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The relationship between energy prices, economic growth and renewable energy consumption: Evidence from Europe

Raymond Li [a,*], Guy C.K. Leung [b]

[a] University of Canberra, Australia
[b] Harvard University, United States of America

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ABSTRACT

This paper revisits the renewable energy-economic growth nexus in seven European countries for the 34-year period of 1985–2018. As the data is in annual frequency, panel data methodologies are employed to benefit from increased explanatory power of the econometric analysis. Electricity generation share weighted price indexes of coal and natural gas are included in a demand specification together with real GDP in explaining renewable energy consumption. Long-run causality is found to flow from all three explanatory variables to renewable energy consumption. Short-run causality is also detected from the two fossil fuel prices to renewable energy consumption. Our results provide empirical support to the important role of economic growth and non-renewable energy prices in the renewable energy transition. On the other hand, renewable energy consumption, capital and labour enter a production equation in determining economic output. The findings show no evidence of Granger causality from renewable energy consumption to economic output.

1. Introduction

This paper revisits the relationship between renewable energy consumption and economic growth (thereafter, the RE-Y nexus), with a specific emphasis on the role of fossil energy prices in determining renewable energy consumption in seven OECD Europe countries. This paper is motivated by the ambiguity in the findings of previous studies on the topic, and more importantly, the lack of studies that control for coal and natural gas prices in analysing the RE-Y nexus. As coal and natural gas are main fossil fuel choices in electricity generation, the competition between these fuels and renewable sources implies the potential influence that the price of these fuels may have on renewable energy production and consumption (IRENA, 2019). In addition to the key hypotheses being tested extensively in the RE-Y nexus literature, this paper aims to address a key research question: "do coal and natural gas prices affect renewable energy consumption?" We adopt panel data econometric techniques to help uncover the missing evidence on this often-overlooked aspect of the RE-Y nexus.

In comparison to the previous studies in the literature, this paper makes the following contributions. First, this is the first paper in the area of RE-Y nexus that includes the price indexes of coal and natural gas as additional variables. Second, rather than using the price indexes as is, we take one step further to weight these price indexes by the respective shares of the fossil fuels in total electricity generation. This step is non-trivial as coal and natural gas are both used in electricity generation in the countries covered in this paper, but the electricity generation share of these fossil fuels are different in each country. Our share-weighted price indexes can help control for the different impacts of changes in coal and natural gas prices in each country. Third, while most studies in this area of research are based either on the demand or production specifications (with the exception of, for example, Luqman et al., 2019), this paper considers each of them separately, with each specification having its own distinct set of explanatory variables. Finally, our data file extends to year 2018, augmenting the literature with more up-to-date results in the field of renewable energy where changes and advances occur rapidly.

In order to curb greenhouse gases emissions and ensure sustainability, the European Union (EU) has put in place directives to promote renewable energy uses in its constituent member countries. The Renewable Energy Directive 2009 (Directive 2009/28/EC) enacted a general target of 20% renewable share in total final energy consumption by year 2020 as well as targets for individual countries. According to data from Eurostat, the EU overall is on course to meeting the target, with renewable's share increasing from 12.6% in 2009 to 18% in 2018. The most significant improvement in renewable's share can be found in the electricity generation sector, where the share climbed from 19%

* Correspondence to: Canberra School of Politics, Economics & Society, University of Canberra, Bruce ACT 2617, Australia.
E-mail address: Raymond.Li@canberra.edu.au (R. Li).

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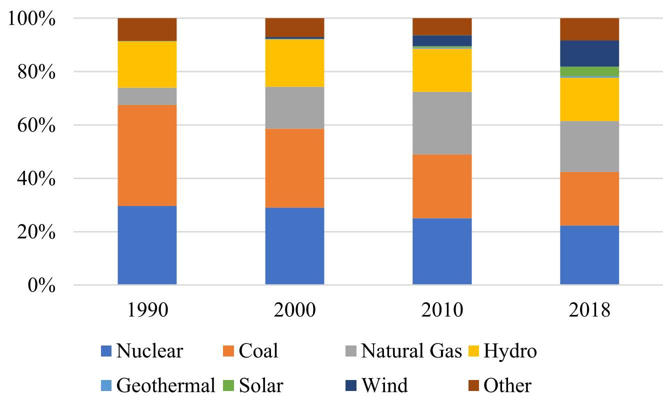

Fig. 1. OECD Europe electricity generation share.
Source: Data Source: IEA Electricity Information 2019.

to 32% within this nine-year period. In 2018, 19.7% of heating and 8% of transportation energy came from renewable sources.

While most EU countries have achieved an increasing share of renewable energy in total final energy consumption, their pathways towards the EU directive goal are far from identical. Some countries have already exceeded their targets (e.g. Sweden, Finland, Denmark, Estonia, etc.) and some are still catching up (e.g. France, Germany, Spain, Netherlands, etc.). Disparity in technology diffusion and differences in equipment stocks and infrastructure are some possible reasons for the dissimilarity in pathways, especially in the transportation and heating sectors. Renewable's share in electricity generation is also very different across the EU countries, but the share has generally been rising across the board through the years. This rising share necessarily means some degree of substitution away from fossil fuel (or nuclear) to renewable sources in electricity generation. Comparing the 2010 and 2018 data in Fig. 1, it is evident that the share of coal and natural gas in electricity generation in OECD Europe have both decreased. Solar, wind and geothermal's share has significantly increased and hydro's share remained rather stable.

Year 2020 will not see the end of EU's effort in promoting renewable energy. In December 2018, the EU has put forward a new Renewable Energy Directive (2018/2001), setting a target of 32% total final energy consumption from renewable sources by 2030. Electricity generation and heating are among the biggest sectors where renewable energy sources can technically and economically compete with non-renewables, and where there is still substantial growth potential. According to a forecast by the International Energy Agency (IEA, 2019), renewable's share in electricity generation and heat production can reach up to 65% and 35% by 2040, respectively.

In the electricity generation sector, coal and natural gas are major competitors to renewable sources. Natural gas also competes with renewables in heating. Apart from technological advancements, an important factor that can influence the renewable energy transition is the price of the competing fossil fuels. The influence can come about entirely as a consequence of economic or business decisions, without the need for government intervention. For example, a rise in fossil fuel prices (especially in the long term) creates a disincentive and can hinder investments on fossil fuel-based projects, possibly relocating the fund to renewables (Knopf et al., 2015). In the shorter term, fossil fuel prices may also affect the economic dispatch of electricity, leading to some substitution away from coal and natural gas generation.

We expect the prices of fossil fuels will have stronger impact on renewable energy consumption if fossil fuels take up a larger share of electricity generation. So rather than estimating the effects of coal and natural gas prices on renewable energy consumption directly, the prices are weighted by the electricity generation share of coal and natural gas. As we will see in Section 2, there is a lack of studies in the existing literature that analyse the RE-Y nexus controlling for the prices of non-renewable energy sources that compete with renewable energy, and this paper aims to fill this research gap in the literature. The contribution of this paper does not only rest on augmenting the existing literature on the renewable energy-economic growth nexus with additional and more up-to-date results on seven European countries, but more importantly, it also highlights the significance of fossil fuel prices in renewable energy transition — something that is often mentioned but not empirically tested.

The rest of this paper is organized as follows. Section 2 reviews the literature. Section 3 briefly discusses the econometric methodologies and Section 4 presents the results. Section 5 further discusses the results and concludes.

2. Literature review and contextual linkage

A growing number of researchers have devoted their effort in examining the RE-Y nexus. Drawing on a long thread of research in the related energy-economic growth nexus literature, much of the renewable energy-economic growth literature have also focused on finding empirical evidence for the *growth*, *conservation*, *feedback*, and *neutrality* hypotheses. The extensive literature on the RE-Y nexus comprises studies covering time periods as far back as 1960 and as recent as 2019. Table 1 provides a summary of the recent studies.

Some of these studies have a focus on specific geographical regions or countries including Asia (Rahman and Velayutham, 2020; Luqman et al., 2019; Shahbaz et al., 2015; Azlina et al., 2014; Fang, 2011; Tiwari, 2011), Europe (Kasperowicz et al., 2020; Can and Korkmaz, 2019; Soava et al., 2018; Saad and Taleb, 2018; Alper and Oguz, 2016; Uçan et al., 2014; Magnani and Vaona, 2013; Ocal and Aslan, 2013; Menegaki, 2011), North America (Cevik et al., 2020; Shahbaz et al., 2018; Troster et al., 2018; Bilgili, 2015; Sari et al., 2008), South and Central America (Al-Mulali et al., 2014; Apergis and Payne, 2011a), Africa (Maji et al., 2019; Mbarek et al., 2018; Brini et al., 2017; Hamit-Haggar, 2016; Ozturk and Bilgili, 2015), and a mix of countries (Amri, 2017; Apergis and Payne, 2011b). Other studies concentrate on the stage of economic development or economic cooperation regions, for example: OECD (Alam and Murad, 2020; Aydin, 2019; Inglesi-Lotz, 2016; Bozkurt and Destek, 2015; Kula, 2014; Salim et al., 2014; Apergis and Payne, 2010), G7 (Tugcu and Topcu, 2018; Chang et al., 2015; Apergis and Payne, 2011b), APEC (Zafar et al., 2019), ASEAN (Tuna and Tuna, 2019), MENA (Kahia et al., 2017), and emerging economies and newly industrialized countries (Banday and Aneja, 2020; Destek and Aslan, 2017; Destek, 2016; Sadorsky, 2009).

The above studies either examine single countries as time-series or group of countries as a panel. The most commonly employed methods include autoregressive distributed lags (ARDL), vector autoregression (VAR), Granger causality, cointegration, and vector error correction (VEC). The resulting empirics paint a mixed picture of causal relationships, leading to the following remarks. First, the majority of studies have found causal relationships in at least one direction, and the neutrality hypothesis (i.e. no causal relationship) is the least popular. Second, the causality from renewable energy consumption to economic growth is maintained in all studies with a focus on Africa.[1] Third, the results are sensitive to the choice of additional explanatory variables other than renewable energy consumption and

[1] Note, however, that Maji et al. (2019) find that renewable energy consumption slows down economic growth in West African countries.

Table 1
Summary of previous studies.

Author	Period	Country/Region	Key methodology	Key Causality/Findings
Alam and Murad (2020)	1970–2012	25 OECD	Panel cointegration	Y → RE in LR
Rahman and Velayutham (2020)	1990–2014	5 south Asian countries	Panel causality	RE → Y in LR; Y → RE in SR
Fan and Hao (2020)	2000–2015	China	VEC	No causality between RE and Y
Kasperowicz et al. (2020)	1995–2016	29 European countries	Panel VEC	RE → Y
Soava et al. (2018)	1995–2015	28 EU countries	Cointegration	RE → Y
Cevik et al. (2020)	1973–2019	USA	Markov-switching VAR	No causality between RE and Y
Banday and Aneja (2020)	1990–2017	BRICS	Bootstrap panel causality	Mixed for different countries
Koengkan and Fuinhas (2020)	1980–2014	5 Mercosur countries	Panel VAR	RE ↔ Y
Can and Korkmaz (2019)	1990–2016	Bulgaria	ARDL bounds test	Mixed
Aydin (2019)	1980–2015	26 OECD	Panel causality	RE ↔ Y
Luqman et al. (2019)	1990–2016	Pakistan	Nonlinear ARDL	RE → Y
Maji et al. (2019)	1995–2014	15 West African Countries	Panel cointegration	RE → Y
Ozcan and Ozturk (2019)	1990–2016	17 emerging countries	Bootstrap panel causality	No causality between RE and Y
Tuna and Tuna (2019)	1980–2015	ASEAN-5	Symmetric and asymmetric causality	No causality between RE and Y
Zafar et al. (2019)	1990–2015	APEC	Panel VEC	Y ↔ RE
Shahbaz et al. (2018)	1960–2016	USA	ARDL bounds testing	Y ↔ RE
Mbarek et al. (2018)	1990–2015	Tunisia	VEC	RE → Y in SR
Saad and Taleb (2018)	1990–2014	12 EU Countries	Panel VEC	Y → RE in SR; RE ↔ Y in LR
Troster et al. (2018)	1989–2016	USA	Quantile autoregression	RE ↔ Y
Tugcu and Topcu (2018)	1980–2014	G7 Countries	ECM; asymmetric causality	Mixed for different energy proxies
Amri (2017)	1990–2012	72 countries	Dynamic simultaneous equation	RE ↔ Y
Kahia et al. (2017)	1980–2012	MENA	Panel VEC	RE ↔ Y
Brini et al. (2017)	1980–2011	Tunisia	ARDL; cointegration	RE → Y in LR; Y → RE in SR
Destek and Aslan (2017)	1980–2012	17 Emerging Economies	Bootstrap panel causality	Mixed for different countries
Alper and Oguz (2016)	1990–2009	New EU Member Countries	Asymmetric causality	RE → Y
Inglesi-Lotz (2016)	1990–2010	34 OECD countries	Panel cointegration	RE → Y
Hamit-Haggar (2016)	1971–2007	11 sub-Saharan African Countries	Panel VEC	RE → Y
Destek (2016)	1971–2011	Newly Industrialised Countries	Asymmetric causality	Mixed for different countries
Bilgili (2015)	1981–2013	USA	Wavelet analysis	RE → Y
Bozkurt and Destek (2015)	1980–2012	4 OECD	Toda–Yamamoto causality	RE → Y in more developed countries
Ozturk and Bilgili (2015)	1980–2009	51 Sub-Sahara African Countries	Panel cointegration	RE → Y
Shahbaz et al. (2015)	1972–2011	Pakistan	ARDL	RE ↔ Y
Chang et al. (2015)	1990–2011	G7 countries	Panel Granger causality	RE ↔ Y
Al-Mulali et al. (2014)	1980–2010	18 Latin American Countries	Panel VEC	RE ↔ Y
Azlina et al. (2014)	1975–2011	Malaysia	VEC	Y → RE
Kula (2014)	1980–2008	19 OECD Countries	Panel cointegration	Y → RE
Uçan et al. (2014)	1990–2011	15 EU Countries	Panel cointegration	RE ↔ Y
Salim et al. (2014)	1980–2011	OECD Countries	Panel VEC	RE ↔ Y
Magnani and Vaona (2013)	1997–2007	Italy	Panel VEC	RE → Y
Ocal and Aslan (2013)	1990–2010	Turkey	Toda–Yamamoto causality	Y → RE
Apergis and Payne (2012)	1990–2007	80 Countries	Panel VEC	RE ↔ Y
Apergis and Payne (2011a)	1980–2006	6 Central American Countries	Panel VEC	RE ↔ Y
Apergis and Payne (2011a,b)	1990–2007	16 emerging market countries	Panel VEC	Y → RE in SR; Y ↔ RE in LR
Fang (2011)	1978–2008	China	Multivariate OLS	RE → Y
Menegaki (2011)	1997–2007	27 European Countries	Panel VEC	No causality between RE and Y
Tiwari (2011)	1960–2009	India	VAR	Y → RE
Apergis and Payne (2010)	1985–2005	20 OECD	Panel VEC	Y ↔ RE
Sadorsky (2009)	1994–2003	18 emerging market countries	Panel VEC	Y → RE
Sari et al. (2008)	2001–2005	USA	ARDL bounds test	Y → RE

GDP (or other measures of economic output). Fourth, although additional explanatory variables (e.g. capital, labour, financial development, trade openness, research and development, CO_2 emissions, non-renewable energy consumption, etc.) are included in the estimation of the causal relationship between renewable energy consumption and economic growth, few studies include energy prices. Finally, although not stated explicitly, a valuable contribution of Luqman et al. (2019), Troster et al. (2018) and Brini et al. (2017) hinges on their inclusion of the oil price as an additional control variable. This is not commonly done in the RE-Y nexus literature.

3. Methodology

Our econometric analysis aims to tease out the relationships among our variables with appropriate and feasible econometric modelling techniques. It entails four main steps. We first identify the panel unit-root characteristics, followed by testing the existence of long-run relationships by panel cointegration tests. The panel error-correction model (ECM) will be estimated if cointegration is found. Finally, we estimate short-run Granger causality among the variables. The econometric methods used in this paper are discussed in extensive details in the original publications. For the sake of brevity, Sections 3.2–3.5 will only illustrate the key aspects of our application of these methods.

3.1. Model framework

The estimation of the RE-Y nexus is typically done through either a demand or production model specification in the empirical literature. Cheng et al. (2021) provide a plausible theoretical framework for an economically meaningful interpretation of energy consumption–income causality regression results. Recognizing the role of renewable energy as an input to production processes and real GDP as a measure of an economy's output (and economic growth), we specify a production equation in the neoclassical economic growth framework, with renewable energy consumption alongside the usual capital and labour inputs to analyse the potential impact that renewable energy may have on real GDP:

$$Y_{it} = f(K_{it}, L_{it}, RE_{it}) \quad (1)$$

where Y_{it} represents real GDP of country i in time period t, K is capital input, L is labour input and RE is renewable energy input. On the other hand, a demand specification focuses on the influence that income (i.e. real GDP), price of coal and price of natural gas may have on the consumption of renewable energy. We specify our demand equation as follows:

$$RE_{it} = f(Y_{it}, PC_{it}, PG_{it}) \quad (2)$$

where PC is the price of coal and PG is the price of natural gas. This formulation can help shed light on the income and substitution effects of renewable energy consumption. Eqs. (1) and (2) will form the basis of our econometric models in this paper.

3.2. Panel unit-root tests

We employ the Pesaran (2007) and Breitung and Das (2005) tests for panel unit root. As the asymptotic properties of both tests are based on $T \to \infty$ followed by $N \to \infty$ (where T and N refers to the size of the time and cross-section dimensions, respectively), these tests are appropriate for our study as we have a panel with $T > N$. Most panel unit root tests are based on a panel version of the Dickey–Fuller regression:

$$\Delta y_{it} = \rho_i y_{it-1} + D'_{it}\omega + \varepsilon_{it} \quad (3)$$

where D'_{it} represents the exogenous variables (including the fixed effects and individual trend terms) and ε_{it} is the error term. Pesaran (2007) augments the panel Dickey–Fuller regression by cross-section averages of lagged levels and first-differences of the individual series to eliminate the potential influence of cross-sectional dependence in the panel. Instead of augmenting the panel ADF regression, Breitung and Das (2005) propose a robust version of the panel Dickey–Fuller test statistic under contemporaneous correlated errors. The Pesaran test allows for variations in the individual unit root processes (ρ_i), while the Breitung and Das test assumes a common unit root process, i.e. $\rho_i = \rho$ for all i.

3.3. Panel cointegration tests

The Pedroni (2004) residual-based and Westerlund (2007) error correction-based tests are adopted to detect cointegration in the data. The Pedroni test collects predicted residuals from a cointegration regression:

$$y_{it} = \sigma_i + \vartheta_i t + \beta_{1i}x_{1i} + \cdots + \beta_{ki}x_{ki} + e_{it} \quad (4)$$

where $x_{1it}, \ldots, x_{kit}$ are k regressors and e_{it} is the residual. The predicted residuals ($\hat{e}_{it}$) are then fitted to a Dickey–Fuller regression model:

$$\hat{e}_{it} = \mu_i \hat{e}_{it-1} + \upsilon_{it} \quad (5)$$

Pedroni (2004) proposes three "group mean" tests that allow μ_i to vary across the panel, and four "panel" tests assuming $\mu_i = \mu$ to test for stationarity of the residuals (i.e. existence of cointegration) in Eq. (5).

The Westerlund (2007) test examines the following error correction model (ECM):

$$\Delta y_{it} = \delta_i' d_t + \alpha_i (y_{it-1} - \beta_i' X_{it-1}) + \sum_{j=1}^{p_i} \eta_{ij} \Delta y_{it-j} + \sum_{j=-q_i}^{p_i} \Psi_{ij}' \Delta X_{it-j} + \phi_i + \upsilon_{it} \quad (6)$$

where d is a vector of deterministic components (e.g. the intercept and trend), X is a vector of explanatory variables, ϕ is a vector of fixed effects, and υ is a vector of random errors. If the error correction term (α) is statistically negative, error correction is said to exist, implying y and X are cointegrated. As in the Pedroni test, Westerlund (2007) also proposes different versions of the test statistics, where the two "group mean" tests do not assume equality of α_i across the panel while the two "panel" tests do.

3.4. Long-run equilibrium modelling

In the error correction framework, long-run Granger causality implies that the dependent variable (y) will adjust to disequilibrium caused by changes in the regressors (X) in the long-run. While cointegration confirms that y will adjust to disequilibrium in the system, we also need to examine the statistical significance of each of the coefficients in the long-run equation to infer long-run Granger causality from a specific element in X to y. On detection of cointegration under the model specifications of Eq. (1) and/or (2), we will estimate an error-correction model with the pooled mean group (PMG) estimator proposed by Pesaran et al. (1999). The PMG estimator restricts the long-run coefficients (α_i and β_i) to be equal across the panel but allows the deterministic components (δ_i) and short-run coefficients (η_{ij} and Ψ_{ij}) to differ. In comparison to the mean group (MG) estimator that assumes both heterogeneous long-run and short-run coefficients, PMG is the efficient estimator if the long-run coefficients are indeed homogeneous. However, if the long-run coefficients are heterogeneous, then the PMG estimator will be inconsistent. The MG estimator is inefficient under long-run homogeneity, but it is always consistent. To examine the validity of the homogeneity assumption, we obtain the MG estimates and compare the long-run coefficients with the Hausman (1978) test.

3.5. Short-run Granger causality test

Dumitrescu and Hurlin (2012) propose a test for homogeneous Granger non-causality between two variables in a panel data VAR model:

$$y_{it} = a_i + \sum_{m=1}^{M} \pi_i^m y_{it-m} + \sum_{m=1}^{M} \theta_i^m x_{it-m} + u_{it} \quad (7)$$

where x and y are stationary variables. Coefficients π and θ can differ across the ith country of the panel. The lag length (M) is chosen by the Akaike Information Criterion. The null hypothesis of Granger non-causality is tested against the alternative hypothesis that some members of the panel exhibit Granger causality:

$$H_0: \theta_i = 0 \quad \forall i = 1, \ldots, N$$
$$H_1: \theta_i = 0 \quad \forall i = 1, \ldots, N_1$$
$$\theta_i \neq 0 \quad \forall i = N_1 + 1, N_1 + 2, \ldots, N$$

where $N_1 \in [0, N - 1]$ is unknown and $N_1 \leq N$. If $N_1 = N$, there is no Granger causality for any individual country in the panel. Conversely, if $N_1 = 0$, there is Granger causality for all countries.

4. Data and empirical results

4.1. Data

Our data file consists of six variables for seven OECD countries in Europe (Germany, Italy, Netherlands, Poland, Spain, Turkey, and United Kingdom), spanning the period of 1985–2018.[2] Similar to the Europe-focused studies of Kula (2014) and Saad and

[2] Our choice of country is determined by data availability for electricity generation shares of coal and natural gas in each country, which are used to weight the fossil fuel price indices.

Table 2
Electricity generation fuel share (2019).

	Natural gas	Coal	Nuclear	Renewables	Other
Germany	14.86%	27.96%	12.26%	36.59%	8.33%
Italy	44.55%	10.45%	0.00%	23.82%	21.17%
Netherlands	58.67%	14.39%	3.23%	18.41%	5.31%
Poland	9.02%	74.37%	0.00%	14.09%	2.52%
Spain	31.17%	4.75%	21.19%	28.10%	14.79%
Turkey	18.84%	37.14%	0.00%	14.70%	29.32%
UK	40.92%	2.13%	17.36%	35.02%	4.58%
Total Europe	19.23%	17.49%	23.25%	20.95%	19.07%

Taleb (2018), data availability is a key factor determining our choice of countries. However, this set of countries offers a good panel for the purpose of this study. A novel aspect of our paper is the inclusion of the electricity generation share-weighted coal and natural gas price indexes in the renewable energy consumption model (Eq. (2)). The rationale for the inclusion of these variables stems from the expected differing impact that coal and natural gas prices can have on renewable energy consumption for different countries with different electricity generation fuel mixes. Our empirical estimation will benefit from a panel of countries with heterogeneous fuel mixes as this provides more variation in the dataset. Table 2 presents the electricity generation fuel shares of each country in 2019. Although all seven European countries in the panel belong to the OECD, these countries paint a diverse picture in terms of the level of economic development, with the Netherlands and Germany leading, and Turkey and Poland lagging behind. To analyse this diversified panel, we have selected econometric techniques that allows for heterogeneity among individual countries. We believe this should at least partly remedy the problem of heterogeneity and produce plausible results.

Our renewable energy consumption (*RE*) and electricity generation shares are derived from BP's 2019 Statistical Review of World Energy data file. We obtain the OECD Europe price indexes for coal and natural gas from the IEA Energy Prices and Taxes database to track the general price levels in Europe. These indexes are then multiplied by each country's electricity generation share of coal and natural gas to generate the influence-weighted price series of coal (*PC*) and natural gas (*PG*). The data for real GDP (*Y*) is acquired from the International Monetary Fund. Finally, the fixed gross capital formation (*K*) and labour force (*L*) data are from World Bank's World Development Indicators databank. To ensure consistency in the cross-section dimension of the data, the variables *RE*, *Y*, *K* and *L* are converted to per capita basis with population data from the World Bank. All data enter the econometric estimations in natural logarithms. Summary statistics for each country are shown in Table 3.

4.2. Panel unit root

Table 4 reports the test statistics of the Pesaran and Breitung and Das tests. Both tests rejects the null hypothesis of unit root for all first differenced variables, eliminating the possibility that any variable is *I*(2). While the Breitung and Das test does not reject the null hypothesis for any variables in level, the Pesaran test rejects the null hypothesis for *PG*. We conclude that all the variables in our dataset are stationary only in first-difference, with the exception that *PG* can potentially be stationary in levels.[3]

[3] Due to the ambiguity of the unit root property of *PG*, we further performed a de-meaned Im et al. (2003) unit root test on the variable. The test suggests stationary in first-difference for the variable.

Table 3
Summary statistics.

		RE	*Y*	*PC*	*PG*	*L*	*K*
Germany	Mean	0.15	37 558.82	30.80	7.15	59.01	6711.92
	S.D.	0.18	5308.90	14.28	4.12	0.99	586.89
Italy	Mean	0.08	33 733.02	9.64	25.51	48.50	5477.16
	S.D.	0.09	2987.16	6.12	16.88	0.80	679.90
Netherlands	Mean	0.08	40 535.75	17.52	38.11	62.39	7372.28
	S.D.	0.07	6831.70	8.92	13.16	3.02	1115.18
Poland	Mean	0.03	16 373.32	59.55	1.65	56.94	6573.27
	S.D.	0.04	5918.27	30.33	1.83	2.21	2093.00
Spain	Mean	0.12	28 962.80	15.50	12.26	54.84	4548.70
	S.D.	0.14	4981.20	5.71	12.05	3.75	901.00
Turkey	Mean	0.01	15 026.75	20.16	24.12	50.21	3317.09
	S.D.	0.03	4656.06	10.79	16.94	3.36	1559.43
UK	Mean	0.07	33 175.31	21.20	21.06	61.69	4470.83
	S.D.	0.10	5550.34	10.25	15.06	0.54	582.19

Notes: *RE* is in tonnes of oil equivalent per person; *Y* is GDP in 2011 international dollar per person; *L* is number of workers per 100 persons; *K* is gross fixed capital formation in constant LCU per person

Table 4
Panel unit root results.

Variable	Pesaran		Breitung and das	
	Level	1st Diff	Level	1st Diff
RE	−2.174	−3.515***	0.403	−2.775***
Y	−2.081	−3.472***	0.955	−6.094***
PC	−2.340	−5.131***	0.652	−5.736***
PG	−3.073***	−5.480***	1.457	−1.402*
K	−1.185	−3.393***	−0.754	−4.357***
L	−2.543	−4.447***	2.286	−4.372***

Notes:
*Denote rejection of H_0 at 10% significance.
***Denote rejection of H_0 at 1% significance.

4.3. Panel cointegration and long-run causality

To detect cointegration in our data series, we perform both the Pedroni (2004) and Westerlund (2007) tests, with renewable energy consumption and real GDP entering these tests as the dependent variable in turn. In the *RE* equation, *Y*, *PC* and *PG* are included; in the *Y* equation, *RE*, *K* and *L* are included, thus covering the demand and production model specifications separately. In order to allow for heterogeneity within the panel, we consider the group mean statistics of the Pedroni test and the group mean version of the Westerlund test. The number of lags in both tests are determined by the Akaike Information Criterion. The panel cointegration results are displayed in Table 5. For the demand specification (dependent variable = *RE*), both the Group-rho and Group-ADF statistics reject the null hypothesis of no cointegration while the Group-PP statistics does not. Evidence of cointegration is found with the Westerlund G_τ statistic but not the G_α statistic. As the G_τ statistic has higher power and less size distortion than the G_α statistic (Westerlund, 2007), it is not surprising that we only find cointegration with the G_τ statistic with our relatively small sample. Turning to the production specification (dependent variable = *Y*), all five test statistics under consideration unequivocally suggest the absence of cointegration among the variables. As there is no evidence of cointegration in the production specification, we may conclude that there is no long-run causality from renewable energy consumption, capital or labour to economic growth.

Since long-run causality is found in the *RE* equation, we estimate an error correction model with 2 lags in the format of Eq. (6) by the PMG estimator with *RE* as the dependent variable and *Y*, *PC* and *PG* as explanatory variables. The Hausman specification test

Table 5
Panel cointegration results.

Pedroni	Dependent variable = *RE*		Dependent variable = *Y*	
	Statistic	*p*-value	Statistic	*p*-value
Group-rho	1.812	0.035	1.142	0.127
Group-PP	0.968	0.167	−0.536	0.296
Group-ADF	1.475	0.070	0.510	0.305
Westerlund	Statistic	*p*-value	Statistic	*p*-value
G_τ	−2.617	0.009	−2.052	0.188
G_α	−2.399	0.989	−2.312	0.813

Table 6
Long-run estimates of the *RE* equation.

Coefficient	Estimate	Std. error	p-value
α	−0.215	0.054	0.000
β_Y	1.544	0.567	0.006
β_{PC}	0.835	0.158	0.000
β_{PG}	0.757	0.078	0.000

yields a χ^2 statistics of 2.46 with a *p*-value of 0.483, confirming that PMG is both an efficient and consistent estimator. The results of the PMG estimation are shown in Table 6. As all the long-run coefficients (α, β_Y, β_{PC} and β_{PG}) are statistically significant, renewable energy consumption will adjust to disequilibrium in the long-run caused by changes in the explanatory variables of the system, corroborating the cointegration test results. In terms of causality interpretations, this indicates long-run causality from economic growth, price of coal and price of natural gas to renewable energy consumption. The size of the estimated error correction term is −0.215, which means on average 21.5% of a deviation from the long-run equilibrium will be eliminated in one year through changes in renewable energy consumption. As the data are in natural logarithm, the estimated β coefficients measure elasticities. The income elasticity (β_Y) of 1.544 suggests that a 1% increase in real GDP will lead to a 1.544% increase in renewable energy consumption on average in the long-run. This highlights the importance of economic growth as a driver of renewable energy consumption. The coefficient estimates for electricity generation share-weighted price indexes of coal and natural gas (β_{PC} and β_{PG}) are both positive, implying that a rise in fossil fuel prices will lead to an increasing use of renewable energy in the long-run, possibly through an incentive to substitute away from fossil fuel-based energy to renewable energy. Cross-price elasticities for coal (or natural gas) can be obtained by multiplying the estimated coefficient of β_{PC} (or β_{PG}) by the electricity generation share of coal (or natural gas) for a specific country. Therefore, the cross-price elasticity will be larger for countries with a higher share of these fossil fuels in electricity generation. Our findings of positive cross-price elasticities conform to the predictions of economic theories on substitutes.

4.4. Short-run Granger causality

As all variables in our study are susceptible of unit roots, we perform the Dumitrescu and Hurlin (2012) short-run Granger non-causality test in first differences. The z-bar statistic is more suitable to our study because we have a panel with more time periods than number of countries. Table 7 summarizes the short-run causality results for the demand and production equations. There is short-run causality from price of coal and price of natural gas to renewable energy consumption, and from labour input to real GDP. No short-run causality is found between renewable energy consumption and real GDP. As suggested by diligent reviewers, we also performed short-run Granger causality tests on individual countries in the panel to describe the own situation of each country. The results are reported in Appendix A. In the single-country setting, the null hypothesis of Granger non-causality cannot be rejected for most of the countries and causal directions. Since there are only 34 time periods for each country, we believe that the non-rejection of H_0 is due to a lack of power of the tests rather than genuine non-causality or differentiated results in the data. These results help justify the use of panel econometrics in analysing this dataset.

Table 7
Short-run panel causality results.

Causal direction	z-bar	p-value
$Y \to RE$	−1.080	0.280
$PC \to RE$	2.050	0.040
$PG \to RE$	2.080	0.038
$RE \to Y$	0.003	0.998
$K \to Y$	−0.173	0.863
$L \to Y$	2.249	0.025

5. Conclusions and policy implications

In this paper we revisited the relationship between renewable energy consumption and economic growth in a group of European countries. We estimated a demand equation with renewable energy consumption as the dependent variable and real GDP, price of coal and price of natural gas as explanatory variables. The price indexes of coal and natural gas are weighted by the share of these fossil fuels in electricity generation, controlling for their relative importance in the countries being studied. We found long-run causality from all three explanatory variables to renewable energy consumption, as well as short-run causality from the fossil fuel price indexes to renewable energy consumption. Economic growth is found to increase renewable energy consumption in the long-run with an income elasticity of 1.544 and 21.5% of the adjustment taking place in one year on average. On the other hand, no long-run causality can be detected from renewable energy consumption, capital or labour to real GDP. Short-run causality from labour input to real GDP is found.

Our results are generally in line with those from many previous studies focusing on European and OECD countries, which also found causality from economic growth to renewable energy consumption (e.g. Alam and Murad, 2020; Aydin, 2019; Saad and Taleb, 2018; Kula, 2014; Uçan et al., 2014; Salim et al., 2014; Ocal and Aslan, 2013; Apergis and Payne, 2010). These results underscore the significance of economic growth in supporting renewable energy consumption, especially in the developed economies.

The lack of causality from renewable energy consumption to real GDP indicates that promotion of renewable energy use will not stimulate economic growth. Unlike in developing countries where renewable energy can act as an instrument for improving the much-needed energy access and energy supply and hence economic output, the European countries included in this paper are generally developed. An increase in renewable energy may not necessarily lead to a significant augmentation of productive resources overall because renewable energy could have simply displaced fossil fuel-based energy. Therefore, while government policies like renewable obligations in the UK can be expected to increase renewable energy consumption, the same effect may not be expected on the macroeconomy. Of course, the countries included in this study are rather heterogeneous in terms of economic development. But taken together with those in the literature, e.g. Ocal and Aslan (2013) in the case of Turkey, our results suggest that governments in the less developed countries can at least look to the more developed neighbours when designing their macroeconomic and renewable energy policies.

Our findings of both short and long-run causality from coal and natural gas prices to renewable energy consumption confirms the substitution that takes place between renewable and non-renewable energy. The fact that short-run causality is found imply that fossil fuel prices may affect the procurement cost and economic dispatch of electricity. These results suggest that on top of setting consumption targets for renewable energy, which Europe already has in place, governments have other means to promote the use of renewable energy through fossil fuel prices. For example, taxes on fossil fuel use or carbon emissions are expected to increase the cost of fossil fuel usage, and these will help speed up the substitution from fossil fuel-based energy to renewable energy. Our results can also be seen as complementary to those of Brini et al. (2017) and Luqman et al. (2019) where no Granger causality is found between renewable energy consumption and the crude oil price. As crude oil products are primarily used in the transportation and industrial sectors, crude oil does not compete head-to-head against renewable energy sources at the same degree as coal and natural gas. Therefore, non-causality is not unexpected.

CRediT authorship contribution statement

Raymond Li: Conceptualization, Data curation, Formal analysis, Methodology, Writing - original draft, Writing - review & editing. **Guy C.K. Leung:** Conceptualization, Validation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Short-run Granger causality results for individual countries

	Germany	Italy	Poland	Spain	UK	Turkey	Netherlands
$Y \rightarrow RE$	0.155	0.347	0.210	0.834	0.012	0.358	0.725
$PC \rightarrow RE$	0.000	0.089	0.595	0.159	0.717	0.545	0.514
$PG \rightarrow RE$	0.526	0.453	0.000	0.086	0.014	0.485	0.145
$RE \rightarrow Y$	0.247	0.151	0.116	0.419	0.350	0.737	0.002
$L \rightarrow Y$	0.072	0.859	0.067	0.522	0.536	0.068	0.358
$K \rightarrow Y$	0.106	0.934	0.676	0.632	0.609	0.343	0.752

Notes: H_0: no Granger causality; p-values are shown

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.egyr.2021.03.030.

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