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The effect of renewable energy consumption on economic growth: Evidence from top 38 countries

Mita Bhattacharya [a,*], Sudharshan Reddy Paramati [b], Ilhan Ozturk [c], Sankar Bhattacharya [d]

[a] Department of Economics, Monash University, Caulfield, Victoria 3145, Australia
[b] International Institute for Financial Studies, Jiangxi University of Finance and Economics, Nanchang, 330013 Jiangxi Province, China
[c] Faculty of Economics and Administrative Sciences, Cag University, Mersin 33800, Turkey
[d] Department of Chemical Engineering, Monash University, Clayton, Victoria 3800, Australia

HIGHLIGHTS

- Deployment of renewables is essential for sustainable development.
- Top 38 countries are selected using the Renewable Energy Country Attractive Index.
- Long-run output elasticities estimated for each country.
- Analysis for both panel and individual countries.
- The message varies for future renewable deployment into the growth process.

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ABSTRACT

This research aims to investigate the effects of renewable energy consumption on the economic growth of major renewable energy consuming countries in the world. Using the Renewable Energy Country Attractiveness Index developed by the Ernst & Young Global Limited, we choose 38 top renewable energy consuming countries to explain the growth process between 1991 and 2012. With panel estimation techniques, our findings establish cross-sectional dependence and heterogeneity across the countries. We confirm the evidence of long-run dynamics between economic growth, and traditional and energy-related inputs. Findings from long-run output elasticities indicate that renewable energy consumption has a significant positive impact on the economic output for 57% of our selected countries. For robustness, we also carried out time-series analyses of long-run output elasticities. Our findings suggest that governments, energy planners, international cooperation agencies and associated bodies must act together in increasing renewable energy investment for low carbon growth in most of these economies.

1. Introduction

The United Nations designated the decade 2014–2024 as the Decade of Sustainable Energy for All (SE4All, [1]). Attaining sustainability in energy use is likely to create a cleaner environment, wider access to electricity, improved energy efficiency with low-carbon renewables, and result in greater investment in cleaner technology. In the global context, there is an increasing deployment of renewable energy that helps in addressing climate change and in creating wider energy access to the billions of people who are still in the poverty trap.

An estimated 19.1% of global final energy consumption was sourced from renewables in 2013.[1] The recent growth in the electricity sector is led by wind, solar PV, and hydropower. The growth in heating capacity is at a steady pace, and the production of biofuels for transport has recently climbed following a slump in 2011–2012. Following the most optimistic scenario developed by the International Energy Agency (IEA), the renewable share of electricity generation will increase to 39% by 2050 from 18.3% in 2002. In reducing the global CO_2 reduction by 50% by 2050, renewables will have a

* Corresponding author.
E-mail addresses: Mita.Bhattacharya@monash.edu (M. Bhattacharya), sudharshanreddy.paramati@griffithuni.edu.au (S.R. Paramati), ilhanozturk@cag.edu.tr (I. Ozturk), Sankar.Bhattacharya@monash.edu (S. Bhattacharya).

[1] http://www.ren21.net/wp-content/uploads/2015/06/GSR2015_KeyFindings_lowres.pdf [2].

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key role in limiting the long-term mean global temperature rise within the limit, between 2.0 and 2.4 °C [3].

Renewables growth in recent years has been driven by government-supported programs through subsidies, tax credits, and other incentives. This has increased the cost-competiveness of renewable energy sources. In many countries, renewables are broadly competitive with conventional energy sources. Along with Europe and the United States, recent renewable energy initiatives have originated in countries in Asia, Africa, and Latin America. This has created emerging manufacturers and installers of renewable energy technologies outside Europe and the United States.

The literature on the energy consumption-economic growth nexus has been widely researched (e.g., [4–6]), however the renewable energy-based studies are still scarce.[2] The growing significance of renewables as a source of energy has created wide interest from both academics and energy policy analysts. Our contribution towards the literature is as follows.

The research makes several important contributions towards the renewable energy-growth nexus literature in Energy Economics. Almost all studies in the literature have considered panels of countries in explaining the dynamic relationship between renewable energy consumption and economic growth. A major criticism related to these studies, we notice, is the selection of panels. Countries within the considered panel have a greater degree of heterogeneity, and also could be cross-sectionally dependent across the panel. To overcome this problem, in this paper we employ recent heterogeneous panel estimation techniques with cross-sectional dependence. This is important, as energy policies set at the international level can also affect individual countries simultaneously, in addition to other exogenous shocks. This is the first piece of research dealing with renewable energy and growth using heterogeneous panel techniques for 38 top renewable energy consuming countries.

Second, unlike other studies, in our study country selection for our panel is not random. For this purpose we utilise the Renewable Energy Country Attractiveness Index (RECAI) developed by Ernst & Young Global Limited. The RECAI ranking is based on macroeconomic, technology, and energy-specific factors for each market.[3] We selected 38 out of 40 top countries following this RECAI index for our panel. It is the first time this index has been used in the literature for selecting a panel of countries.

Third, along with traditional inputs, we selected both renewable and non-renewable energy consumption so that we can identify the relative effect of each of these in the economic growth process.

Fourth, with long-run dynamics, we estimate the long-run output elasticities with respect to each type of energy for the panel and individual countries. These elasticities reflect both the time dimensions and the cross-sectional nature of the panel and provide significant power compared to the studies based on only time series techniques. These estimates are useful for policy purposes, as they reflect the long-run demand for renewable and non-renewable energy sources in the growth process for these countries.

The rest of the paper is organized as follows. Section 2 provides an overview of the energy consumption-growth hypotheses with a focus on the empirical literature on the studies explaining the dynamics of renewable energy consumption and economic growth. A brief update of renewable energy resources in different countries is presented in Section 3. Section 4 discusses the model, data and descriptive statistics of variables. In Section 5, we describe econometric methodology and empirical findings. Section 6 presents conclusions and provides policy suggestions.

[2] For detailed reviews, see [7,8].

[3] http://www.ey.com/Publication/vwLUAssets/RECAI_44/$FILE/RECAI%2044_June%202015.pdf [9].

2. An overview of literature

The energy consumption-economic growth nexus can be analysed under four hypotheses. The *growth hypothesis* assumes energy as a major source of input into the growth process, and uni-directional causality exists from energy consumption to economic growth. In this scenario, energy conservation policies will have a negative impact on economic growth. The *conservation hypothesis* implies that economic growth causes consumption of energy. Under this situation, conservation policy will not affect economic growth. The *feedback hypothesis* implies a bi-directional relationship between energy consumption and economic growth. This hypothesis suggests any change in energy consumption will affect economic growth with a reverse effect. The *neutrality hypothesis* indicates that energy consumption and economic growth are independent and do not affect each other. Most of the literature examines the relationship between electricity consumption and income, or the nexus of energy-income-emissions. The literature over the past decades has produced varied findings across countries under each of these hypotheses. No consensus has emerged from these studies. We refrain from the voluminous literature here.[4]

Our objective here is to review the scant literature on the role of renewable energy in explaining sustainable economic growth. A bi-directional causation was established between renewable energy consumption and economic growth by [10] for 18 emerging economies. Sadorsky reports that in the long run, a 1% increase in real income per capita increased the consumption of renewable energy per capita by approximately 3.5% for these economies. Bowden and Pyne [11] analysed the sectoral causal relationship between renewable and non-renewable energy consumption and economic growth in the US. Their findings established no causality between renewable energy consumption and real GDP in the commercial and industrial sectors, while positive uni-directional causality exists from residential renewable energy consumption to real GDP. On renewables, there are only a few studies examining the effects of biomass biofuels on the environment with varying results. Ozturk and Bilgili [12] reviewed this literature and investigated 51 African countries. They found that a 1% increase in biomass will increase GDP by 0.82% in these countries.

A summary of literature is presented in Table 1 to conserve space. It is noticeable that the findings from the literature are mixed even for the studies where energy-mix is disaggregated. Given that there is currently a worldwide effort to increase the share of renewable sources, we consider a panel study instead of a case study on a single country. The selection of countries following the RECAI index and heterogeneous panel estimation techniques provide new findings in the literature.

3. Renewable energy resources – overview of current status in sampled countries

Renewable energy is sourced from natural processes (e.g. sunlight and wind) and is either inexhaustible or can be replenished. Major types of renewable energy are solar, wind, geothermal, hydropower, bio-energy, and ocean power. The share of renewables has increased significantly in the electricity, heating and cooling, and transport sectors. Following the report from the Renewable Energy Policy Network for the 21st Century (REN21), China led in global investment in renewable power and fuels, followed by United States, Japan, United Kingdom and Germany. China was in the forefront in hydropower, solar PV, wind, and solar water heating. In terms of renewable power capacity per capita, the five top countries are Denmark, Germany, Sweden, Spain and

[4] Ref. [11] and follow references.

Table 1
Recent literature review on renewables-growth nexus.

Study	Methodology	Period	Country	Findings
Sadosky [10]	Panel, FMOLS	1994–2003	18 emerging countries	GDP > RE
Apergis and Payne [13]	Panel	1985–2005	20 OECD countries	GDP <> RE
Apergis and Payne [14]	Panel	1992–2007	13 Eurasian countries	GDP <> RE
Apergis and Payne [15]	Panel	1980–2006	6 Central American countries	GDP <> RE
Menegaki [16]	Panel, random effect	1997–2007	27 European countries	GDP and RE are neutral to each other
Fang [17]	OLS	1978–2008	China	RE > GDP
Tiwari [18]	Structural VAR	1960–2009	India	RE > GDP
Apergis and Payne [19]	Panel	1990–2007	80 countries	GDP <> EC (RE, NRE)
Salim and Rafiq [20]	Panel	1980–2006	6 major emerging countries	GDP <> RE in the short-run
Tugcu et al. [21]	ARDL approach for cointegration; Hatemi-J (2012) for causality test	1980–2009	G7 countries	The relationship is different for countries and varies with specification
Ai-mulali et al. [22]	FMOLS	1980–2009	108 countries	79% feedback; 2% conservation; 19% neutrality
Ozturk and Bilgili [12]	Dynamic panel analysis	1980–2009	51 Sub-Sahara African countries	Biomass has positive effect on GDP
Cho et al. [23]	Panel vector error correction model	1990–2010	31 OECD and 49 non-OECD countries	GDP > RE fo developed and GDP <> RE for less-developed countries
Bilgili and Özturk [24]	Panel, DOLS	1980–2009	G7 countries	Biomass has positive effect on GDP

Note: EC: Energy Consumption; RE: Renewables; NRE: Non-renewables.

Portugal. Rankings for different sources based on capacity per capita were[5]:

- Hydropower – China, Brazil, Canada, United States and Russia.
- Solar PV – Germany, Italy, Belgium, Greece and Czech Republic.
- Wind power – Denmark, Sweden, Germany, Spain and Ireland.
- Geothermal – Iceland, New Zealand, Hungary, Turkey and Japan.

In recent years, the growth of renewables was faster in the developing non-OECD countries compared with the OECD countries. Renewables accounted for 80% of new generation in the OECD, while for non-OECD countries; renewables reached only 35% of growth. Also, developing newly-emerging countries were investing at a faster pace in renewables [25].

Global investment in renewable power increased almost fourfold (from USD $36 billion to $139 billion) for developed countries, while for developing countries the growth factor is just over 14 (from $9 billion to $131 billion), and increased from $45 billion to $270 billion for the whole world between 2004 and 2014 as reported in [2].

Some of the major statistics are reported here from [2]:

- China had the largest renewable energy investments in 2014 with $83.3 billion, the US was second at $38.3 billion, and Japan ranked third with $35.7 billion.
- Investment in developing countries, at $131.3 billion, increased to 36% on the previous year and came the closest ever to overhauling the total for developed economies, at $138.9 billion additional to China, Brazil ($7.6 billion), India ($7.4 billion) and South Africa ($5.5 billion) were all in the top 10 of investing countries, while more than $1 billion was invested in Indonesia, Chile, Mexico, Kenya and Turkey.
- Wind, solar, biomass and waste-to-power, geothermal, small hydro, and marine power contributed an estimated 9.1% of world electricity generation in 2014, compared with 8.5% in 2013.
- In 2014, the global market was dominated by record investment in solar and wind, which accounted for 92% of overall investment in renewable power and fuels. Investment in solar jumped 29% to $149.6 billion, the second-highest figure ever, while wind investment increased 11% to a record $99.5 billion. Investment in Europe advanced less than 1% to $57.5 billion.[6]

Fig. 1 depicts disaggregated sources of renewables for our study period. This is apparent that within renewable energy-mix, use of biomass dominated in our selected countries compared to geothermal, hydropower, solar, waste, and wind. Biomass includes crop residues, forest and wood process residues, wastes from animal and human sources, purpose-grown energy crops, and short rotation forestry residues. Growing demand for biomass reduces import dependency on other non-renewable sources, increases rural employment, and offers a less carbon-intensive source of energy. In addition, a steady increase in hydropower and the rapid expansion of wind and solar has already cemented the position of renewables as an indispensable part of the global power mix. One important consequence of the rapid expansion of renewable power generation has been the declining generation costs.

4. Model, data and descriptive statistics

4.1. Model and data

We propose here a simple production function where, along with traditional inputs, renewable and non-renewable sources of energy are used into the production process.[7] The conventional neo-classical one-sector aggregate production technology is employed, where capital, labour, and energy are treated as separate inputs.

$$Y_{it} = f\ (\mathrm{GFCF}_{it}; \mathrm{LF}_{it}; \mathrm{REC}_{it}; \mathrm{NREC}_{it}) \tag{1}$$

The subscripts i and t denote country and time period respectively. We use real GDP or output (Y) in constant 2005 US dollars as a measure of economic output, real gross fixed capital formation (GFCF) in constant 2005 US dollars is used as a proxy for the growth of capital stock, and total labour force (LF) is used as a measure of available labour in the market. All of these data are obtained from the World Development Indicators (WDI) online database published by the World Bank [27]. The required data on renewable and non-renewable energy consumption is collected from the U.S. Energy Information Administration (EIA) [28]. Two energy sources are used in the production function, being renewable energy consumption (REC), and non-renewable energy consumption (NREC).[8] By following ([15,22]), we use renewable

[5] For detail, see page 20, REN21 Renewables 2015 Global Status Report [2].
[6] http://fs-unep-centre.org/publications/global-trends-renewable-energy-investment-2015 [26].

[7] We do not consider other control variables as used in the literature. Here our focus is to examine the substitution process of energy and non-energy type inputs into the economic growth.
[8] We could not include disaggregated data within the renewables (all types) due to non-availability of the data for all countries across the time period.

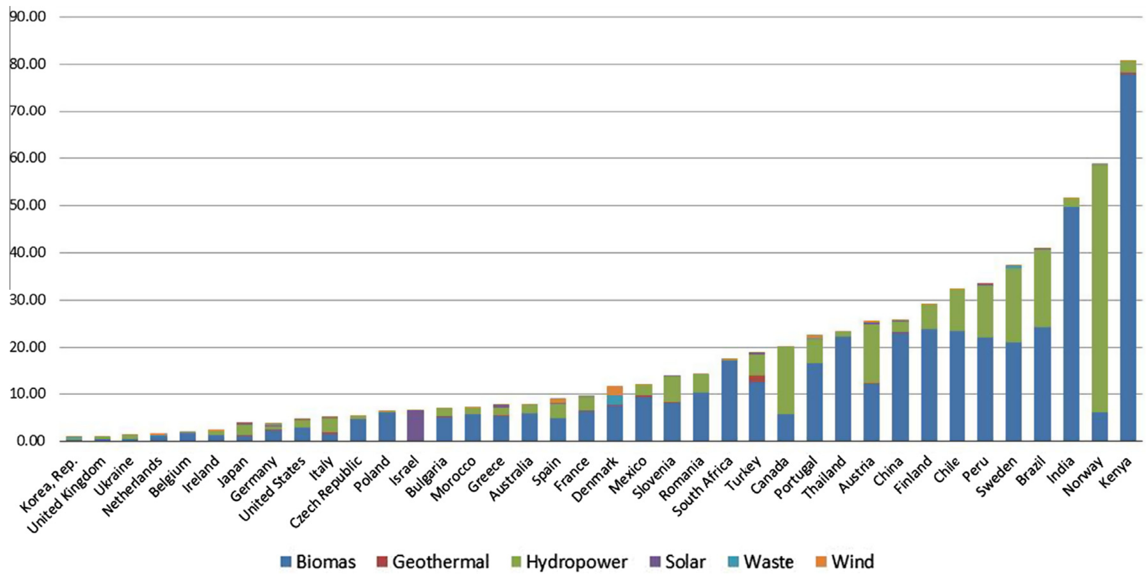

Fig. 1. Percentage of renewable energy sources in total final energy consumption: 1990–2010. *Source:* Sustainable Energy for All, World Bank [27].

energy consumption as electricity consumption generated from various renewable energy sources and measured in billion kilowatt-hours. On the other hand, non-renewable energy sources include coal and coal products, oil, and natural gas. In this study the non-renewable energy consumption is used as the aggregate of these four energy sources in quadrillion Btu units. It is important to normalise the data series and transform the data for all these four fuel sources into a common unit. Of the other variables, the output and GFCF are measured in monetary units while labour is measured in numbers. Eq. (1) can be parameterised as follows:

$$Y_{it} = \mathrm{GFCF}_{it}^{\beta 1i}\mathrm{LF}_{it}^{\beta 2i}\mathrm{REC}_{it}^{\beta 3i}\mathrm{NREC}_{it}^{\beta 4i} \tag{2}$$

The transformation of data series into natural logarithm avoids the problems associated with dynamic properties of the data series. The log transformation of the data series is a preferred approach, as each resulting coefficient in a regression equation can be interpreted as elasticities.[9] The empirical equation is developed as follows:

$$\ln\ Y_{it} = \beta_{1i}\ln \mathrm{GFCF}_{it} + \beta_{2i}\ln \mathrm{LF}_{it} + \beta_{3i}\ln \mathrm{REC}_{it} + \beta_{4i}\ln \mathrm{NREC}_{it} + \varphi\ it \tag{3}$$

where β_{1i}, β_{2i}, β_{3i} and β_{4i} are elasticities of output with respect to gross fixed capital formation, labour, renewables, and non-renewables, respectively. Φ is the error term.

We use a balanced panel of 38 countries covering the period from 1991 to 2012. The selection of our sample countries is based on the 'Renewable Energy Country Attractiveness Index' (RECAI) prepared by the Ernst & Young. Out of the first 40 ranked countries, we selected 38: Australia, Austria, Belgium, Brazil, Bulgaria, Canada, Chile, China, the Czech Republic, Denmark, Finland, France, Germany, Greece, India, Ireland, Israel, Italy, Japan, Kenya, Republic of Korea, Mexico, Morocco, the Netherlands, Norway, Peru, Poland, Portugal, Romania, Slovenia, South Africa, Spain, Sweden, Thailand, Turkey, Ukraine, the United Kingdom, and the United States. We excluded countries – Saudi Arabia (rank 35) and Taiwan (rank 21) – due to unavailability of data for our chosen variables and time period. We analysed the model between 1991 and 2012, the longest time period for which data are available for the variables. This selected period is dictated by availability of our data for the balanced panel. Also most of the initiatives for renewables have taken place during this time. Fig. 1 presents the percentage of renewable energy sources in total final energy consumption between 1990 and 2010.

4.2. Descriptive statistics of the variables

Table 2 presents the average annual growth rates for each of the variables in our model. There was heterogeneity across countries for these statistics. For example, the average annual real GDP growth was 10.35% for China, followed by India (6.75%), Israel (5.11%) and Chile (5.07%). The highest average annual consumption of renewables is recorded for Israel (43.77%), South Africa (39.67%), Morocco (16.30%) and Belgium (12.22%). Countries where the annual growth rate of renewable energy consumption compared to non-renewables was significantly higher were Belgium, Bulgaria, China, the Czech Republic, Denmark, Germany, Greece, Ireland, Israel, Morocco, the Netherlands, Poland, Portugal, South Africa, Spain and the United Kingdom. Amongst these, the annual growth rates of non-renewables was negative for Bulgaria (−0.97%), the Czech Republic (−0.59%), Denmark (1.48%), Germany (−0.53%), Poland (−0.01%) and the United Kingdom (−0.50%). Only in six countries, such as Australia, Brazil, Canada, Chile, India and Peru, non-renewable energy consumption was higher than renewables for the sample period.

Table 3 shows the correlations among the variables for the given balanced panel data set. This table suggests that output had higher correlation with capital and non-renewable energy consumption, and the lowest correlation with labour. These findings indicate that capital and non-renewable energy played a significant role in promoting economic activities across the countries. However, results also suggest that renewable energy consumption had the highest correlations with output which indicates that it also plays an important role in economic growth.

5. Econometric methodology and empirical findings

In the following sub-sections we describe appropriate econometric methodology and apply these for our sample countries.

[9] Following [14] and others, we use log-linear model.

Table 2
Average annual growth of each of our variable in the model: 1991–2012 (percent).

Country	Y	GFCF	LF	REC	NREC
Australia	3.338	5.842	1.642	2.022	2.378
Austria	1.997	1.200	0.984	2.454	0.688
Belgium	1.797	2.093	0.927	12.227	0.604
Brazil	3.063	3.994	2.216	3.577	4.677
Bulgaria	2.092	7.324	−0.839	7.491	−0.978
Canada	2.579	3.820	1.261	1.277	1.376
Chile	5.078	8.950	2.455	3.804	4.915
China	10.355	13.601	0.981	10.773	6.362
Czech Republic	2.429	4.389	0.267	9.458	−0.593
Denmark	1.563	2.357	0.013	13.575	−1.489
Finland	2.295	1.936	0.268	2.976	−0.179
France	1.651	1.592	0.748	2.386	−0.154
Germany	1.339	0.930	0.219	9.934	−0.531
Greece	1.167	−0.238	0.956	8.961	0.513
India	6.750	9.130	1.594	4.338	5.433
Ireland	4.646	4.531	2.189	11.512	1.755
Israel	5.119	2.270	3.511	43.774	3.799
Italy	0.803	0.290	0.222	3.920	−0.044
Japan	0.826	−1.045	0.021	1.092	0.851
Kenya	3.405	7.734	2.831	4.534	4.338
Korea, Rep.	5.117	3.311	1.310	5.996	4.879
Mexico	2.780	4.037	2.426	3.338	2.036
Morocco	3.807	5.205	1.905	16.307	4.430
Netherlands	2.060	1.938	1.192	11.520	0.583
Norway	2.536	4.234	1.061	1.902	1.604
Peru	5.048	9.063	3.248	3.465	5.375
Poland	4.314	6.810	0.160	11.975	−0.014
Portugal	1.301	0.317	0.581	10.792	0.980
Romania	2.134	7.197	−0.407	1.378	−2.317
Slovenia	2.226	3.331	0.900	2.076	1.542
South Africa	2.834	5.148	2.312	39.679	2.235
Spain	2.165	1.581	1.881	8.826	1.723
Sweden	2.216	2.250	0.400	2.978	−0.420
Thailand	4.239	2.357	0.989	7.431	6.142
Turkey	4.162	6.326	1.500	6.722	4.425
Ukraine	−0.842	−1.935	−0.449	3.577	−2.552
United Kingdom	2.133	2.382	0.535	10.794	−0.503
United States	2.618	3.308	1.003	2.075	0.419

Note: Growth rates are calculated using original data.

5.1. Issues related to heterogeneity and cross-sectional dependence

We notice a significant degree of heterogeneity across countries for our variables from Table 2. First, since it is possible to estimate a separate regression for each country, it is natural to consider heterogeneous panel models where the parameters can differ across countries. One can test for equality of the parameters, rather than assuming it, as one is forced to do in the small T case. This homogeneity hypothesis is very often rejected and the differences in the estimates between countries can be large. Therefore, researchers should employ appropriate technique in estimating heterogeneous panel.

In addition, we believe that there is cross-sectional dependence across our panel countries due to regional and macroeconomic linkages from common global shocks (for instance, the Asian financial crisis, great recession, and national trade, energy and fiscal policies which may have spill-over effects across countries). If the cross-sectional dependence is large and not dealt with proper estimation techniques, one may get little improvement in efficiency from panel estimators relative to a single time-series. On the other hand, this cross-section dependence may allow one to estimate unobserved common factors, such as global cycles, that cannot be estimated from a single time-series. Under this scenario, the standard panel unit root tests may provide biased results.[10]

Table 3
Correlations for the panel data set.

	Y	GFCF	LF	REC	NREC
Y	1	0.987***	0.619***	0.620***	0.869***
GFCF		1	0.632***	0.604***	0.869***
LF			1	0.572***	0.818***
REC				1	0.548***
NREC					1

Notes: Variables are in natural logarithms.
*** Indicates statistical significance at 1% level.

5.2. Estimation steps and empirical findings

5.2.1. Test for cross-sectional dependence

Pesaran [32] demonstrates that violation often leads to undesirable finite sample properties of the IPS test. Therefore, we used the general diagnostic test for cross-section dependence in panels proposed by [33] to find whether the cross-sectional dependence existed within our panel variables.[11] This test uses the correlation-coefficients between the time-series for each panel country. For this test, the null hypothesis assumes cross-sectional independence against the alternative hypothesis of cross-sectional dependence. The rejection of null hypothesis confirmed the existence of cross-sectional dependence across the countries. Table 4 displays the findings of the Pesaran CD test for the considered variables. The null hypothesis of cross-sectional independence was strongly rejected for all of the variables. We conclude the presence of cross-sectional dependence as expected.

5.2.2. Panel unit root test

For the panel with cross-sectional dependence, the first generation unit root tests tend to over-reject the null hypothesis (reference). Therefore, to address the cross-sectional dependence while identifying the order of integration of the variables in the panel, we applied the recently developed technique. With average individual statistics, [33] develops a panel root t-statistic as cross sectional augmented IPS (CIPS) test. This test considers both heterogeneity and cross-sectional dependence across panels, and is considered a popular second-generation panel unit root test. The findings are in lower panel of Table 4, which show that all of the variables were integrated of same order, i.e., I (1). This also indicates that all of the variables are non-stationary at levels, and stationary at their first-order differentials. The CIPS test results suggest that there may be a long-run equilibrium relationship among the variables since all of the variables are integrated with the same order. We explore this in the following section.

5.2.3. Panel cointegration test

In the next step, we examine whether a long-run equilibrium relationship exists between the variables. Each of our variables is integrated of order one, we conducted panel cointegration test developed by [34,35]. Seven test statistics are proposed: the panel v-statistic, panel rho-statistic, panel PP-statistic (nonparametric), panel ADF-statistic (parametric), group rho-statistic, group PP-statistic (nonparametric), and group ADF-statistic (parametric). The findings are presented in Table 5. Out of seven test statistics, five confirm the presence of cointegration among the variables. Therefore, following the [34,35] test in the series, we conclude that real GDP, real gross fixed capital formation, labour force, renewable, and non-renewable consumption series shared a long-run

[10] Ref. [29] develops a test (IPS) which allows heterogeneous autoregressive unit root process across cross-sections based on a test-statistic that is the average of the individual (i.e., for each cross-sectional unit) ADF statistics. Ref. [30] proposes a panel unit root test (ADF-Fisher) based on [31] and is appropriate for unbalanced panel. These are based on cross-sectional independence across panel.

[11] Mathematical expressions for each technique are not defined here to conserve space.

Table 4
Tests for cross-sectional dependence and unit root.

Variable	Y	GFCF	LF	REC	NREC
Pesaran CD test	113.370***	79.430***	71.390***	76.960***	36.780***
P-value	0.000	0.000	0.000	0.000	0.000
The unit root test with cross-sectional dependence					
CIPS test (level)	5.123	3.036	3.861	1.033	1.171
CIPS test (first difference)	−1.832**	−3.104***	−3.386***	−10.783***	−5.656***

** Indicates the rejection of null hypothesis of cross-sectional independence (CD test) and the null hypothesis of unit root at 5% significance level. CIPS test is estimated using constant and trend with 1 lag.
*** Indicates the rejection of null hypothesis of cross-sectional independence (CD test) and the null hypothesis of unit root at 1% significance level. CIPS test is estimated using constant and trend with 1 lag.

Table 5
Pedroni panel cointegration test results.

	Statistic	Prob.	Weighted Statistic	Prob.
Alternative hypothesis: common AR coefs. (within-dimension)				
Panel v-statistic	8.345***	0.000	8.398***	0.000
Panel rho-statistic	3.072	0.999	3.147	0.999
Panel PP-statistic	−3.466***	0.000	−3.399***	0.000
Panel ADF-statistic	−4.332***	0.000	−4.119***	0.000
		Statistic		Prob.
Alternative hypothesis: individual AR coefficients (between-dimension)				
Group rho-statistic		5.215		1.000
Group PP-statistic		−8.727***		0.000
Group ADF-statistic		−7.642***		0.000

Notes: Variables: Y, GFCF, LF, REC & NREC.
Trend assumption: Deterministic intercept and trend.
Lag selection: Automatic based on SIC with a max lag of 3.
Newey-West automatic bandwidth selection with Bartlett kernel.
*** Denote rejection of null hypothesis of no cointegration at 1% significance level.

equilibrium relationship. For robustness, we also estimated long-run relationships among the variables using two other panel cointegration techniques such as [36] and Fisher-type Johansen cointegration test which is proposed by [30]. The results from these two cointegration tests also confirmed the existence of long-run equilibrium relationship among the variables.

5.2.4. Panel data analysis of long-run output elasticities

The long-run output elasticities are estimated using ordinary least square (OLS), dynamic OLS (DOLS) and fully modified OLS (FMOLS) models. The empirical findings of these models are presented in Table 6. The three approaches produce very similar results for each variable in terms of sign and significance, however in terms of magnitude they vary slightly. For the empirical interpretation, we only consider DOLS and FMOLS results, since these two approaches account for serial correlation and endogeneity that may exist in the model. For the DOLS results, a 1% increase in renewable energy consumption increased output by 0.101%, while, a 1% increase in non-renewable energy consumption increased output by 0.280%. For the FMOLS results, a 1% increase in renewable energy consumption increased output by 0.109%, while a 1% increase in non-renewable energy consumption increased output by 0.277%. Each of the variables in the DOLS and FMOLS estimations are statistically significant at 1% level. The findings on long-run output elasticities suggest that along with traditional inputs such as capital and labour, both renewables and non-renewables played a significant role in the process of economic development in the selected sample countries. Based on these findings, we argue that non-renewable energy consumption plays a bigger role in economic output, therefore policy advisers need to promote the generation and use of renewable energy to ensure sustainable economic development in future.

5.2.5. Heterogeneous panel causality test

Once the long-run dynamics are established among the variables, the next step is to find the direction of causality in the short-run. For this purpose, we conduct a pairwise [37] panel causality test. The significance of this approach is that it assumes all the coefficients to be different across cross-sections. This test requires variables to be stationary; we therefore apply on the first difference of the series. The findings established unidirectional causality from output to capital, output to labour, and non-renewable energy consumption to output. We could not establish any unidirectional or bidirectional causality between output and renewable energy consumption in the short-run. As deployment of renewables needs infrastructure investment and long-term planning, we are more interested with long-run elasticities which we established in the above section (see Table 7).

5.2.6. Time-series analysis of long-run output elasticities

Since we presented panel data analysis of long-run output elasticities above, we further aimed to examine the time-series analysis of long-run output elasticities for each individual country. This is very important to understand the dynamic impact of renewable energy consumption on output across the sample countries. The long-run output elasticities are estimated using the FMOLS model and results are displayed in Table 8. The long-run elasticities of output with respect to renewable energy was inelastic, with a

Table 6
Panel data analysis of long-run output elasticities.

Variable	DOLS		FMOLS	
	Coefficient	*t*-Statistic	Coefficient	*t*-Statistic
GFCF	0.440	31.585***	0.395	30.154***
LF	0.144	2.753***	0.185	33.764***
REC	0.101	15.239***	0.109	10.795***
NREC	0.280	10.592***	0.277	30.588***
R-squared	0.999		0.998	

Notes: DOLS and FMOLS are the ordinary least square, dynamic and fully modified ordinary least square methods, respectively.
*** Denotes the significance level at 1%.

Table 7
Heterogeneous panel causality test.

Null Hypothesis:	Zbar-Stat.	Prob.
GFCF does not homogeneously cause Y	−1.288	0.198
Y does not homogeneously cause GFCF	2.829***	0.005
LF does not homogeneously cause Y	−0.280	0.780
Y does not homogeneously cause LF	3.583***	0.000
REC does not homogeneously cause Y	−0.333	0.740
Y does not homogeneously cause REC	0.189	0.850
NREC does not homogeneously cause Y	1.733*	0.083
Y does not homogeneously cause NREC	−1.329	0.184

* Denotes rejection of null hypothesis at 10% significance levels.
*** Denotes rejection of null hypothesis at 1% significance levels.

Table 8
Long-run output elasticities using FMOLS Models (Dependent variable: Output).

Variable	GFCF	LF	REC	NREC	Constant	R^2	Adjusted R^2
Australia	0.089	0.624**	−0.010	0.695***	13.732***	0.996	0.996
Austria	0.644***	0.897***	0.171**	0.238***	−3.928	0.988	0.987
Belgium	0.423***	0.554	0.013	0.286***	7.292	0.987	0.986
Brazil	0.349***	0.993***	−0.008	−0.069**	0.478	0.996	0.995
Bulgaria	0.235***	0.340	0.220***	−0.129	13.362***	0.930	0.926
Canada	0.082	1.078***	0.222**	0.574***	5.066***	0.993	0.993
Chile	0.080**	0.548***	0.118***	0.518***	14.639***	0.997	0.997
China	0.383***	2.207***	0.260***	0.088	−29.114***	0.999	0.999
Czech Rep.	0.613***	−4.440***	0.165***	−0.079	79.153***	0.959	0.957
Denmark	0.297***	−0.183	0.069***	−0.057*	21.493***	0.996	0.996
Finland	0.301***	2.929***	0.283***	0.369***	−25.506***	0.971	0.970
France	0.253***	1.398***	0.117***	0.451***	−3.711***	0.990	0.989
Germany	0.391***	0.270	0.150***	0.801***	10.755	0.980	0.979
Greece	0.331***	−0.103	0.154***	0.416	19.204*	0.950	0.948
India	0.541***	−0.056	−0.118*	0.451***	13.708***	0.997	0.997
Ireland	−0.030	1.133***	0.033	0.846***	10.718**	0.989	0.989
Israel	0.313***	0.804***	−0.061***	0.776***	6.145*	0.981	0.980
Italy	0.268***	−0.322*	0.170***	0.556***	24.789***	0.967	0.966
Japan	−0.301***	−0.354	0.041	0.688***	41.632***	0.859	0.852
Kenya	0.211***	0.324***	0.082***	0.212***	14.007***	0.995	0.995
Korea, Rep.	0.113**	5.739***	0.084***	−0.631***	−71.790***	0.996	0.995
Mexico	0.124***	0.278***	0.005	0.722***	18.026***	0.997	0.997
Morocco	0.409***	0.202	0.021*	0.289***	12.095***	0.993	0.993
Netherlands	0.214***	0.768***	0.071***	−0.028	9.381***	0.997	0.997
Norway	0.259***	0.595***	0.221***	0.475***	10.367***	0.978	0.976
Peru	−0.060	0.435***	0.175**	0.714***	19.392***	0.995	0.994
Poland	0.185**	−3.387***	0.351***	−0.572***	78.552***	0.986	0.985
Portugal	0.126***	1.568***	0.025**	−0.011	−1.492	0.989	0.989
Romania	0.348***	−0.731***	0.100**	0.093**	28.497***	0.981	0.980
Slovenia	0.501***	1.785***	0.127	−1.064***	−13.654*	0.902	0.897
South Africa	0.452***	0.300**	−0.006	−0.036	10.249***	0.984	0.983
Spain	0.044	0.499***	0.066***	0.443***	17.205***	0.997	0.997
Sweden	0.673***	0.900*	0.043	0.378	−4.253	0.969	0.967
Thailand	0.168***	0.569***	−0.012	0.502***	11.237***	0.993	0.992
Turkey	0.173***	0.144	0.011	0.658***	19.248***	0.997	0.997
Ukraine	0.591***	1.562**	−0.162*	−0.765***	−13.697	0.924	0.920
United Kingdom	0.276***	0.507*	0.160***	0.533***	10.755*	0.994	0.994
United States	0.312***	2.134***	−0.072***	−0.675***	−15.543***	0.997	0.996

positive sign for Austria (0.171), Bulgaria (0.220), Canada (0.222), Chile (0.118), China (0.260), the Czech Republic (0.165), Denmark (0.069), Finland (0.283), France (0.117), Germany (0.150), Greece (0.154), Italy (0.170), Kenya (0.082), Korea Republic (0.084), Morocco (0.021), the Netherlands (0.071), Norway (0.221), Peru (0.175), Poland (0.351), Portugal (0.025), Romania (0.100), Spain (0.066) and the United Kingdom (0.160). For these countries, the renewable energy consumption had a significant positive effect on economic growth in the long-run. These findings suggest that higher renewable energy consumption in these countries will generate greater economic output. From these results, we can infer that these countries were moving towards sustainable economic growth in the long-run. In most cases, employment elasticities are high compared to capital. These countries are Austria, Canada, Chile, China, Finland, France, Kenya, Korea, Netherlands, Peru, Portugal, Slovania, Spain, United Kingdom. These reflect deployment of renewables is associated with long-run job creation.

However countries such as India (−0.118), Ukraine (−0.162), the US (−0.072) and Israel (−0.061), the long-run output elasticities were statistically significant but had negative coefficients, implying that the increase in renewable energy consumption led to a decrease in output growth. Our findings suggest that these countries may continue to use non-renewable energy sources for future growth process.

For eleven countries- Australia, Belgium, Brazil, Ireland, Japan, Mexico, Slovenia, South Africa, Sweden, Thailand and Turkey we could not establish renewables energy as a significant driver of the economic growth process. Deployment of renewables was in early stage for these countries. In general, the elasticity values for real GDP to renewable energy consumption are low compared to other studies by [14] for Eurasia, and by [15] for Central American countries as a whole. Our findings highlight a great degree of heterogeneity across countries in deployment of renewable energy sources in their energy mix. From these results, we can draw important policy implications. For these eleven countries renewable energy consumption had no significant positive impact on economic output; rather it appeared to have pulled down their economic activities. This might be due to the fact that these countries were not able to make use of renewable energy sources more effectively in the production process to enhance economic output. Therefore, we would advise the policy makers of those countries to develop more effective policies towards promoting the generation and use of renewable energy which ensures the steady sustainable economic development with low carbon emissions.

6. Conclusions and policy implications

The worldwide attention towards sustainable development has accelerated renewable energy consumption in recent decades. High and volatile energy prices, and the geopolitical debate surrounding fossil fuel use will accelerate the development and market accessibility for renewable energy by various governments. This paper estimates the possible effect on economic growth of renewable versus non-renewable energy sources across countries.

Using heterogeneous panel estimation techniques, we established the long-run dynamics of real GDP with traditional and energy related inputs for 38 renewable energy-consuming countries following the RECAI indices developed by the Ernst &

Young Global Limited. We chose the time period between 1991 and 2012, covering the period when most of the renewable initiatives have been implemented across countries. The analysis uncovers cross-sectional dependence across the countries. Analysing the long-run output elasticities, we segregate our selected countries into three major groups.

Within the first group of countries, we established renewable energy sources as a significant driver in economic growth. These countries are for Austria, Bulgaria, Canada, Chile, China, the Czech Republic, Denmark, Finland, France, Germany, Greece, Italy, Kenya, Republic of Korea, Morocco, the Netherlands, Norway, Peru, Poland, Portugal, Romania, Spain and the United Kingdom. In most of these countries, significant shift towards renewables occurred during our study period. For example in China, renewable energy deployment is supported by the Renewable Energy Law (REL) [38] of 2005 and its 2009 amendment. The National Development and Regulation Commission (NDRC) [28] and the National Energy Agency (NEA) [39] are responsible in setting targets at the central and regional/local levels. Out of these countries, shift from non-renewables to renewables is very prominent in Bulgaria, China, Czech Republic, Denmark, Greece, Korea, Netherlands, Poland and Portugal in the long run. For many of these countries, deployment of renewables is creating jobs in the economy.

In the second group, we found renewable energy sources had a negative effect on economic growth of five countries – India (−0.118), Ukraine (−0.162), the United States (−0.072) and Israel (0.061). We highlight here characteristics in energy-mix from some of these countries, which may cause slow deployment process with an adverse effect on economic growth. For example, the Indian energy sector is predominantly coal-based (69%), with 5% non-hydro renewables and 12% hydropower. Financing and coordination between renewable resource rich states (Tamil Nadu, Gujarat and Rajasthan) and the rest of the country are major challenges for grid-integration purposes. Ukraine is rich in natural resources and a gateway to Russia's gas supply to Europe; but renewables energy constitutes only 3% of its energy supply. In the United States, coal and natural gas combined supplies 67% of total energy. Israel has a predominantly hydrocarbon-led energy sector, with statistics from the Israel Electric Corporation (2009) [40], showing 6% of electricity production from coal, and 33% from natural gas and diesel. A close look in their energy-mix and current status of renewable energy sources suggest replacing non-renewable with renewable sources may jeopardise economic growth. These countries should follow a gradual process for deployment.

Finally, for eleven countries – Australia, Belgium, Brazil, Ireland, Japan, Mexico, Slovenia, South Africa, Sweden, Thailand and Turkey – we could not establish that renewable energy sources would be a significant driver of or barrier to economic growth. One possible explanation for the result for these countries is that they have not been able to make use of renewable energy sources effectively in the production process, and it therefore has almost no impact on the economic output. Therefore, policy advisers of these countries should focus on investing renewable energy effectively so the increase in demand for energy consumption from various economic activities can make use of renewable energy sources. This has been happening in recent years in most of these countries.

For example, Australian government has set the Renewable Energy Target (RET) [41] both in large-scale (wind, hydro) and small-scale (solar) projects schemes, so that about 23.5% of Australia's electricity will be generated from renewables by 2020. Turkey has developed the National Renewable Energy Action Plan in achieving 30 per cent of its total installed capacity from renewable sources by 2023. In June 2015, Brazil signed a treaty with the US in increasing renewable energy sources to 20% by 2030 (IRENA, 2015) [42]. Belgium has targeted to have 13% power from renewables by 2020, up from 2% in 2005. Ireland's target is 20% renewables power by 2020, while Japan's target is to have 22–24% power from renewables post-2020. Sweden has targeted to have at least 50% renewables by 2020. In most cases, these countries are largely dependent on international trade. Therefore, low-carbon energy-mix will have no significant detrimental effect on economic growth.

The deployment of renewables has increased in the last two decades for most of the countries. The effects of renewable deployment are different across countries due to many factors as discussed in various reports by international bodies.[12] Our findings support the heterogeneity across countries in their stages of deployment process and the role of renewable energy in influencing the economic growth process.

We highlight some limitations of our model in explaining the economic growth process considering renewables as an energy source. While the deployment of renewables depends on many factors within and across countries, it is important to take a long-term view of the deployment process considering cost, efficiency, infrastructure, regulatory barriers, and institutional structure of any country. For example, the integration of renewables with the grid is a major challenge as the grids are largely built to cater for fossil fuel generated baseload electricity. This has been emphasised in [47]. There is strong regulation perceptions, acting as a barrier for increase in renewable investment [48].We do not consider these factors which may directly or indirectly affect economic growth due to renewable deployment.[13] Further, we could not include disaggregated data within the renewables due to unavailability of data for long period of time.

Creating an investment climate, developing human expertise, and removing financial and political barriers are some of the major steps towards deployment of renewables, and most of the OECD and some non-OECD countries have been engaged in this process. On the financial side, feed-in tariffs, establishing quota, investment subsidies, tax or credit incentives, sales tax exemptions for solar cells, and green certificate trading are major instruments followed for deployment purposes. On the policy side, governments, energy planners, international cooperation agencies, utilities, and associated bodies must act together in implementing strategies for renewable deployment across countries.

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