel data model to study
88 the drivers of RE in European countries and concluded that energy security was a
89 stimulator for RE use [20]. After examining the role of different energy sources in
90 economic growth, Marques and Fuinhas (2011) pointed out the negative effect of RE
91 in promoting economic growth [21]. Menz and Vachon (2006) developed a regression
92 equation through the OLS method for the wind power sector in 30 American states
93 and discussed the contribution of different policy regimes on wind power
94 development [22]. However, there is a lack of empirical research on the determinants
95 of RE in developing countries [23]. Although Europe and the USA have taken a
96 leading role in the RE market, China and Brazil has become emerging contributors to
97 the world's RE consumption. The internal mechanisms of RE development in
98 developing countries and their comparison with that of developed economies are
99 relevant to further understand the determinants that have promoted or hampered RE
100 development in the world.

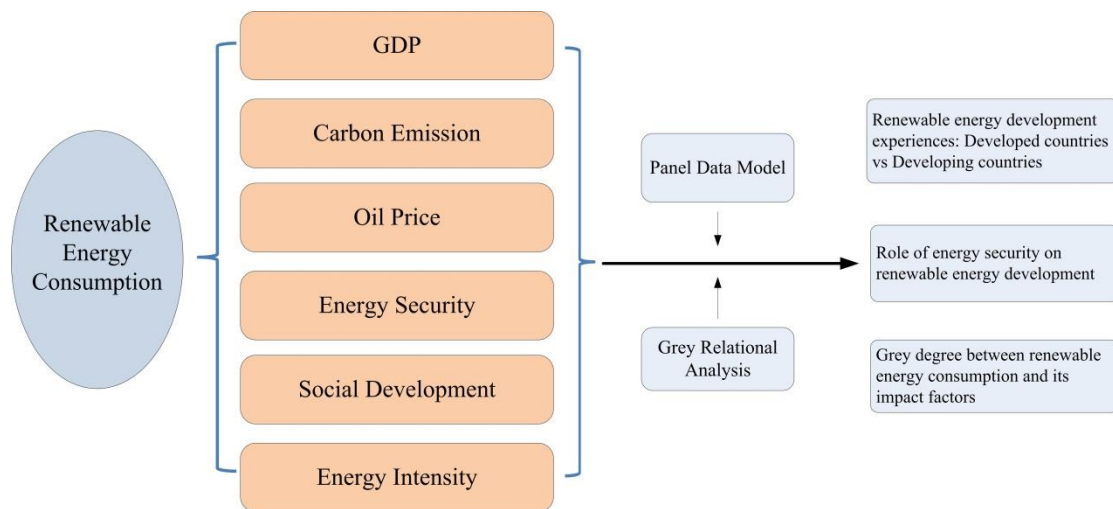
101 Based on the previous studies, this paper chooses various countries that are
102 deploying RE and applies panel data techniques to explore the influencing factors
103 governing RE development. Due to the differences in economic development levels
104 and situations surrounding energy use, these 32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

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

119 **2 Methodologies**

120 *2.1. Conceptual framework for the determinant analysis of renewable energy*
121 *development*

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



133

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

134

135 *2.2. Panel estimators for renewable energy development*

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

143 In this paper the variables are chosen in accordance with economic theory and
 144 data availability. As is standard in energy development models, income [25] is
 145 measured by per capita real GDP. With the growing public concern about climate
 146 change [26, 27], per capita CO₂ emissions is an important incentive for RE
 147 consumption. Hydrogen-based RE can be a substitute for fossil fuel consumption, and
 148 the price of oil, natural gas and coal should be considered among the drivers of
 149 renewable energy development. Traditionally, the price of energy generated from
 150 fossil fuels is lower than the price of energy generated from renewables. Changes in
 151 the price of traditional energy sources will influence the use of renewable energy

152 through the competitiveness of renewable energy in the energy market. However, due
 153 to lack of data availability for energy prices in these 32 countries, this paper only
 154 considers the effect of oil price on renewable energy utilization. Hydrogen-based
 155 renewable energy consumption is measured by per capita renewable electricity
 156 generation, and a linear relationship between the natural logarithm of renewable
 157 energy consumption per capita (RE) and its impact factors is postulated as follows
 158 equation (1).

$$159 \quad RE_{it} = \alpha_{0i} + \alpha_{1i}GDP_{it} + \alpha_{2i}CO2_{it} + \alpha_{3i}OP_{it} + h(v_{1,it}, v_{2,it}, \dots) + \varepsilon_{it} \quad (1)$$

160 Where $i = 1, 2, \dots, 32$ denotes the country and $t = 1980, 1981, \dots, 2011$ denotes the
 161 time period. RE_{it} , GDP_{it} , $CO2_{it}$ and OP_{it} represent the natural logarithms of
 162 renewable energy consumption per capita and per capita CO₂ emission, per capita real
 163 GDP of country i in year t , while v_{kg} represents controlling variables we
 164 employed to examine the contribution of other indicators for RE consumption (these
 165 variables include socio-economic development, energy demand, energy security and
 166 the time variable), and ε_{it} is assumed to be independent and identically distributed
 167 with a zero mean and constant variance. More details about the variables will be
 168 discussed in Section 2.4. The panel data model is run with the software EViews 7.

169 2.3. Grey relational degree between renewable energy consumption and its drivers

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

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

$$184 \quad X_i D = (x_i(1)d, x_i(2)d, \dots, x_i(n)d), \quad x_i(k)d = x_i(k) - x_i(1), \quad (k = 1, 2, \dots, n) \quad (2)$$

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

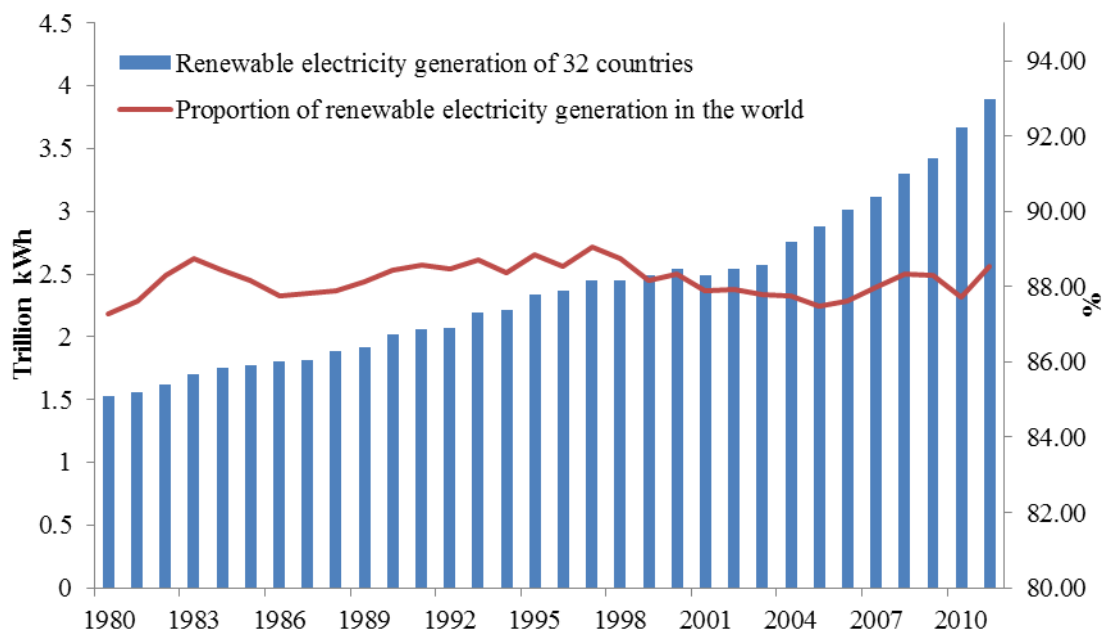
189 If $s_i - s_j = \int_1^n (X_i^0 - X_j^0) dt$, $\varepsilon_{ij} = \frac{1 + |s_i| + |s_j|}{1 + |s_i| + |s_j| + |s_i - s_j|}$, the ratio ε_{ij} is the absolute

190 degree of Grey incidence between RE use and GDP for the targeted country. The
 191 higher the Grey relational degree is, the closer the relationship between RE
 192 consumption and the driver.

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

196 *2.4. Data descriptions and data sources*

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



212

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

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

233 **Table 1**

234 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

235

236 Table 1 shows the definition and sources of data used in this paper. Apart from
 237 the variables (GDP, CO₂ 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>

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

251 **3. Results and discussion**

252 *3.1. Impacts of economic development and carbon emissions on renewable energy* 253 *consumption*

254 The specification test in this paper is done to check whether the results are fragile
 255 when other relevant factors are included in our model. Because our main purpose is to
 256 find the factors governing RE consumption, this paper applies 5 models, as listed in
 257 Table 2. Model 1 considers the impacts of economic development, global warming,
 258 and the price of fossil fuel on RE development [19]. Based on Model 1, Models 2, 3,
 259 4, and 5 correspond to the effects of energy security, energy intensity, social
 260 development, and the effect of lobbying for traditional energy use.

261 **Table 2**

262 **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)

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

265 The pooled least squares (PLS) and fixed effect (FE) ordinary least squares (OLS)
 266 estimators of these 5 models are listed in the corresponding columns of Table 3, from
 267 which several conclusions can be derived. The emphasis is on the robustness of
 268 RE-income, CO₂, oil price relationships, and other factors' impacts on RE
 269 development.

270 Income level is significantly and positively related to renewable electricity
 271 generation in all models, which implies that RE development relies on economic
 272 development. Carbon emissions have a negative effect on RE development in most of

273 these models. The role of climate change on RE use suggests that the current levels of
 274 CO₂ are not enough incentive to switch to renewables. Social pressure seems to have
 275 been insufficient to stimulate the use of renewables, and international agreements
 276 should be more ambitious in coping with climate change. Economic theory generally
 277 postulates that the price of traditional fossil energy sources should encourage
 278 renewable energy consumption. Even though oil price is positively related to RE
 279 development, in almost all cases it is not a major factor in explaining the use of
 280 renewables. The theoretical support of the price mechanism on renewables may be
 281 more complex than the simple direct mechanism of high prices of fossil fuel in
 282 making renewables more attractive. During the timespan in our study, the roles of IEA
 283 and OPEC in the setting of oil prices may result in mixed results.

284 **Table 3**

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

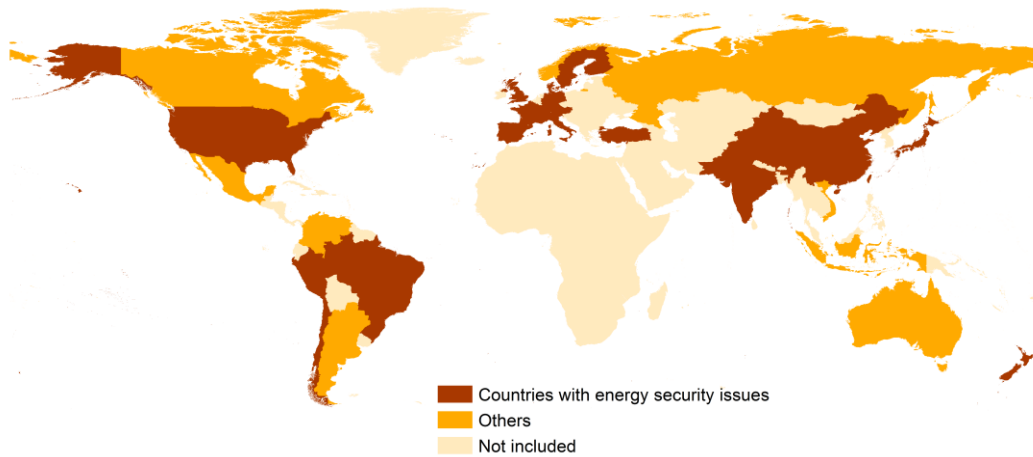
	M1		M2		M3		M4		M5	
	PLS	FE	PLS	FE	PLS	FE	PLS	FE	PLS	FE
GDP	0.815 ***	1.036 ***	1.083 ***	1.256 ***	3.077 ***	0.514 ***	0.888 ***	0.904 ***	0.375 ***	1.319 ***
CO ₂	-0.305 ***	-0.050	-0.924 ***	-0.428 ***	-2.156 ***	0.368 **	-0.609 ***	-0.156	-2.156 ***	0.368 **
Oil Price	0.086	0.019	0.117	0.069 *	0.139 *	-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	37.79 3***	-13.13 6***	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

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

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

295 3.2. Concern of energy security and renewable energy development

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



303

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

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

314 3.3. Comparison between developing and developed countries

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

322 Table 4 shows that the pooled least squares estimator is more robust than the FE
323 estimator. GDP and industrialization are positively and significantly related to the use
324 of RE. Unlike the results from Table 3, urbanization has a different effect on RE
325 development in developed and developing countries. It has a positive relationship

326 with RE consumption in developed countries, while a negative connection occurs in
 327 developing nations. This fact reflects the different energy needs of the urbanization
 328 process in developed and developing economies. Generally speaking, the urbanization
 329 process in developed countries is relatively more advanced than in developing
 330 countries. In the advanced phases of urbanization, the demand for renewable energy
 331 may be higher than in other stages with lower urbanization rates.

332

333 **Table 4**

334 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

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

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

340

341 3.4. Relational analysis between renewable energy consumption and its impact factors

342 According to the method presented in Section 2.3, the connections between
 343 renewable energy consumption and its impact factors among 32 nations are listed in
 344 Table 5. First, the results for the average relational degrees for all countries (last
 345 column) suggest that the relationships between renewable energy consumption and
 346 GDP, CO₂, energy intensity, and energy use are much closer than those of energy
 347 security, urbanization and industrialization, which indicates that concerns about
 348 energy security and social development did not act as important incentives for RE use.
 349 This result further verifies the weak connection between social development and RE
 350 use (shown in Table 3) and the validity of the conclusion in Section 3.2.

351 Comparison of the Grey relational degrees between developing and developed
 352 countries indicates that renewable energy consumption has closer relationships with
 353 GDP, energy security, and industrialization in developing nations than that in
 354 advanced economies, and that there are big gaps in the Grey degrees between CO₂,
 355 energy intensity, and industrialization between developing and developed nations.
 356 Depending on the relational degree, the stimulus effects of energy security and
 357 sustainable urbanization process have more potential for improvement. Special

358 concern about the results of China suggests that energy intensity and GDP have closer
 359 relational degrees than that of urbanization, energy security. Public acceptance of
 360 renewable technology should be the priority for government.

361

362 **Table 5**

363 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

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

366

367 **4. Conclusions and policy implications**

368 *4.1. Conclusions*

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

372 (1) Economic development provides the basis for the use of renewable energy, while
373 concern about climate change is insufficient to stimulate the use of renewables. The
374 results show that income is a positive contributor to RE consumption, and the prices
375 of fossil-based fuels (e.g., oil prices) were not decisive for the development of
376 renewables over the analyzed period. Therefore, it was not entirely the market forces
377 that encouraged renewables, but other factors as well. Scarcity of fossil fuel and the
378 competitiveness of renewable technology were not enough to promote RE
379 consumption during the study period, and social awareness about climate change
380 mitigation and CO₂ reduction was not a sufficient incentive to motivate a switch from
381 traditional to renewables.

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

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

401 *4.2 Policy implications*

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

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

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

413 (2) Policies for RE development in developing and developed countries should be
414 different. Economic development provides an important base for RE development, but
415 developing nations should focus more on economic development before attempting
416 sustainable energy development. Public awareness about climate change mitigation
417 and CO₂ reduction ought to be the impetus for RE use, and should be paid attention to.
418 Renewables could be a wise choice for countries with energy security issues, and
419 indicates that renewable energy development should be considered in their national
420 energy policy.

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

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

444

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