

# Examining the determinants of renewable energy deployment: Does the choice of indicator matter?

Eyup Dogan<sup>1,2</sup>  | Roula Inglesi-Lotz<sup>3</sup>  | Buket Altinoz<sup>4</sup>

<sup>1</sup>Department of Economics and Finance, University of Sharjah, Sharjah, United Arab Emirates

<sup>2</sup>Department of Economics, Abdullah Gul University, Kayseri, Turkey

<sup>3</sup>Department of Economics, University of Pretoria, Pretoria, South Africa

<sup>4</sup>Vocational School, Nisantasi University, Istanbul, Turkey

## Correspondence

Eyup Dogan, Department of Economics and Finance, University of Sharjah, Sharjah, United Arab Emirates.  
Email: edogan@sharjah.ac.ae

## Summary

Comprehending the determinants of renewable energy (RE) deployment has preoccupied the energy literature as well as policymakers internationally due to countries' overall shift away from fossil fuels in the energy mix. As stated in the literature, empirical studies that analyze the determinants of RE deployment use a number of different indicators for RE. The effect of an ambiguous choice of the proxy might produce various outcomes and thus create inconsistencies in the policy recommendations. This study aims at filling this gap in the literature comparing and contrasting not only the use of RE indicators but also, for robustness purposes, using indicators at aggregate and per capita forms for a global sample, developed countries, and developing countries. For the empirical purpose, this study employs two econometric techniques: the pooled ordinary least squares with robust SEs and the augmented mean group estimator, which account for cross-sectional dependence in the dataset. The results show that a 1% increase in gross domestic product (GDP) or GDP per capita leads to an increase in RE between 0.05% and 1.01% and a 1% increase in energy price causes an increase in RE between 0.07% and 0.99% with respect to various proxies, implying that the magnitudes of impacts of income and oil price are quite smaller when RE is proxied with RE consumption than when it is proxied with RE production. In addition, their impacts dramatically change across the choice between the share of RE and the levels of RE. More interestingly, not only the size of the effect of carbon emissions but also its direction changes across indicators. Overall, the choice of RE indicator is of great importance in putting forward reliable and consistent policy suggestions.

## Highlights

- This study uses a number of renewable energy indicators to analyze the determinants of renewable energy deployment.

**Abbreviations:** ADF, augmented Dickey-Fuller; AMG, augmented mean group; BTU, British thermal units; CADF, cross-sectional augmented Dickey-Fuller; CD-test, cross-sectional dependence test; CIPS, cross-sectional Im-Pesaran-Shin; EU, European Union; G7, group of seven; OECD, Organization of Economic Co-operation and Development; OLS, ordinary least squares; OPEC, Organization of Petroleum Exporting Countries; RE, renewable energy.

- Impacts of income and oil price are smaller when renewable energy is proxied with consumption.
- Not only the size of the effect of carbon emissions but also its direction changes across indicators.

**KEYWORDS**

energy, environment, income, oil price, renewable energy deployment

**1 | INTRODUCTION**

Renewable energy (RE) is at the center of the world agenda because it plays an active role in providing energy security<sup>1</sup> and reducing gas emissions<sup>2</sup> while energy demand/consumption increases at a remarkable pace. Regarding RE sources, they are mainly categorized as solar, wind, geothermal, biomass, hydrogen, and hydro-power energy. The contribution of RE deployment to sustainability is directly related to the RE source development. More specifically, hydropower which accounts for 83.6% of total RE sources is the most common of RE sources and causing fewer emissions than others.<sup>3</sup> The increase in energy consumption triggers the electricity demand and especially the daily electricity consumption increases. Admittedly, focusing on high sustainability in electricity generation is important to mitigate the environmental impacts of this energy demand and to provide RE deployment.<sup>4</sup> Given the specific importance of hydropower in RE sources, focusing on the environmental impacts of hydropower energy projects is an inevitability.<sup>5</sup> Many studies have reached that RE plants cause emissions in the construction phase.<sup>5-7</sup> Therefore, it is a fact that the emission-reducing effect of RE deployment is strengthened by ensuring that the development of RE sources is realized through environmentally friendly. However, energy conversion from RE sources instead of fossil energy sources contributes to environmental quality<sup>5</sup> and ultimately the RE deployment is the main interest of this study.

The growing interest inspires researchers to explore the determinants of RE deployment.<sup>8</sup> Income and oil price as economic factors and carbon emissions as an environmental indicator are widely used indicators to explain RE deployment as shown in the review study of Bourcet.<sup>9</sup> Besides, the review study states that the effect of each determinant on RE deployment is ambiguous. Moreover, a body of literature demonstrates that economic growth, carbon emissions, and oil prices contribute to the RE development<sup>10-15</sup> even though a group of studies shows that they have a negative impact on RE.<sup>16-19</sup> The effect of various variables; especially, economic growth, prices, and pollution on RE is a widely studied issue in the literature. For example, financial development,<sup>20-25</sup> trade

openness,<sup>23,26,27</sup> and globalization<sup>28,29</sup> are recently considered as determinants of RE deployment for small country groups and single countries. As clear from the literature review, only gross domestic product (GDP) (economic growth), oil price, and CO<sub>2</sub> (pollution) are available for a large country group.

In the context of the above explanations, another aspect of studies carried out in the literature to determine affecting factors of the RE deployment is the use of different proxies for RE. In regard to different proxies (indicators), the share of RE production<sup>11,18,30,31</sup> levels of RE production,<sup>32,33</sup> the share of RE consumption,<sup>22,34</sup> and levels of RE consumption.<sup>28,29,35-38</sup> More concretely, the relationship between RE deployment and income, emissions, and prices are investigated by many studies in the related literature using different RE deployment indicators. First, there are studies reaching economic growth has a positive impact on the share of production as a proxy of RE deployment<sup>14,31,39,40</sup> and studies confirming that economic growth reduces it.<sup>18,31</sup> The positive effect of growth is determined by Brunnschweiler,<sup>41</sup> Pleiffer and Mulder<sup>42</sup> for the level of production and by Sadorsky,<sup>16</sup> Salim and Rafiq,<sup>43</sup> Lu,<sup>36</sup> and Nyiwul<sup>37</sup> for the level of per capita consumption, and Padhan et al,<sup>28</sup> Gozgor et al<sup>29</sup> for the level of consumption. Furthermore, Le et al<sup>38</sup> confirmed the U-shaped relationship between RE and national income. Second, some studies suggest that pollution contributes to RE deployment indicators, which are share of production,<sup>11,44</sup> level of production,<sup>13,32,45,46</sup> and level of consumption.<sup>10,12,28,29,36,38,43,47</sup> However, it is also noteworthy that pollution has a negative impact especially on the share of production<sup>17,31,39,48,49</sup> and share of consumption.<sup>22</sup> Third, there is evidence that prices reduce the share of production<sup>11,17,31,50</sup> and the level of consumption,<sup>12,16,37</sup> but contribute to the level of production<sup>13,15,41,45,46</sup> and to the level of consumption.<sup>28,29,38</sup> Consequently, the findings of the relevant studies in terms of RE deployment are ambiguous. With respect to this notice, the novelty brought by this current study becomes clearer; such that, empirical results are dependent on the choice of RE deployment indicator and there is no clear definition of RE deployment. For example, the positive effect of any explanatory variable on production and on consumption

does not mean the same. Moreover, depending on whether the increase in question is absolute or relative, the results have different meanings. Thus, by revealing these details, this study is likely to shape policy implications based on the choice of the dependent variable in analyzing the determinants of RE deployment.

Furthermore, the literature uses either absolute (aggregate) or per capita levels for the above-mentioned proxies and determinants. Overall, these indicators can be categorized into three groups: share,<sup>11,14,22,30,31,39</sup> absolute levels,<sup>12,28,29,32,35,43</sup> and per capita levels.<sup>19,38,41,45-47,51</sup> Absolute measurements related to RE ignore differences such as population, energy markets, and the level of economic development of countries. Thus, per capita measurements can be a better proxy in this logic. Besides, indicators calculated with levels as a share of total energy may lead to the most effective results because this measurement means the substitution of RE sources with other energies, and the potential increase in the share of RE is critical in reducing the share of fossil energy sources.<sup>9</sup> From another view of differentiation, the analysis of RE deployment with either production or consumption only creates some gaps since RE production and consumption differ from each other; such that, consumption is the measure of the ultimate amount used in a country while production is about a country's implementation of environmentally friendly policies in energy.<sup>9</sup> This distinction of measurements refers to problems in identifying RE deployment. Moreover, the use of different proxies may result in differences in estimation output and policy recommendations although these indicators are used for the same model and country group. At this point, the noticeable gap in the relevant literature is the necessity to focus on a single or a few RE deployment indicator and/or to consider the results obtained specifically for the RE indicator used is neglected while explaining the determinants of RE deployment. Therefore, unlike previous literature, this study primarily highlights the proxy choice problem in analyzing its determinants.

In light of the above considerations and discussions, this study is the first attempt to discuss and show how the choice of proxy for RE matters in grasping its supporting and opposing determinants. Contrary to the fact that studies in the literature focus on different proxies for RE deployment, this study is brought together all these employed proxies to show whether the choice of proxy impacts estimation outcomes and policy implications. Thus, this study aims to clarify the implications for the RE deployment by approaching the previous studies from a new perspective. In other words, this study is the first attempt to fill this gap while studies in the literature do not focus on the difference between RE production and consumption indicators and their measurements. Considering the possible differences in outcomes depending on the

proxy of RE deployment, new and more applicable conclusions specific to each proxy are achieved. It is aimed to eliminate the confusion in the policy processes arising from the choice of the proxy by considering the existing literature as a whole. In addition to this, neglected points in the relevant literature are also considered in the selection of sample and method. To carry out the mentioned aim, this study uses income, oil price, and carbon emissions as explanatory variables because (a) they are the common determinants to each various proxy and model; (b) these are the widely used factors in the literature; and (c) they are available for a large group of countries. Alongside the fundamental aim, the second contribution of this study is extensive coverage. It covers not only a global sample but also developed and developing countries. Thus, the effects tested on eight different proxies are presented comparatively for developed and developing countries, and a comprehensive discussion of policy-making processes is initiated. Third, previous studies could not reach a consensus on the effects of income, oil price, and environment on RE deployment. This study aims to help the energy literature reaching a consensus on the mentioned nexus. Fourth, this paper methodologically contributes to the current literature using the pooled ordinary least squares (OLS) with robust SEs<sup>52,53</sup> and the augmented mean group (AMG) estimator,<sup>54-57</sup> which consider heterogeneity and cross-sectional dependence in the data. Relevant studies in the literature generally focus on static estimation methods based on conventional OLS approaches such as fixed effects, random effects, GLS,<sup>31,37,40,49,50</sup> or dynamic methods such as generalized method of moments estimation approach<sup>12,35,39,41</sup> introduced by Arellano and Bond.<sup>58</sup> On the other hand, these approaches, which are mostly adopted, have strong assumptions that may lead to inconsistent estimates. Since Driscoll and Kraay SEs and AMG estimators cope with deviations from main assumptions, using these methods provides more robust results to the existing literature. Thus, the relationship between the proxies of RE deployment obtained from the US Energy Information Administration<sup>59</sup> and the explanatory variables drawn from the World Bank's World Development Indicators<sup>60</sup> is addressed by the above-mentioned methods.

This paper is constructed as follows. Section 2 presents the dataset and the main models. Section 3 explains the methods and discusses empirical results. The last section concludes the study and reveals policy implications.

## 2 | MODEL AND DATASET

To examine the impact of economic growth and oil price (economic factors), and CO<sub>2</sub> emissions (environmental factor) as per the studies of Sadorsky,<sup>10</sup> Apergis and

Payne,<sup>45</sup> Lu,<sup>36</sup> and Bourcet<sup>9</sup> the following model is postulated in Equation (1):

Generic model specification:

$$\text{Renewable Energy}_{it} = f(\text{Economic growth}_{it}, \text{Environment}_{it}, \text{Price}_{it}). \quad (1)$$

All the estimations will be conducted for the full sample of all countries, and separately for the group of developed and developing countries both for robustness purposes as well as for deriving recommendations for the optimal choice of a proxy for RE. The estimated model specifications are inspired by Marques and Fuinhas,<sup>17</sup> Nyiwul,<sup>37</sup> and Bamati and Raoofi<sup>15</sup> as follows:

- Model 1:  $PRE_{it} = f(GDP_{it}, CO2_{it}, PRICE_{it})$ ,
- Model 2:  $CRE_{it} = f(GDP_{it}, CO2_{it}, PRICE_{it})$ ,
- Model 3:  $SPRE_{it} = f(GDP_{it}, CO2_{it}, PRICE_{it})$ ,
- Model 4:  $SCRE_{it} = f(GDP_{it}, CO2_{it}, PRICE_{it})$ ,
- Model 5:  $PREPC_{it} = f(GDPPC_{it}, CO2PC_{it}, PRICE_{it})$ ,
- Model 6:  $CREPC_{it} = f(GDPPC_{it}, CO2PC_{it}, PRICE_{it})$ ,
- Model 7:  $SPREPC_{it} = f(GDPPC_{it}, CO2PC_{it}, PRICE_{it})$ ,
- Model 8:  $SCREPC_{it} = f(GDPPC_{it}, CO2PC_{it}, PRICE_{it})$ ,

where RE is proxied with eight indicators: RE production (PRE), RE consumption (CRE), per capita RE production (PREPC), per capita RE consumption (CREPC), the share of RE production in total energy production (SPRE), the share of RE consumption in total energy consumption (SCRE), the share of per capita RE production in per capita total energy production (SPREPC), and the share of per capita RE consumption in per capita total energy consumption (SCREPC); in addition, economic growth as GDP and per capita GDP (GDPPC), the environment as carbon dioxide emissions (CO<sub>2</sub>), per capita carbon dioxide emissions (CO<sub>2</sub>PC), and price of crude oil (PRICE),  $i = 1, \dots, 72$  denotes the country and  $t = 1980, \dots, 2016$  denotes the time period.

The proxies employed here for RE are selected for two main reasons: firstly, they cover all the range of indicators used in the literature to proxy RE when evaluating its determinants or impact<sup>15,17,37</sup> and secondly, worldwide the policymakers have put targets and made commitments on improving the role of RE in the supply mixes of their countries by improving a number of indicators (refer to Sustainable Development Goal 7 and its target indicators).

This study employs annual data on proxies for RE, economic growth (GDP/GDPPC), environment (CO<sub>2</sub>/per capita CO<sub>2</sub> emissions), and oil prices for 72 countries (24 developed and 48 developing) (countries are listed in Appendix) for the period from 1980 to 2016. The RE and total energy data are in quadrillion British thermal units borrowed from US Energy Information Administration.

The price is the average annual oil price per barrel in US \$ taken from the Organization of Petroleum Exporting Countries database. Last, GDP in constant 2010 US\$ and CO<sub>2</sub> emissions in metric tons and population are retrieved from the World Development Indicators.

The eight models are aimed at identifying the impact of economic growth, carbon dioxide emissions, and oil prices on RE deployment. As discussed in the literature review, a variety of factors are tested in the literature as to their validity as predictors of RE. Working in this study with a global panel of many countries as the data availability allowed us, we chose these three control variables to capture basic differences among the countries representing their economic conditions, environmental status, and alternative fuels available.

More specific aim is to reveal differences in the use of indicators for RE deployment in terms of three explanatory variables commonly used in the literature. Thus, the difference that the use of various RE indicators create in terms of policy-making is observed more clearly by determining the effects of the most widely used economic and environmental variables<sup>13,15,17,19,35,37,47,50,61,62</sup> on different proxies. The fact that the studies in the literature achieve different results is the inspiration of these models. For instance, Marques and Fuinhas<sup>17</sup> used the share of RE production as a dependent variable. They revealed that GDP, CO<sub>2</sub>, and oil prices have a negative impact on RE deployment. Bamati and Raoofi<sup>15</sup> found that GDP and oil prices lead to an increase in RE production per capita, but CO<sub>2</sub> emissions mitigate it. Nyiwul<sup>37</sup> analyzed the effect of these variables on RE consumption per capita. Findings suggest that GDP and CO<sub>2</sub> emissions contribute to RE deployment, but oil prices decrease it. Therefore, this study essentially tests the hypothesis that the effect of these independent variables on all RE indicators is ambiguous. This result essentially highlights the indicator matter of the RE deployment. The difference emerging in the effect of the same explanatory variables on different RE indicators makes it inevitable to consider each proxy of RE deployment separately.

## 2.1 | Estimation strategy

To investigate the effect the choice of the RE proxy has on the dynamics between RE, and economic growth, oil price, and emissions, the study follows empirically the following steps. The stationarity properties of the series provide an indication of the approach and econometric techniques to be employed in the study. In most studies, first-generation panel unit root tests are performed with the assumption that cross-sections are independent. However, as per Kasman and Duman,<sup>63</sup> “cross-sectional

dependence can be the case due to unobserved common factors, externalities, regional and economic linkages". Therefore, to select the most appropriate panel unit root test for the dataset, this study starts with by performing diagnostic tests including cross-sectional dependence and slope homogeneity tests, as proposed by Pesaran and Yamagata<sup>64</sup> and CD-test by Pesaran.<sup>65</sup>

Following and in the case of cross-sectional dependence and heterogeneity, we examine the univariate properties of the series variables making use of the cross-sectional augmented Dickey-Fuller (CADF) panel unit root test by Pesaran<sup>65</sup> to prevent a spurious regression. The conclusion of the tests indicate the existence of nonstationarity, the next step is to focus on the long-run relationship (cointegration). To do so, the study employs the cointegration test proposed by Westerlund.<sup>66</sup> In the case of a cointegrated relationship confirmed, the next step is to estimate the parameters of the models, as discussed in the previous section. A pooled regression model (OLS) is to be estimated to take into consideration the existence of cross-sectional dependence using the robust SEs as proposed by Driscoll and Kraay,<sup>52</sup> as well as the AMG estimator introduced by Eberhardt and Teal<sup>54,56</sup> to secure robustness to cross-sectional dependence and heterogeneity (Figure 1).

## 2.2 | Methodological limitations

The data period and sample selection are the main limits of econometric analysis. In this study, which focused on 72 countries (24 developed and 48 developing), the sample limitation is largely eliminated. However, since the data period is inevitably dependent on official statistics,

data for the largest possible sample for the period 1980 to 2016 are obtained. Therefore, adopting methods appropriate for the time and sample size ( $N > T$ ) is another limit. The analysis phase of the study is completed in accordance with this situation. Also, due to the heterogeneity and cross-sectional dependency detected in the diagnostic tests, estimation methods that consider these problems are preferred. Thus, the feature of the dataset limits the choice of estimation methods.

## 3 | EMPIRICAL RESULTS AND DISCUSSIONS

### 3.1 | Cross-sectional dependence and slope homogeneity tests

Firstly, this study employs the cross-sectional dependence test developed by Pesaran<sup>65</sup> to examine if the panel data groups are cross-sectional independent and the Pesaran and Yamagata<sup>64</sup> to evaluate the slope homogeneity. Table 1 presents the results that show: (a) the null hypothesis of no cross-sectional dependence is rejected and hence, cross-sectional dependence is confirmed for all models at 1% level of significance and (b) the null hypothesis of slope homogeneity is rejected at 1% level of significance, and hence slope heterogeneity is present.

### 3.2 | Panel unit root tests

The panel unit root test proposed by Pesaran<sup>66</sup> is constructed based on the following CADF:

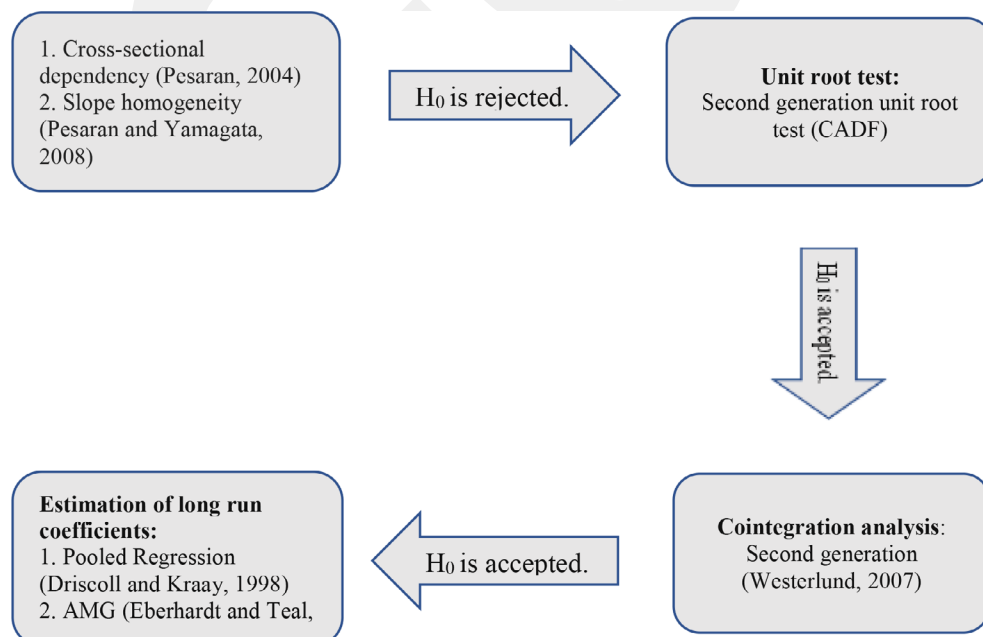


FIGURE 1 Flowchart of estimation stages [Colour figure can be viewed at wileyonlinelibrary.com]

**TABLE 1** Results from cross-sectional dependence and slope homogeneity tests

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
CD-test	30.24 <sup>a</sup>	33.19 <sup>a</sup>	11.12 <sup>a</sup>	31.69 <sup>a</sup>	28.39 <sup>a</sup>	30.22 <sup>a</sup>	11.65 <sup>a</sup>	25.35 <sup>a</sup>
Δadj	42.62 <sup>a</sup>	46.76 <sup>a</sup>	42.35 <sup>a</sup>	36.99 <sup>a</sup>	39.03 <sup>a</sup>	41.73 <sup>a</sup>	42.38 <sup>a</sup>	36.55 <sup>a</sup>

<sup>a</sup>1% level of significance.

**TABLE 2** Results of the cross-sectional augmented Dickey-Fuller panel unit root test

	Global	Developed	Developing		Global	Developed	Developing
PRE	-2.373	-2.393	-2.287	dPRE	-3.123 <sup>a</sup>	-2.890 <sup>a</sup>	-3.050 <sup>a</sup>
CRE	-2.084	-2.326	-2.168	dCRE	-2.946 <sup>a</sup>	-2.690 <sup>a</sup>	-2.936 <sup>a</sup>
SPREPC	-2.458	-1.903	-2.532	dSPRE	-2.892 <sup>a</sup>	-3.114 <sup>a</sup>	-2.746 <sup>a</sup>
SCREPC	-1.980	-2.190	-1.987	dSCRE	-2.739 <sup>a</sup>	-2.658 <sup>b</sup>	-2.745 <sup>a</sup>
PREPC	-2.388	-2.437	-2.497	dPREPC	-3.111 <sup>a</sup>	-2.900 <sup>a</sup>	-3.043 <sup>a</sup>
CREPC	-2.140	-2.338	-2.325	dCREPC	-2.942 <sup>a</sup>	-2.679 <sup>b</sup>	-2.925 <sup>a</sup>
SPRE	-2.458	-1.903	-2.532	dSPRE	-2.892 <sup>a</sup>	-3.114 <sup>a</sup>	-2.746 <sup>a</sup>
SCRE	-1.980	-2.190	-1.987	dSCRE	-2.739 <sup>a</sup>	-2.658 <sup>b</sup>	-2.745 <sup>a</sup>
GDP	-1.961	-1.748	-1.940	dGDP	-2.970 <sup>a</sup>	-2.931 <sup>a</sup>	-2.879 <sup>a</sup>
GDPPC	-1.925	-1.684	-1.904	dGDPPC	-2.991 <sup>a</sup>	-2.877 <sup>a</sup>	-2.890 <sup>a</sup>
CO <sub>2</sub>	-1.753	-2.592	-1.795	dCO <sub>2</sub>	-2.663 <sup>a</sup>	-2.911 <sup>a</sup>	-2.751 <sup>a</sup>
CO <sub>2</sub> PC	-1.831	-2.557	-1.957	dCO <sub>2</sub> PC	-2.662 <sup>a</sup>	-2.861 <sup>a</sup>	-2.719 <sup>a</sup>
PRICE	-2.089	-2.217	-2.139	dPRICE	-2.871 <sup>a</sup>	-2.866 <sup>a</sup>	-2.837 <sup>a</sup>

<sup>a</sup>1% level of significance;

<sup>b</sup>5% level of significance.

$$\Delta y_{it} = \alpha_i + \rho_i y_{it-1} + \beta_i \bar{y}_{t-1} + \sum_{j=0}^k \gamma_{ij} \Delta \bar{y}_{it-1} + \sum_{j=0}^k \delta_{ij} \Delta \bar{y}_{it-1} + \varepsilon_{it}, \tag{2}$$

where  $\alpha_i$  is a deterministic term,  $\bar{y}$  is the cross-sectional mean at time  $t$  and  $k$  is the lag order.  $t_i(N, T)$  is the  $t$ -statistic of the estimate of  $\rho_i$  in the equation above to compute individual ADF statistics. These  $t$ -ratios (named cross-sectional Im-Pesaran-Shin (CIPS)) are identified as below:

$$CIPS = (1/N) \sum_{i=1}^N t_i(N, T), \tag{3}$$

where  $t_i$  forms statistics from each CADF model for each  $i$  of the panel. Pesaran<sup>53</sup> provide critical values of CIPS. Table 2 presents the results of the CADF panel unit root test for all variables included in the eight models for the global, developed, and developing country panels. The findings indicate that the series are nonstationary at levels and stationary at first difference: hence, the variables are characterized as I(1) processes.

### 3.3 | Panel cointegration test

In the case of nonstationary series, there is a variety of testing procedures to use in the literature; this study chooses the cointegration test developed by Westerlund.<sup>66</sup> The null hypothesis of the test is that of no cointegration, under the assumption that all series are nonstationary. The test uses four statistics: Gt, Ga, Pt, and Pa. The Ga and Gt statistics test  $H_0: \alpha_i = 0$  vs  $H_1: \alpha_i < 0$  for at least one of the series,  $i$ , starting from a weighted average of the individually estimated coefficients  $\alpha_i$  and their respective  $t$ -ratios. The Pa and Pt test statistics pool all information over the cross-sectional dimension of the dataset to test the same hypothesis as above.

The Westerlund (2007) model is structured as follows:

$$\Delta y_{it} = \delta' d_t + \alpha_i (y_{it-1} - \beta_i x_{it-1}) + \sum_{j=1}^{p_i} a_{ij} \Delta y_{it-j} + \sum_{j=-q_1}^{p_i} \gamma_{ij} \Delta x_{it-j} + \varepsilon_{it}, \tag{4}$$

where  $d_t$  shows the deterministic elements,  $N$  is the cross-sections, and  $T$  is the number of observations. As

TABLE 3 Results from the Westerlund (2007) panel cointegration test

(a) Global sample								
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
Gt	-4.699 <sup>a</sup>	-3.909 <sup>a</sup>	-2.629 <sup>a</sup>	-6.572 <sup>a</sup>	-5.091 <sup>a</sup>	-4.177 <sup>a</sup>	-1.265	-5.452 <sup>a</sup>
Ga	-1.206	-0.445	0.576	-3.522 <sup>a</sup>	-2.131 <sup>b</sup>	-1.599 <sup>c</sup>	0.516	-4.302 <sup>a</sup>
Pt	-8.630 <sup>a</sup>	-5.414 <sup>a</sup>	-8.797 <sup>a</sup>	-7.088 <sup>a</sup>	-9.083 <sup>a</sup>	-5.604 <sup>a</sup>	-7.308 <sup>a</sup>	-7.150 <sup>a</sup>
Pa	-6.866 <sup>a</sup>	-5.363 <sup>a</sup>	-7.462 <sup>a</sup>	-6.644 <sup>a</sup>	-7.726 <sup>a</sup>	-5.548 <sup>a</sup>	-6.804 <sup>a</sup>	-7.257 <sup>a</sup>
(b) Developed countries								
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
Gt	-2.737 <sup>a</sup>	-1.566 <sup>c</sup>	-1.308 <sup>c</sup>	-2.558 <sup>a</sup>	-2.565 <sup>a</sup>	-1.839 <sup>b</sup>	-1.263	-2.356 <sup>a</sup>
Ga	0.345	0.818	1.183	-1.793 <sup>b</sup>	-0.071	-0.357	0.485	-1.451 <sup>c</sup>
Pt	-5.792 <sup>a</sup>	-3.686 <sup>a</sup>	-6.065 <sup>a</sup>	-4.454 <sup>a</sup>	-6.041 <sup>a</sup>	-3.673 <sup>a</sup>	-6.104 <sup>a</sup>	-4.264 <sup>a</sup>
Pa	-3.416 <sup>a</sup>	-2.226 <sup>b</sup>	-4.669 <sup>a</sup>	-3.425 <sup>a</sup>	-3.983 <sup>a</sup>	-2.303 <sup>b</sup>	-4.771 <sup>a</sup>	-3.473 <sup>a</sup>
(c) Developing countries								
	Model 1	Model 2	Model 3:	Model 4	Model 5	Model 6	Model 7	Model 8
Gt	-4.464 <sup>a</sup>	-4.378 <sup>a</sup>	-2.611 <sup>a</sup>	-4.935 <sup>a</sup>	-4.874 <sup>a</sup>	-4.853 <sup>a</sup>	-0.987	-5.065 <sup>a</sup>
Ga	0.518	0.523	1.292	0.074	0.172	-0.236	1.523	-1.550 <sup>c</sup>
Pt	-5.120 <sup>a</sup>	-5.470 <sup>a</sup>	-6.186 <sup>a</sup>	-6.052 <sup>a</sup>	-5.499 <sup>a</sup>	-4.738 <sup>a</sup>	-4.695 <sup>a</sup>	-5.127 <sup>a</sup>
Pa	-3.081 <sup>a</sup>	-3.074 <sup>a</sup>	-4.064 <sup>a</sup>	-3.290 <sup>a</sup>	-3.325 <sup>a</sup>	-2.828 <sup>a</sup>	-3.532 <sup>a</sup>	-3.644 <sup>a</sup>

<sup>a</sup>1% level of significance;

<sup>b</sup>5% level of significance;

<sup>c</sup>10% level of significance.

Kasman and Duman<sup>63</sup> explain, the Westerlund<sup>66</sup> have the following advantages:

- It has good small sample properties and high power.
- The joint null hypothesis is that *all* cross-sections in the panel are cointegrated.
- Relying on McCoskey and Kao<sup>55</sup> test, it accommodates correlation within and between the individual units in the cross-sections.
- It is considered more reliable than panel cointegration tests that are based on asymptotic distributions.

As seen in Table 3, the null of no cointegration is rejected for the majority of the tests in all models for the global sample as well as the developed and developing panels.

### 3.4 | Panel long-run estimators

Having confirmed a cointegrated relationship in all models, the next step is to proceed with the estimation of the parameters. This study uses two modeling approaches for robustness purposes: firstly, a pooled regression model (OLS) with estimated SEs by Driscoll and Kraay<sup>52</sup>

to take into account cross-sectional dependence, and secondly, the AMG estimator as was proposed by Eberhardt and Teal.<sup>54</sup> The AMG includes a common dynamic process to consider cross-sectional dependence as follows:

$$\begin{aligned} \Delta EFP_{it} &= b' \Delta A_{it} + \sum_{t=2}^T c_T \Delta D_t + u_{it} \rightarrow \hat{c}_t \\ &\equiv \hat{\mu}_t EFP_{it} = a_i + b'_i A_{it} + c_i t + d_i \hat{\mu}_t + u_{it} \hat{b}_{AMG} = N^{-1} \sum_i \hat{b}_i, \end{aligned} \quad (5)$$

where  $A$  is the vector of the independent variables,  $D$  is the dummy variable that captures period effects while  $c$  is the one that captures time effects, and  $u$  is the error term. Sections 3.4.1 to 3.4.3 present the technical results of the pooled OLS and the AMG estimators for the global, developed, and developing countries' panel, respectively. The dependent variable is RE, proxied by PRE, CRE, PREPC, CREPC, SPRE, SCRE, SPREPC, and SCREPC.

#### 3.4.1 | Empirical results: Global sample

The pooled OLS estimates with SEs for the full sample are presented in Table 4 where the coefficient estimates can be

**TABLE 4** Results from ordinary least squares with robust SEs and augmented mean group estimator for global panel

<b>(a) Ordinary least squares with robust SE</b>								
	<b>Model 1</b>	<b>Model 2</b>	<b>Model 3</b>	<b>Model 4</b>	<b>Model 5</b>	<b>Model 6</b>	<b>Model 7</b>	<b>Model 8</b>
GDP	0.09 <sup>a</sup> (0.032)	0.07 <sup>b</sup> (0.033)	0.07 <sup>a</sup> (0.034)	0.05 <sup>b</sup> (0.026)	—	—	—	—
GDPPC	—	—	—	—	0.09 <sup>a</sup> (0.034)	0.07 <sup>b</sup> (0.035)	0.07 <sup>a</sup> (0.034)	0.05 <sup>b</sup> (0.027)
CO <sub>2</sub>	0.64 <sup>b</sup> (0.040)	0.66 <sup>c</sup> (0.041)	−0.23 <sup>c</sup> (0.026)	−0.26 <sup>c</sup> (0.030)	—	—	—	—
CO <sub>2</sub> PC	—	—	—	—	0.55 <sup>c</sup> (0.037)	0.58 <sup>c</sup> (0.043)	−0.33 <sup>c</sup> (0.023)	−0.34 <sup>c</sup> (0.032)
PRICE	0.15 <sup>c</sup> (0.027)	0.13 <sup>c</sup> (0.022)	0.08 <sup>c</sup> (0.023)	0.07 <sup>c</sup> (0.016)	0.12 <sup>c</sup> (0.023)	0.10 <sup>c</sup> (0.018)	0.07 <sup>c</sup> (0.022)	0.05 <sup>c</sup> (0.014)
CONS	−0.62 (0.631)	−0.08 (0.634)	1.33 <sup>b</sup> (0.717)	1.88 <sup>c</sup> (0.522)	−0.12 (0.233)	0.13 (0.228)	1.97 <sup>c</sup> (0.239)	2.07 <sup>c</sup> (0.187)
<b>(b) Augmented mean group estimator</b>								
	<b>Model 1</b>	<b>Model 2</b>	<b>Model 3</b>	<b>Model 4</b>	<b>Model 5</b>	<b>Model 6</b>	<b>Model 7</b>	<b>Model 8</b>
GDP	0.95 <sup>c</sup> (0.287)	0.89 <sup>c</sup> (0.270)	0.12 (0.208)	0.50 <sup>a</sup> (0.238)	—	—	—	—
GDPPC	—	—	—	—	1.01 <sup>c</sup> (0.253)	0.95 <sup>c</sup> (0.246)	0.29 (0.185)	0.57 <sup>c</sup> (0.211)
CO <sub>2</sub>	−0.33 <sup>c</sup> (0.120)	−0.38 <sup>c</sup> (0.134)	−0.37 <sup>c</sup> (0.135)	−0.87 <sup>c</sup> (0.134)	—	—	—	—
CO <sub>2</sub> PC	—	—	—	—	−0.31 <sup>c</sup> (0.121)	−0.37 <sup>c</sup> (0.135)	−0.36 <sup>c</sup> (0.138)	−0.88 <sup>c</sup> (0.133)
PRICE	0.99 <sup>c</sup> (0.382)	0.81 <sup>c</sup> (0.256)	0.31 <sup>c</sup> (0.122)	0.39 <sup>c</sup> (0.128)	0.65 <sup>c</sup> (0.241)	0.48 <sup>c</sup> (0.158)	0.23 <sup>a</sup> (0.093)	0.26 <sup>c</sup> (0.091)
CONS	−22.32 <sup>c</sup> (7.49)	−20.49 <sup>c</sup> (6.66)	0.80 (5.335)	−9.42 <sup>b</sup> (5.852)	10.1 <sup>c</sup> (2.551)	−8.93 <sup>c</sup> (2.156)	−0.97 (1.71)	−3.46 <sup>b</sup> (1.843)

Note: Values in brackets are SEs.

<sup>a</sup>5% level of significance;

<sup>b</sup>10% level of significance;

<sup>c</sup>1% level of significance.

interpreted as long-run estimates. Regarding the first outcome (*impact of income on RE deployment is ambiguous*), income presents positive and statistically significant elasticities across the estimation techniques and the majority of the model specifications with the exception of Model 3 and 8 in the AMG estimation. The elasticities vary between 0.05 and 1.01: meaning that depending on the proxy for RE, a 1% increase in GDP or GDPPC will lead to an increase in RE (various proxies) between 0.05% and 1.01%, ceteris paribus. The difference might seem marginal but it can make a bit difference in policy planning.

The results of the estimations with regards to the second outcome dealing with the impact of CO<sub>2</sub> emissions on RE deployment are not as straightforward. The coefficient parameters are positive and statistically significant in pooled OLS estimations when dependent variables are PRE (Model 1), CRE (Model 2), PREPC (Model 5), CREPC (Model 6), but negative for all the others (Models 4, 5, 7, and 8); while for the AMG estimator, an increase in emissions will lead to decreases in RE (negative elasticities) for all models.

The third outcome of the study states that the impact of oil prices on RE deployment is not clear. In Table 4, it can be seen that for all estimation techniques and model specifications, the elasticity is positive and statistically significant. Such a positive coefficient confirms the supporting studies: the higher the oil price, the higher the RE in the countries regardless of the proxy chosen, ceteris paribus. However, the share indicators (Models

3, 4, 7, and 8) have lower elasticities than the levels estimators (Models 1, 2, 5, and 6). Moreover, coefficient estimates also differ across the aggregate (absolute) and per capita levels. Therefore, the choice of RE proxy is as influential to the elasticity as the choice of estimator.

### 3.4.2 | Empirical results: Developed countries

Table 5 presents the estimation results for the developed countries. The coefficients of GDP and GDPPC to the various RE proxies are positive and statistically significant when using the pooled OLS estimator. However, the difference is that when using the AMG estimator, the income parameter is mostly statistically insignificant, although positive. The choice of methodology, thus, can play an important role in the findings and hence, the policy recommendations provided.

Oil price elasticities show the same trend as the results in the full sample: the elasticity is positive and statistically significant; however, the share indicators have lower elasticities than the levels estimators. Furthermore, coefficient estimates also differ across the aggregate and per capita levels. Finally, the findings of the CO<sub>2</sub> emissions' elasticity resemble the results of the full sample when the AMG estimator is used: the increase in carbon emissions decreases RE deployment. However, results greatly differ when the OLS estimator is used: the effect

**TABLE 5** Results from ordinary least squares with robust SEs and augmented mean group estimator for the developed countries

<b>(a) Ordinary least squares with robust SE</b>								
	<b>Model 1</b>	<b>Model 2</b>	<b>Model 3</b>	<b>Model 4</b>	<b>Model 5</b>	<b>Model 6</b>	<b>Model 7</b>	<b>Model 8</b>
GDP	0.15 <sup>a</sup> (0.054)	0.09 <sup>b</sup> (0.045)	0.13 <sup>b</sup> (0.051)	0.08 <sup>c</sup> (0.040)	—	—	—	—
GDPPC	—	—	—	—	0.14 <sup>a</sup> (0.046)	0.09 <sup>b</sup> (0.034)	0.12 <sup>a</sup> (0.041)	0.07 <sup>b</sup> (0.030)
CO <sub>2</sub>	0.93 <sup>a</sup> (0.064)	0.96 <sup>a</sup> (0.053)	0.06 (0.057)	0.04 (0.046)	—	—	—	—
CO <sub>2</sub> PC	—	—	—	—	-0.56 <sup>b</sup> (0.217)	-0.57 <sup>b</sup> (0.251)	-1.96 <sup>a</sup> (0.242)	-1.46 <sup>a</sup> (0.236)
PRICE	0.10 <sup>a</sup> (0.027)	0.08 <sup>a</sup> (0.021)	0.11 <sup>a</sup> (0.018)	0.05 <sup>a</sup> (0.016)	0.18 <sup>a</sup> (0.053)	0.17 <sup>a</sup> (0.040)	0.23 <sup>a</sup> (0.065)	0.13 <sup>a</sup> (0.034)
CONS	-3.19 <sup>a</sup> (1.16)	-1.94 <sup>a</sup> (0.959)	-1.17 (1.08)	-0.02 (0.87)	2.06 <sup>a</sup> (0.455)	2.70 <sup>a</sup> (0.334)	5.21 <sup>a</sup> (0.540)	4.40 <sup>a</sup> (0.328)
<b>(b) Augmented mean group estimator</b>								
	<b>Model 1</b>	<b>Model 2</b>	<b>Model 3</b>	<b>Model 4</b>	<b>Model 5</b>	<b>Model 6</b>	<b>Model 7</b>	<b>Model 8</b>
GDP	0.64 <sup>c</sup> (0.333)	0.39 (0.416)	0.11 (0.382)	0.13 (0.436)	—	—	—	—
GDPPC	—	—	—	—	0.55 <sup>c</sup> (0.328)	0.39 (0.445)	0.16 (0.392)	0.14 (0.494)
CO <sub>2</sub>	-1.38a (0.360)	-1.24 <sup>a</sup> (0.306)	-0.66 <sup>b</sup> (0.264)	-1.59 <sup>a</sup> (0.314)	—	—	—	—
CO <sub>2</sub> PC	—	—	—	—	-1.15 <sup>a</sup> (0.277)	-1.26 <sup>a</sup> (0.301)	-0.69 <sup>b</sup> (0.273)	-1.60 <sup>a</sup> (0.306)
PRICE	1.39 <sup>a</sup> (0.491)	1.02 <sup>b</sup> (0.452)	0.68 (0.480)	0.86 <sup>c</sup> (0.467)	1.03 <sup>b</sup> (0.526)	0.75 (0.331)	0.63 (0.431)	0.60 <sup>c</sup> (0.365)
CONS	-11.04 (7.954)	-2.88 (10.13)	0.92 (9.969)	3.06 (10.371)	-4.32 (3.540)	-1.15 (3.911)	0.78 (4.097)	2.24 (4.255)

Note: Values in brackets are SEs.

<sup>a</sup>1% level of significance;

<sup>b</sup>5% level of significance;

<sup>c</sup>10% level of significance.

**TABLE 6** Results from ordinary least squares with robust SEs and augmented mean group estimator for the developing countries

<b>(a) Ordinary least squares with robust SE</b>								
	<b>Model 1</b>	<b>Model 2</b>	<b>Model 3</b>	<b>Model 4</b>	<b>Model 5</b>	<b>Model 6</b>	<b>Model 7</b>	<b>Model 8</b>
GDP	0.03 <sup>a</sup> (0.017)	0.02 (0.015)	0.01 (0.014)	0.02 <sup>a</sup> (0.011)	—	—	—	—
GDPPC	—	—	—	—	0.03 <sup>a</sup> (0.016)	0.03 <sup>a</sup> (0.015)	0.01 (0.01)	0.02 <sup>a</sup> (0.012)
CO <sub>2</sub>	0.54 <sup>b</sup> (0.030)	0.54 <sup>b</sup> (0.028)	-0.37 <sup>b</sup> (0.012)	-0.34 <sup>b</sup> (0.018)	—	—	—	—
CO <sub>2</sub> PC	—	—	—	—	0.34 <sup>b</sup> (0.035)	0.36 <sup>b</sup> (0.024)	-0.64 <sup>b</sup> (0.020)	-0.46 <sup>b</sup> (0.02)
PRICE	0.21 <sup>b</sup> (0.036)	0.19 <sup>b</sup> (0.032)	0.13 <sup>b</sup> (0.040)	0.11 <sup>b</sup> (0.024)	0.16 <sup>b</sup> (0.029)	0.15 <sup>b</sup> (0.025)	0.11 <sup>b</sup> (0.041)	0.07 <sup>b</sup> (0.019)
CONS	0.66 <sup>c</sup> (0.289)	0.86 <sup>b</sup> (0.260)	2.94 <sup>b</sup> (0.295)	2.69 <sup>b</sup> (0.203)	-0.12 (0.125)	0.01 (0.012)	1.96 <sup>b</sup> (0.133)	2.05 <sup>b</sup> (0.093)
<b>(b) Augmented mean group estimator</b>								
	<b>Model 1</b>	<b>Model 2</b>	<b>Model 3</b>	<b>Model 4</b>	<b>Model 5</b>	<b>Model 6</b>	<b>Model 7</b>	<b>Model 8</b>
GDP	0.54 <sup>b</sup> (0.311)	0.46 (0.316)	0.02 (0.22)	0.17 (0.275)	—	—	—	—
GDPPC	—	—	—	—	0.65 <sup>c</sup> (0.321)	0.48 <sup>a</sup> (0.267)	0.22 (0.214)	0.25 (0.209)
CO <sub>2</sub>	-0.02 (0.150)	-0.01 (0.145)	-0.39 <sup>c</sup> (0.167)	-0.62 <sup>b</sup> (0.138)	—	—	—	—
CO <sub>2</sub> PC	—	—	—	—	0.01 (0.150)	-0.01 (0.151)	-0.34 <sup>c</sup> (0.173)	-0.61 <sup>b</sup> (0.141)
PRICE	0.79 <sup>b</sup> (0.195)	0.72 <sup>b</sup> (0.209)	0.23 <sup>b</sup> (0.085)	0.35 <sup>b</sup> (0.100)	0.53 <sup>b</sup> (0.144)	0.44 <sup>b</sup> (0.126)	0.13 <sup>b</sup> (0.048)	0.24 <sup>b</sup> (0.071)
CONS	12.71 <sup>a</sup> (7.24)	-20.87 (7.57)	1.33 (5.703)	2.01 (-6.83)	-6.88 <sup>b</sup> (2.418)	-5.33 <sup>b</sup> (1.968)	-0.43 (1.76)	-1.01 (1.684)

Note: Values in brackets are SEs.

<sup>a</sup>10% level of significance;

<sup>b</sup>1% level of significance;

<sup>c</sup>5% level of significance.

of emissions is negative when RE is proxied with per capita values but it is positive when RE is proxied with absolute values. This is an interesting outcome of how the choice of proxy matters for the overall conclusion and policy suggestion.

### 3.4.3 | Empirical results: Developing countries

The results of the estimations for the developing countries' sample are presented in Table 6. The income

elasticities of the estimations are positive but not statistically significant in Models 2, 3, and 7 at pooled OLS and all Models, except 1 and 5 for the AMG estimator. The coefficients are lower in magnitude than those of the developed countries. The pooled OLS estimator provides the same sign and statistical significance for the CO<sub>2</sub> emissions parameter with the developed countries panel: positive for Models 1, 2, 5, and 6, but negative for the rest. The AMG elasticity for CO<sub>2</sub> emissions is negative and statistically significant for models where the dependent is SPRE and SCRE in aggregate and per capita (Models 3, 4, 7, and 8). These are the same as the global sample but somewhat different than developed countries.

### 3.5 | Synthesis of results

From the empirical findings, overall, it can be seen that the coefficients for income and per capita are found to be positive and statistically significant for 14 out of 16 model specifications for the global panel, 10 out of 16 model specifications for the developed countries, and 8 out of 16 model specifications for the developing countries. Such results show that there is certain robustness in the choice of the proxy for RE in a panel context as this study. The magnitude of the income elasticities varies from 0.05 to 1.01 depending on the choice of indicator, where the per capita models present higher elasticities: showing that an increase of economic growth by 1%, an increase of RE is expected between 0.05% and 1%, *ceteris paribus*. These results of positive income elasticities agree with studies such as Sadorsky,<sup>10,16</sup> Bruunschweiler,<sup>41</sup> Pfeiffer and Mulder,<sup>42</sup> Inglesi-Lotz,<sup>57</sup> and Eren et al.<sup>67</sup> This finding for the positive impact of economic growth to RE confirms a priori expectations that as countries get richer tend to secure financial stability and political willingness to proceed with energy transition from fossil fuels dominance toward a bigger role played by renewables. This is confirmed in the models presenting income elasticities similar for indicators of total RE and shares to the supply mix.

On the contrary, the coefficient of CO<sub>2</sub> emissions varies in magnitude and direction in the various model specifications. For the Global panel's OLS estimation, the parameters are found to be positive (emissions are a positive contributor factor) in Models 1 and 2 (an aggregate form of indicator) and Models 5 and 6 (per capita form of indicator) while for the AMG estimator, it is found to be negative and statistically significant in all model specifications. For the developed countries panel, using the OLS estimation, all the per capita model specifications present negative and statistically significant parameters for emissions; while the aggregate model specifications present positive parameters

(statistically significant for Models 1 and 2 and nonsignificant for Models 3 and 4). The AMG-estimated parameters are all statistically significant and negative, *ceteris paribus*. For the developing countries panel, the OLS-based estimators are found to be positive and statistically significant for Models 1, 2, 5, and 6, while negative and statistically significant for Models 3, 4, 7, and 8. All in all, the choice of econometric technique, choice of aggregate or per capita indicator, and proxy for RE can affect the resulted parameter/elasticity. Both for aggregate and per capita level, the findings show that increases in emissions lead to increases in RE consumption and production, *ceteris paribus*. However, the share of RE consumption to total consumption and production tends to decrease with increases in emissions, *ceteris paribus*.

The negative carbon emissions parameters agree with the findings by Shafiei and Salim<sup>68</sup> while the positive coefficients with those of Menyah and Wolde-Rufael<sup>69</sup> and Apergis et al.<sup>70</sup> The coefficient of oil price is found to be positive and statistically significant for the vast majority of the model specifications. The positive sign of the parameter seems to be robust to changes in the proxy for RE and economic growth as well as choosing total or per capita form. However, the size of the effect of oil prices changes across between the share and levels; and, between absolute values and per capita values. The positive sign is in line with Apergis and Payne<sup>45,46</sup> and Bamati and Raoofi.<sup>15</sup> This sign is as expected, considering that the countries in our sample can consider oil and renewable energies as substitute goods. Last, the proxy choice is important in determining how large the impact of oil prices on RE deployment.

All in all, the results show that the impact of economic growth on RE is found to be consistently positive, irrespective of the econometric method and indicator choice. However, the magnitude of the elasticity varies substantially between the two estimators as well as the group of countries examined. As expected, the developing countries present lower-income elasticities: although as their income increase, the RE increases its role (either in total or share), the rate is lower due to socioeconomic constraints and growing from a lower base. Hence, the first hypothesis of our study that income has a positive impact on RE deployment is confirmed.

The proxy chosen for RE plays certainly a significant role in the conclusions made for the impact of carbon emissions on the various indicators measuring RE deployment. In the literature review section, it was discussed that there is no consensus on the direction of the impact of emissions' changes to RE deployment. The results of this study confirm this inconsistency and lack of robustness: increases in CO<sub>2</sub> emissions lead to increases in RE consumption and production in aggregate and per capita level, however, to decreases in the

share of RE in consumption and production both in total and per capita level, *ceteris paribus*. Finally, the coefficient of oil prices is robustly found to be positive and statistically significant. This result is as expected due to the substitutability of oil and RE: higher oil prices lead to decreases in oil demand and hence, increases in RE. The choice of the methodological approach might, however, affect the magnitude of the elasticity.

As a short summary, the output positively and consistently affects RE irrespective of the choice of proxy even though the impact level changes across proxies and country groups. Similarly, a positive change in oil prices increases RE deployment due to the expected substitutability of oil and RE.

#### 4 | CONCLUSION AND POLICY IMPLICATIONS

Comprehending the determinants of RE deployment has preoccupied the academic literature as well as policymakers internationally due to countries' overall shift away from fossil fuels in their supply mixes. These factors account for economic and environmental differences among countries and through the years. To do so, the literature has made use of a variety of indicators to quantify RE. Bourcet<sup>9</sup> discusses that the effect of the choice of the proxy for RE is ambiguous and might create inconsistencies in the policy recommendations from modeling studies. This study aims at filling this gap in the literature comparing and contrasting not only the use of various RE indicators but also for robustness purposes, using indicators at aggregate and per capita forms and employing two econometric techniques: pooled OLS with robust SEs as per Driscoll and Kraay<sup>52</sup> to account for cross-sectional dependence and the AMG estimator by Eberhard and Teal.<sup>54,56</sup> An important finding is that the estimated economic growth impact to RE is consistently positive, regardless of the choice of proxy or econometric method—while the only thing that varies is the size of the elasticity that depends on the sample of countries.

The results are significant from a policy perspective: designing policies that will promote renewable energies requires a thorough understanding of the robustness of modeling approaches and choices of indicators, with which this study assists. The positive robust income elasticities can assist the policymakers in ensuring that macroeconomic policies that promote economic growth and development will be positive contributors to a future with more renewable energies in the supply mix. The elasticities seem to be higher in the developed countries showing that the impact of economic growth intensifies as the development level improves. The inconsistent results for the elasticities of CO<sub>2</sub>

emissions inform the policymakers that the same change in emissions levels will have a different effect on the total level of RE vis-à-vis that share of RE in the total supply mix. Finally, particularly for countries that are receivers of oil price information, the robust positive elasticities indicate that RE becomes more and more a preferred option for consumption and production of energy, once the oil becomes more expensive; hence, the choice between oil and renewable is influenced by the cost of oil in the market.

Last, an important limitation of this study is data availability. Future research studies may check the determinants of RE using more explanatory variables (ie, financial development and foreign direct investment), and may also focus on individual countries and specialized country groups, that is, European Union and organization of economic co-operation and development, using a number of different proxies. This kind of attempt in the future can present a more reliable and robust policy-based outcomes.

#### SYMBOLS VARIABLES

CO <sub>2</sub>	carbon dioxide emissions
CO <sub>2</sub> PC	per capita carbon dioxide emissions
CRE	renewable energy consumption
CREPC	per capita renewable energy consumption
GDP	gross domestic product
GDPPC	per capita gross domestic product
PRE	renewable energy production
PREPC	per capita renewable energy production
PRICE	price of crude oil
SCORE	share of renewable energy consumption in total energy consumption
SCOREPC	share of per capita renewable energy consumption in per capita total energy consumption
SPRE	share of renewable energy production in total energy production
SPREPC	share of per capita renewable energy production in per capita total energy production

#### SYMBOLS AND PARAMETERS

$A_{it}$	vector of independent variables
$D$	dummy variable
$i$	units
$k$	lag order
$t$	time period
$\bar{y}$	cross-sectional mean
$\alpha_i$	deterministic term
$\varepsilon_{it}$	error term

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## ORCID

Eyup Dogan  <https://orcid.org/0000-0003-0476-5177>

Roula Inglesi-Lotz  <https://orcid.org/0000-0001-7509-4687>

## REFERENCES

- Hamed TA, Bressler L. Energy security in Israel and Jordan: the role of renewable energy sources. *Renew Energy*. 2019;135:378-389.
- Akram R, Chen F, Khalid F, Ye Z, Majeed MT. Heterogeneous effects of energy efficiency and renewable energy on carbon emissions: evidence from developing countries. *J Clean Prod*. 2020;247:119122.
- Kurigi A, Pinheiro AN, Sordo-Ward A, Garrote L. Flow regime aspects in determining environmental flows and maximizing energy production at run-of-river hydropower plants. *Appl Energy*. 2019;256:113980. <https://doi.org/10.1016/j.apenergy.2019.113980>.
- Jadoon TR, Ali MK, Hussain S, Wasim A, Jahanzaib M. Sustaining power production in hydropower stations of developing countries. *Sustain Energy Technol Assess*. 2020;37:100637.
- Nautiyal H, Goel V. Sustainability assessment of hydropower projects. *J Clean Prod*. 2020;265:121661. <https://doi.org/10.1016/j.jclepro.2020.121661>.
- Varun G, Bhat IK, Prakash R. Life cycle analysis of run-of-river small hydropower plants in India. *Open Renew Energy J*. 2008;1(1):11-16.
- Varun G, Prakash R, Bhat IK. Life cycle energy and GHG analysis of hydroelectric power development in India. *Int J Green Energy*. 2010;7(4):361-375. <https://doi.org/10.1080/15435075.2010.493803>.
- Ankrah I, Lin B. Renewable energy development in Ghana: beyond potentials and commitment. *Energy*. 2020;198:117356. <https://doi.org/10.1016/j.energy.2020.117356>.
- Bourcet C. Empirical determinants of renewable energy deployment: a systematic literature review. *Energy Econ*. 2020;85:104563. <https://doi.org/10.1016/j.eneco.2019.104563>.
- Sadorsky P. Renewable energy consumption and income in emerging economies. *Energy Policy*. 2009;37(10):4021-4028. <https://doi.org/10.1016/j.enpol.2009.05.003>.
- Aguirre M, Ibikunle G. Determinants of renewable energy growth: a global sample analysis. *Energy Policy*. 2014;69:374-384. <https://doi.org/10.1016/j.enpol.2014.02.036>.
- Omri A, Nguyen DK. On the determinants of renewable energy consumption: international evidence. *Energy*. 2014;72(1):554-560. <https://doi.org/10.1016/j.energy.2014.05.081>.
- Apergis N, Payne JE. Renewable energy, output, carbon dioxide emissions, and oil prices: evidence from South America. *Energy Source B Econ Plann Policy*. 2015;10(3):281-287. <https://doi.org/10.1080/15567249.2013.853713>.
- Papiez M, Smiech S, Frodyma K. Determinants of renewable energy development in the EU countries. A 20-year perspective. *Renew Sustain Energy Rev*. 2018;91:918-934. <https://doi.org/10.1016/j.rser.2018.04.075>.
- Bamati N, Raoofi A. Development level and the impact of technical factor on renewable energy production. *Renew Energy*. 2020;151:946-955. <https://doi.org/10.1016/j.renene.2019.11.098>.
- Sadorsky P. Renewable energy consumption, CO<sub>2</sub> emissions and oil prices in the G7 countries. *Energy Econ*. 2009;31(3):456-462. <https://doi.org/10.1016/j.eneco.2008.12.010>.
- Marques AC, Fuinhas JA. Do energy efficiency measures promote the use of renewable sources? *Environ Sci Policy*. 2011;14:471-481. <https://doi.org/10.1016/j.envsci.2011.02.001>.
- Marques AC, Fuinhas JA, Manso JP. A quantile approach to identify factors promoting renewable energy in European countries. *Environ Resource Econ*. 2011;49:351-366. <https://doi.org/10.1007/s10640-010-9436-8>.
- Geng J-B, Ji Q. Technological innovation and renewable energy development: evidence based on patent counts. *Int J Global Environ Issues*. 2016;15(3):217-234. <https://ssrn.com/abstract=2804590>.
- Rafindadi AA, Ozturk I. Effects of financial development, economic growth and trade on electricity consumption: evidence from post-Fukushima Japan. *Renew Sustain Energy Rev*. 2016;54:1073-1084. <https://doi.org/10.1016/j.rser.2015.10.023>.
- Riti JS, Shu Y, Song D, Kamah M. The contribution of energy use and financial development by source in climate change mitigation process: a global empirical perspective. *J Clean Prod*. 2017;148:882-894. <https://doi.org/10.1016/j.jclepro.2017.02.037>.
- Khan H, Khan I, Binh TT. The heterogeneity of renewable energy consumption, carbon emission and financial development in the globe: a panel quantile regression approach. *Energy Rep*. 2020;6:859-867. <https://doi.org/10.1016/j.egyr.2020.04.002>.
- Qamruzzaman M, Jianguo W. The asymmetric relationship between financial development, trade openness, foreign capital flows, and renewable energy consumption: fresh evidence from panel NARDL investigation. *Renew Energy*. 2020;159:827-842. <https://doi.org/10.1016/j.renene.2020.06.069>.
- Asongu SA, Odhiambo NM. Inequality, finance and renewable energy consumption in Sub-Saharan Africa. *Renew Energy*. 2021;165:678-688. <https://doi.org/10.1016/j.renene.2020.11.062>.
- Assi AF, Isiksal AZ, Tursoy T. Renewable energy consumption, financial development, environmental pollution, and innovations in the ASEAN + 3 group: evidence from (P-ARDL) model. *Renew Energy*. 2021;165:689-700. <https://doi.org/10.1016/j.renene.2020.11.052>.
- Alam MM, Murad MW. The impacts of economic growth, trade openness and technological progress on renewable energy use in organization for economic co-operation and development countries. *Renew Energy*. 2020;145:382-390. <https://doi.org/10.1016/j.renene.2019.06.054>.
- Zhao P, Lu Z, Fang J, Paramati SR, Jiang K. Determinants of renewable and non-renewable energy demand in China. *Struct Change Econ Dynam*. 2020;54:202-209. <https://doi.org/10.1016/j.strueco.2020.05.002>.
- Padhan, H., Padhang, P. C., Tiwari, A. K., Ahmed, R. & Hammoudeh, S. (2020). Renewable energy consumption and robust globalization(s) in OECD countries: do oil, carbon emissions and economic activity matter?. *Energy Strat Rev*. 32, 1–15. <https://doi.org/10.1016/j.esr.2020.100535>.
- Gozgor G, Mahalik MK, Demir E, Padhan H. The impact of economic globalization on renewable energy in the OECD countries. *Energy Policy*. 2020;139:111365. <https://doi.org/10.1016/j.enpol.2020.111365>.

30. Chang T-H, Huang C-M, Lee M-C. Threshold effect of the economic growth rate on the renewable energy development from a change in energy price: evidence from OECD countries. *Energy Policy*. 2009;37(12):5796-5802. <https://doi.org/10.1016/j.enpol.2009.08.049>.
31. Marques AC, Fuinhas JA, Manso JRP. Motivations driving renewable energy in European countries: a panel data approach. 2010; 38(11):6785-6877. <https://doi.org/10.1016/j.enpol.2010.07.003>.
32. Bengochea A, Faet O. Renewable energies and CO<sub>2</sub> emissions in the European Union. *Energy Source B Econ Plann Policy*. 2012;7(2):121-130. <https://doi.org/10.1080/15567240902744635>.
33. Baldwin E, Carley S, Brass JN, Maclean LM. Global renewable electricity policy: a comparative policy analysis of countries by income status. *J Comp Policy Anal Res Pract*. 2017;19(3):277-298. <https://doi.org/10.1080/13876988.2016.1166866>.
34. Cadoret I, Padovano F. The political drivers of renewable energies policies. *Energy Econ*. 2016;56:261-269. <https://doi.org/10.1016/j.eneco.2016.03.003>.
35. Wu L, Broadstock DC. Does economic, financial and institutional development matter for renewable energy consumption? Evidence from emerging economies. *Int J Econ Policy Emerg Econ*. 2015;8(1):20. <https://doi.org/10.1504/IJEPEE.2015.068246>.
36. Lu W-C. Renewable energy, carbon emissions, and economic growth in 24 Asian countries: evidence from panel cointegration analysis. *Environ Sci Pollut Res*. 2017;24:26006-26015. <https://doi.org/10.1007/s11356-017-0259-9>.
37. Nyiwul L. Economic performance environmental concerns, and renewable energy consumption: drivers of renewable energy development in Sub-Sahara Africa. *Clean Technol Environ Policy*. 2017;19:437-450. <https://doi.org/10.1007/s10098-016-1229-5>.
38. Le T-H, Nguyen CP, Park D. Financing renewable energy development: insights from 55 countries. *Energy Res Soc Sci*. 2020;68:101537. <https://doi.org/10.1016/j.erss.2020.101537>.
39. Romano AA, Scandurra G. The investments in renewable energy sources: do low carbon economies better invest in green technologies? *Int J Energy Econ Policy*. 2011;1(4):3416.
40. Narbel PA. What is really behind the adoption of new renewable electricity generating technologies? *Energy Sustain Dev*. 2013;17:386-390. <https://doi.org/10.1016/j.esd.2013.03.002>.
41. Brunnschweiler CN. Finance for renewable energy: an empirical analysis of developing and transition economies. *Environ Dev Econ*. 2010;15(3):241-274.
42. Pfeiffer B, Mulder P. Explaining the diffusion of renewable energy technology in developing countries. *Energy Econ*. 2013; 40:285-295. <https://doi.org/10.1016/j.eneco.2013.07.005>.
43. Salim RA, Rafiq S. Why do some emerging economies proactivity accelerate the adoption of renewable energy? *Energy Econ*. 2012; 34:1051-1057. <https://doi.org/10.1016/j.eneco.2011.08.015>.
44. Przychodzen W, Przychodzen J. Determinants of renewable energy production in transition economies: a panel data approach. *Energy*. 2020;191(15):116583. <https://doi.org/10.1016/j.energy.2019.116583>.
45. Apergis N, Payne JE. The causal dynamics between renewable energy, real GDP, emissions and oil prices: evidence from OECD countries. *Appl Econ*. 2014;46(36):4519-4525. <https://doi.org/10.1080/00036846.2014.964834>.
46. Apergis N, Payne JE. Renewable energy, output, CO<sub>2</sub> emissions, and fossil fuel prices in Central America: evidence from a nonlinear panel smooth transition vector error correction model. *Energy Econ*. 2014;42:226-232. <https://doi.org/10.1016/j.eneco.2014.01.003>.
47. Ackah I, Kizys R. Green growth in oil producing African countries: a panel data analysis of renewable energy demand. *Renew Sustain Energy Rev*. 2015;50:1157-1166. <https://doi.org/10.1016/j.rser.2015.05.030>.
48. Marques AC, Fuinhas JA. Drivers promoting renewable energy: a dynamic panel approach. *Renew Sustain Energy Rev*. 2011;15:1601-1608. <https://doi.org/10.1016/j.rser.2010.11.048>.
49. Marques AC, Fuinhas JA. Are public towards renewables successful? Evidence from European countries. *Renew Energy*. 2012;44:109-118. <https://doi.org/10.1016/j.renene.2012.01.007>.
50. Valdes Lucas JN, Frances GE, Gonzalez ESM. Energy security and renewable energy deployment in the EU: liaisons dangereuses or virtuous circle? *Renew Sustain Energy Rev*. 2016;62:1032-1046. <https://doi.org/10.1016/j.rser.2016.04.069>.
51. Gan J, Smith CT. Drivers for renewable energy: a comparison among OECD countries. *Biomass Bioenergy*. 2011;35:4497-4503. <https://doi.org/10.1016/j.biombioe.2011.03.022>.
52. Driscoll JC, Kraay AC. Consistent covariance matrix estimation with spatially dependent panel data. *Rev Econ Stat*. 1998;80(4): 549-560. <https://doi.org/10.1162/003465398557825>.
53. Pesaran MH. A simple panel unit root test in the presence of cross-section dependence. *J Appl Economet*. 2007;22(2):265-312. <https://doi.org/10.1002/jae.951>.
54. Eberhardt, M., & Teal, F. (2010). Productivity analysis in global manufacturing production, 515. <https://ora.ox.ac.uk/objects/uuid:ea831625-9014-40ec-abc5-516ecfdb2118>
55. McCoskey S, Kao C. A residual-based test of the null of cointegration in panel data. *Econom Rev*. 1998;17(1):57-84. <https://doi.org/10.1080/07474939808800403>.
56. Eberhardt M, Teal F. Econometrics for grumblers: a new look at the literature on cross-country growth empirics. *J Econ Surv*. 2011; 25(1):109-155. <https://doi.org/10.1111/j.1467-6419.2010.00624.x>.
57. Inglesi-Lotz R. The impact of renewable energy consumption to economic welfare: a panel data application. *Energy Econ*. 2016;53:58-63.
58. Arellano M, Bond S. Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations. *Rev Econ Stud*. 1991;58(2):277-297.
59. U.S. Energy Information Administration (EIA). <https://www.eia.gov/renewable/data.php>
60. World Bank, World development indicators database. <https://databank.worldbank.org/source/world-development-indicators>
61. Bayulgen O, Ladewing JW. Vetoing the future: political constraints and renewable energy. *Environ Politics*. 2017;26:49-70. <https://doi.org/10.1080/09644016.2016.1223189>.
62. Lin B, Omoju OE. Focusing on the right targets: economic factors driving non-hydro renewable energy transition. *Renew Energy*. 2017;113:52-63. <https://doi.org/10.1016/j.renene.2017.05.067>.
63. Kasman A, Duman YS. CO<sub>2</sub> emissions, economic growth, energy consumption, trade and urbanization in new EU member and candidate countries: a panel data analysis. *Econ Model*. 2015;44:97-103.
64. Pesaran M, Yamagata T. Testing slope homogeneity in large panels. *J Econom*. 2008;142(1):50-93. <https://doi.org/10.1016/j.jeconom.2007.05.010>.
65. Pesaran, M. H. (2004). General diagnostic tests for cross section dependence in panels (SSRN scholarly paper ID 572504). Social science research network. <https://papers.ssrn.com/abstract=572504>

66. Westerlund J. Testing for error correction in panel data. *Oxf Bull Econ Stat.* 2007;69(6):709-748.
67. Eren BM, Taspinar N, Gokmenoglu KK. The impact of financial development and economic growth on renewable energy consumption: empirical analysis of India. *Sci Total Environ.* 2019; 663:189-197. <https://doi.org/10.1016/j.scitotenv.2019.01.323>.
68. Shafiei S, Salim R. Non-renewable and renewable energy consumption and CO<sub>2</sub> emissions in OECD countries: a comparative analysis. *Energy Policy.* 2014;66:547-556.
69. Menyah K, Wolde-Rufael Y. Energy consumption, pollutant emissions and economic growth in South Africa. *Energy Econ.* 2010;32(6):1374-1382.
70. Apergis N, Payne JE, Menyah K, Wolde-Rufael Y. On the causal dynamics between emissions, nuclear energy, renewable energy, and economic growth. *Ecol Econ.* 2010;69(11):2255-2260.

**How to cite this article:** Dogan E, Inglesi-Lotz R, Altinoz B. Examining the determinants of renewable energy deployment: Does the choice of indicator matter? *Int J Energy Res.* 2021;45: 8780–8793. <https://doi.org/10.1002/er.6413>

## APPENDIX A.

### List of countries

Albania	Cameroon	France	Japan	Pakistan	Switzerland
Algeria	Canada	Gabon	Laos	Peru	Tanzania
Angola	Chile	Ghana	Malawi	Philippines	Thailand
Argentina	China	Greece	Malaysia	Portugal	Trinidad and Tobago
Australia	Colombia	Guatemala	Mexico	Romania	Tunisia
Austria	Congo-Brazzaville	Hungary	Morocco	South Africa	Turkey
Bangladesh	Congo-Kinshasa	India	Myanmar	South Korea	United Kingdom
Belgium	Cote d'Ivoire	Indonesia	Nepal	Spain	United States
Bhutan	Cuba	Iran	The Netherlands	Sudan	Venezuela
Bolivia	Denmark	Iraq	New Zealand	Suriname	Vietnam
Brazil	Ecuador	Ireland	Nigeria	Swaziland	Zambia
Bulgaria	Egypt	Italy	Norway	Sweden	Zimbabwe