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ECONOMIC AND SOCIAL DRIVERS OF RENEWABLE ENERGY CONSUMPTION IN THE EUROPEAN UNION: AN ECONOMETRIC ANALYSIS[2]

Renewable energy aspires to boost decarbonisation and power the circular economy in accordance with the Green Deal objectives. The transition, however, faces many challenges and understanding the drivers behind it is essential. This paper analyses 27 European Union countries for the period 2008 – 2020 to identify economic and social determinants influencing renewable energy consumption. The results indicate that the population density, education, economic growth, digitalisation and research and development have a considerable positive impact. Urbanisation, on the other hand, appears to exert a negative influence. In addition, the empirical findings reveal a unidirectional causal relationship running from education, economic growth and energy poverty towards renewable energy consumption. This research provides useful insights into important drivers of renewable energy adoption which can facilitate or hinder the energy transition and achievement of carbon neutrality goals.

Keywords: Renewable energy consumption; Circular economy; Energy transition; European Union; Panel data
JEL: O13; P18; Q42; Q53; Q56

1. Introduction

Unprecedented environmental, social and economic challenges threaten the future and well-being of the next generations. Exhaustible resources have fuelled economic growth, being a main source of materials and energy. Yet, waste and pollution arise at every step of supply and manufacturing. If current tendencies persist, future generations will face even harsher temperature amplitudes and meteorological phenomena, higher biodiversity loss, extreme resource depletion and worsening environmental pollution. To protect nature, production and consumption should take a turn towards less primary extraction, reduced resource usage and minimum or zero waste and pollution.

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Sustainable development is a means to adapt to ongoing changes and ensure that the needs of future generations are safely met. It aims at eradicating poverty and inequality, and protecting peace, justice and human rights. In the meantime, the circular economy provides the technical solutions that allow for traditional but environmentally sustainable economic progress. It is a regenerative industrial system that achieves longer product lifetime through durability, maintenance, reuse, refurbishing, repair and recycling. The circular economy is usually powered by renewable energy sources, uses non-toxic renewable, biodegradable or recycled materials, and aspires to zero waste and pollution with the help of eco-design and innovative business models (EMF, 2023a).

Tracking progress towards sustainability and circularity is part of the transition and allows for comparisons. Countries should learn from each other's experience to identify successful sustainability strategies, set reasonable goals and develop corresponding policies. Circular economy indicators are abundant in literature and a single metric cannot grasp the wide concept. Overlooking some sustainability dimensions, though, may result in shifting the burden from resource depletion to economic, social and environmental failures (Corona et al., 2019). Most indicators, however, relate to the preservation of materials, while measurements of product life extension and reduction of idle time, which are of particular interest to circular development, are lacking (Parchomenko et al., 2019; Moraga et al., 2019; Moraga et al., 2021).

The numerous metrics also present another challenge. They make it difficult to create a unified monitoring framework and evaluate the circularity of products, processes, organisations, countries or regions (Ahmed et al., 2022; Cagno et al., 2023). The European Union Circular Economy Monitoring Framework (CEMF) was introduced in 2018 to track circular progress in line with the Green Deal's main objectives. Yet, just like many other monitoring frameworks it mainly focuses on material aspects and largely neglects society and the environment. This is a source of criticism regarding the European evaluation approach. To gain a better understanding of the transition, it may be useful to consider indicators for greenhouse gas emissions, energy use, land use, and water use, for example (Llorente-González, Vence, 2019).

The energy aspect is of particular interest to climate change and should be accounted for in such monitoring frameworks. A single metric cannot fully cover the concept of energy transition and there are a number of important indicators, such as energy-related CO_2 emissions, final energy carbon intensity, electrification of end-use consumption, energy intensity of the economy and clean energy investment (IEA, 2019). A commonly used indicator is the renewable energy consumption (Vera, Langlois, 2007; Sheinbaum-Pardo et al., 2012; Yu et al., 2020; Niu et al., 2023). While it typically serves as a comprehensive measure of the green transition, to ensure a more accurate assessment, it should be analysed along with the energy mix, total energy consumption and potentially negative environmental impacts of the technologies in use (EEA, 2015; Wang et al., 2021).

This paper reports the empirical findings of an econometric analysis of a panel of 27 EU countries for the period 2008-2020. The research aims to identify important factors that promote or hinder renewable energy consumption among a set of twelve macro-level economic and social variables. Five initial hypotheses were formulated:

H1: GDP per capita as a proxy for economic development has a significant positive impact on renewable energy consumption.

H2: Research and development expenditure as a proxy for innovation has a significant positive impact on renewable energy consumption.

H3: Digitalisation, approximated by the frequency of internet use and electronic interaction with public authorities, has a positive impact on renewable energy consumption.

H4: Education is a significant factor in renewable energy consumption.

H5: High levels of greenhouse gas emissions influence renewable energy consumption negatively.

The paper is structured as follows: Section 2 reviews extant literature, Section 3 describes the data and methods used for the analysis, Section 4 presents the results and Section 5 discusses the significance of the main findings. Section 6 provides conclusive remarks.

2. Literature Review

Conventional energy sources are a reliable and efficient driver of economic growth but their use is linked to environmental pollution and climate change. Additionally, fossil fuels are subject to depletion and become more and more expensive. Renewables, on the other hand, are vital not only for the energy transition but also for circularity as they limit the use of exhaustible resources and lower the generation of waste and pollution (EMF, 2023b). Relationships among renewable energy, the circular economy and the environment are interdependent and dynamic on the path to climate change mitigation and environmental protection (Majeed, Luni, 2020). A circular economy is impossible to achieve without renewables as sustainable power sources (Klemeš et al., 2023). At the same time, clean energy can benefit from circularity to address its reliance on scarce materials (Kötter et al., 2023). This symbiosis is of primary importance because the much-needed transition requires a shift to a material-intensive energy system, where an exponential demand for critical materials is at hand (Gate C, 2023).

The links between renewable energy and environmental quality have been widely discussed but only a few studies in the literature focus on the factors that promote or impede renewable energy production and consumption in countries or regions (Marques et al., 2010; Papież et al., 2018; Akarsu, Korucu-Gümüşoğlu, 2019, Bersalli et al., 2020; Saba, Biyase, 2022; Marra, Colantonio, 2022; Tu et al., 2022). Exploring these determinants is essential for informed policy-making and business decisions that will address the challenges and benefit from the opportunities before the energy transition.

Recent papers (Saba, Biyase, 2022; Marra, Colantonio, 2022; Tu et al., 2022) identify institutional factors, such as good control of corruption, as instrumental in the development of the renewable energy sector. Institutions provide legislative and financial incentives to economic agents, encouraging the adoption of green technologies (Omri et al., 2022). Promotion policies significantly affect renewable energy investment, but tax incentives are not enough (Bersalli, 2020). To accomplish a policy objective, comprehensive knowledge of consumer preferences towards renewable sources is needed. The political regime also seems to matter as people in more democratic societies tend to tolerate green technologies better (Chaikumbung, 2021).

Technological innovation and social acceptance of information technologies are also essential for the transition and governments should focus on creating robust policies to raise awareness and improve digital literacy (Mishra et al., 2022). Digitalisation facilitates information distribution and enhances technological progress. It helps the integration of renewable energy sources and reduces final energy consumption and intensity. This effect appears to be stronger in developing economies than in wealthier countries and regions (Li et al., 2022; Xu et al., 2022; Shahbaz et al., 2022; Haldar et al., 2023). Digitalisation demonstrates high potential for dematerialisation and decarbonisation in the short run but the long-term effects remain uncertain because of an increased consumption and higher energy demand (Dehghan Shaban, Shahnazi, 2019; Kouton, 2019). To promote sustainability, digitalisation should improve energy efficiency and position renewable energy as a substitute for any rise in consumption.

While technical aspects are essential to the development of renewable solutions, the process involves many important multi-level stakeholders (Omri et al., 2022). Factors, such as economic growth, urbanisation, industrialisation and population growth and density, have an impact on the share of renewable energy according to Malik et al. (2014). Other studies add to these determinants R&D expenditure, foreign direct investment, trade openness and government effectiveness (Kocsis, Kiss, 2015; Akarsu, Korucu-Gümüşoğlu, 2019; Alam et al., 2020; Adedoyin et al., 2020; Islam et al., 2022). Sustainable development indicators, such as the human development index, carbon emissions and ecological footprints are analysed alongside other factors. For example, CO_2 emissions per capita and related environmental degradation are linked to economic development and income inequality, in particular (Hao et al., 2016). An increasing income gap contributes to rising CO_2 emissions because poor people can rarely afford eco-friendly goods or services. However, they have lower final energy consumption. Meanwhile, the wealthiest economies produce even higher emissions, but considerable R&D spending partially counteracts the increase (Wan et al., 2022). Therefore, narrowing the income gap and conducting sound investment policies are key to reducing the overall energy consumption and promoting renewables.

A number of papers have studied the relationship between economic growth and renewable energy and have found it to be predominantly negative (Sharma et al., 2021; Tu et al., 2022; Li et al., 2022; Fernández-Amador et al., 2023). Whether it is positive or negative usually depends on the level of GDP (Akarsu, Korucu-Gümüşoğlu, 2019; Marra, Colantonio, 2022; Wang et al., 2022). Some studies (Marques et al., 2010; Papież et al., 2018; Bersalli et al. 2020) suggest that the wealthiest countries tend to invest more in renewable energy because of a higher R&D budget, better regulation and promotion policies. When it comes to causality, results are again mixed, pointing to a one-way causal relationship from GDP to renewable energy (Ben Jebli, Ben Youssef, 2015), from renewable energy to GDP (Yildirim et al., 2012) or a two-way causal relationship (Apergis, Payne, 2010; 2011; Chang et al., 2015). One of the studies (Sharma et al., 2021) even reveals that economic growth and renewable energy demonstrate a two-way negative relationship in the short run. Despite the negative short-term economic implications, though, renewable energy can become a future source of opportunities, if consistent policies and adequate incentives ensure a just and inclusive transition. These aspects should be prioritised, especially in countries with high income inequality to prevent a worsening energy poverty situation (Revez et al., 2020).

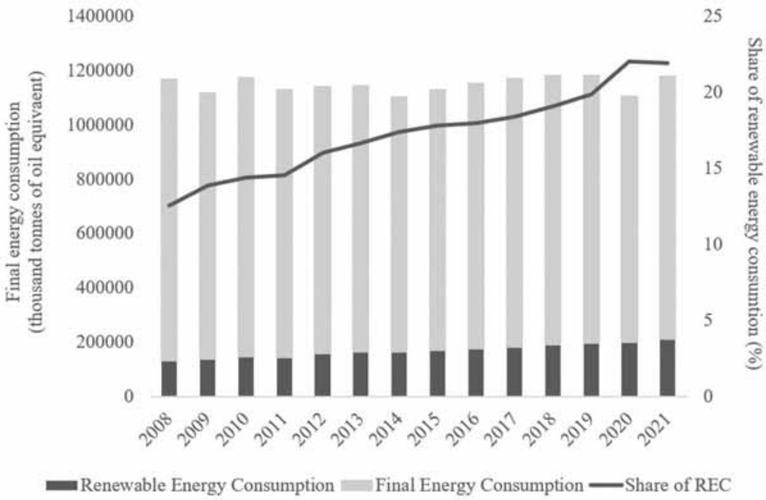
The COVID-19 pandemic and the Russian-Ukrainian conflict have presented both stimuli and challenges for the energy transition. A contraction of economic activity and the ongoing crisis have led to severe social, economic and environmental impacts (Nicola et al., 2020; Baker et al., 2020; Pereira et al., 2022). The pandemic triggered an unprecedented drop in fuel and energy demand, clearing the way for an accelerated transition to more sustainable energy sources (Chiaramonti, Maniatis, 2020; Zhong et al., 2020). Renewable energy generation was indirectly enhanced by reduced air pollution – greenhouse gas emissions, in particular. The improved quality of air during lockdowns increased the amount of sunlight reaching land and boosted solar panel productivity (Naderipour et al., 2020). Aided by a decline in renewable energy costs, the share of renewable energy (mainly solar and wind power) in the energy mix of many countries and regions grew (Zhong et al., 2020; Klemeš et al., 2021; Li et al., 2022). However, the rising uncertainty interfered with investment decisions and the completion of renewable projects (Tsao et al., 2021). Apart from scarce funding, factors, such as supply-chain delays, also hindered their finalisation (IEA, 2020a; 2020b).

The European Union has set ambitious targets in response to international agreements regarding environmental concerns. Since it is one of the world's top emitters and more than 70% of its greenhouse gas emissions originate from fuel combustion, the transition towards cleaner sources is of primary importance (EP, 2023). Meanwhile, a recent report identifies the EU as one of the leading zero-carbon competitors along with China, the US, Japan and India (Kalcher, 2023). This sets a good example of how countries could address their climate impact, improve energy security and prosper economically. Exploring factors that influence renewable energy consumption in the region may prove useful in helping other countries in their energy transition.

Figure 1 shows the final and renewable energy consumption of 27 EU member countries between 2008 and 2021. The year 2021 is not included in any further analysis. It is used only once to gain a general insight into the post-COVID energy consumption. Final energy consumption remained rather stable throughout the years, declining slightly in 2009 due to the Global Financial Crisis and in 2020 at the onset of the pandemic. Meanwhile, the share of renewable energy increases slowly but persistently, starting from 12.55% in 2008 to reach 19.89% in 2019 and jumping to 22.04% in 2020. This marks a total increase of 74.70% over the 13-year period. However, 2021 brings a lower renewable energy share of 21.93%.

Looking at the data, a specific pattern emerges. Global crises reduce final energy consumption and stimulate the renewable energy sector, but the impact is short-lived and matters quickly go back to pre-crisis levels, slowing the growth of the renewable energy share. As much as financial and health crises challenge the world, they also bring it closer to the achievement of climate targets. Governments should take advantage of such events and prolong their effect on energy consumption through sound investment policies and incentives.

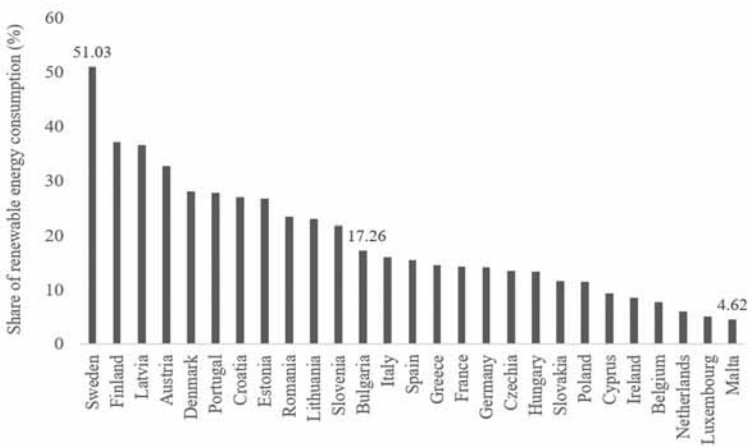
Figure 1. Average EU-27 energy consumption for the period 2008-2021



The graphical representation was created by the author based on data sourced from Eurostat (2023a).

Figure 2 summarises the country's performance in the studied period by showing the average renewable energy share for each country. The EU-27 average is 17.33% between 2008 and 2020, which means that just about 37% of the countries perform above it. Sweden demonstrates strong leadership, followed by Finland, Latvia and Austria. Bulgaria keeps the average EU level, while the Netherlands, Belgium and Malta fall substantially behind their renewable energy targets.

Figure 2. The average share of renewable energy consumption by country for the period 2008-2020



The graphical representation was created by the author based on data sourced from Eurostat (2023a).

The Russian-Ukrainian war further threatens the successful energy transition and the achievement of the Sustainable Development Goals (Pereira et al., 2022). On the path to decarbonisation, energy security remains at risk, especially since the conflict exposed Europe's high dependence on Russian fossil fuels (Prisecaru, 2022). The need for energy diversification and local renewable production has initially presented an opportunity for the development of low-carbon energy sources (De Rosa et al., 2022). Although the European Union still remained a net energy importer, a major supplier diversification followed in 2022 after the sanctions imposed on Russia (Eurostat, 2023b). However, the threatened energy security and fluctuations in energy prices seem to have given rise to the use of fossil fuels as a reliable solution again (Zakeri et al., 2022). To meet climate targets, the energy transition needs to be secured through proper policies and recovery plans, green financing and international cooperation (Tian et al., 2022).

3. Data and Methods

3.1. Data

This paper analyses a panel of 27 EU member countries over the period 2008-2020. The sample was selected according to data availability. It includes Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden. The data were sourced from Eurostat, the World Bank, the United Nations and Climate Watch.

The thirteen variables of interest are closely linked to SDGs. For example, the dependent variable 'renewable energy consumption' is of primary importance to SDGs 7, 11 and 12 addressing the access to affordable and clean energy, the development of sustainable cities and communities, and responsible consumption and production practices. The energy transition is also necessary to achieve a circular economy and it is the foremost step in climate action under SDG 13. A compilation of twelve explanatory variables was made by the author based on extant literature and the identification of new potentially influential factors. Table 1 lists all variables, starting with 'renewable energy consumption' as the dependent variable.

Since economic, social and environmental dimensions intertwine when it comes to sustainability and circularity, indicators used to track their progress are often influenced by the same determinants. Frequently used circular economy metrics usually depend on common factors, such as GDP per capita and R&D expenditure (Pantcheva, Mengov, 2022; Pantcheva, 2023), as well as higher education and urbanisation (Sidique et al., 2010; Kostakis, Tsagarakis, 2021). The effect of educational attainment on renewable energy consumption was tested in this study via a specific proxy variable, EST.

Macroeconomic variables, such as gross domestic product per capita, research and development expenditure, and trade openness have been previously found to influence renewable energy consumption. The role of the government was also considered in this paper via the regulatory quality index because of its potential positive impact (Ibarra-Yunez, Pérez-Henríquez, 2017). Digitalisation as an important driver of the renewable energy sector has been identified in various papers (Xu et al., 2022; Shahbaz et al., 2022; Haldar et al., 2023). This research focuses on the potential effects of the frequency of internet use and digital government interactions.

Table 1. Description of the variables

Variable	Full name	Unit of measure	Definition	Data source
REC	Renewable energy consumption	Percentage	The share of renewable energy consumption in gross final energy consumption. The indicator is used as a measure of the progress towards decarbonisation.	Eurostat, 2023a
EG	E-government activities	Percentage	The share of all individuals that have interacted with public authorities over the internet.	Eurostat, 2023a
EP	Energy poverty	Percentage	The share of the population unable to keep their homes adequately warm.	Eurostat, 2023a
EST	Secondary, post-secondary and tertiary education	Percentage	The share of individuals aged 15-64 who were involved in upper secondary, post-secondary non-tertiary or tertiary education.	Eurostat, 2023a
FIU	Frequency of Internet use	Percentage	The share of all individuals that have accessed the internet at least once a week.	Eurostat, 2023a
GDPPC	Gross domestic product	PPS per capita	The ratio of GDP to the average population each year, expressed in purchasing power standards to allow for comparisons among countries.	Eurostat, 2023a
GHGEPC	Greenhouse gas emissions	Tonnes of CO_2 equivalents per capita	The ratio of total greenhouse gas emissions to the average population each year, including emissions from land use, land use change and forestry.	Climate Watch, 2023
GRQ	Government regulatory quality	Index	The indicator reflects perceptions of how sound government policies are and whether they promote private sector development.	The World Bank, 2023a
PD	Population density	People per km^2	The ratio of the average annual population to the total land area of a country in square kilometres.	The World Bank, 2023b
PGR	Population growth rate	Percentage	The average annual exponential rate of growth of the population.	United Nations, 2023
RDE	Research and development expenditure	Percentage	The share of gross domestic expenditures on research and development (R&D) as a share of GDP. It covers basic research, applied research and experimental development in the Business enterprise, Government, Higher education and Private non-profit sectors.	The World Bank, 2023b
TO	Trade openness	Percentage	The sum of exports and imports of goods and services as a share of GDP.	The World Bank, 2023b
UP	Urban population	Percentage	The people living in urban areas as a share of the total population of a country.	United Nations, 2023

Indicators, regarding the population, such as population density, population growth rate and urbanisation (Salim, Shafiei, 2014), were considered in view of their links to energy consumption. A number of studies (Pagliaro, Meneguzzo, 2020; Biernat-Jarka et al., 2021; Wang et al., 2022) have examined the alleviation effect of renewable energy on energy poverty. The current study, however, assumed a different approach and tested whether energy poverty itself influences renewable energy consumption. Since other greenhouse gases less known than CO_2 also contribute to climate change (Akarsu, Korucu-Gümüşoğlu, 2019; Naderipour et al., 2020), one more variable, greenhouse gas emissions per capita, was added to the list of potential factors.

To the best of the author's knowledge, this paper is the first to examine the specific impact of energy poverty, the frequency of internet use, digital government interactions, education (as approximated by EST) and greenhouse gas emissions per capita on the consumption of renewable energy. Identifying determinants that link renewable energy consumption to other circular economy metrics can strengthen the case for including this energy indicator in the European Union Circular Economy Monitoring Framework. The study also contributes to existing literature by analysing a different period and set of countries.

3.2. Methods

3.2.1. Descriptive statistics

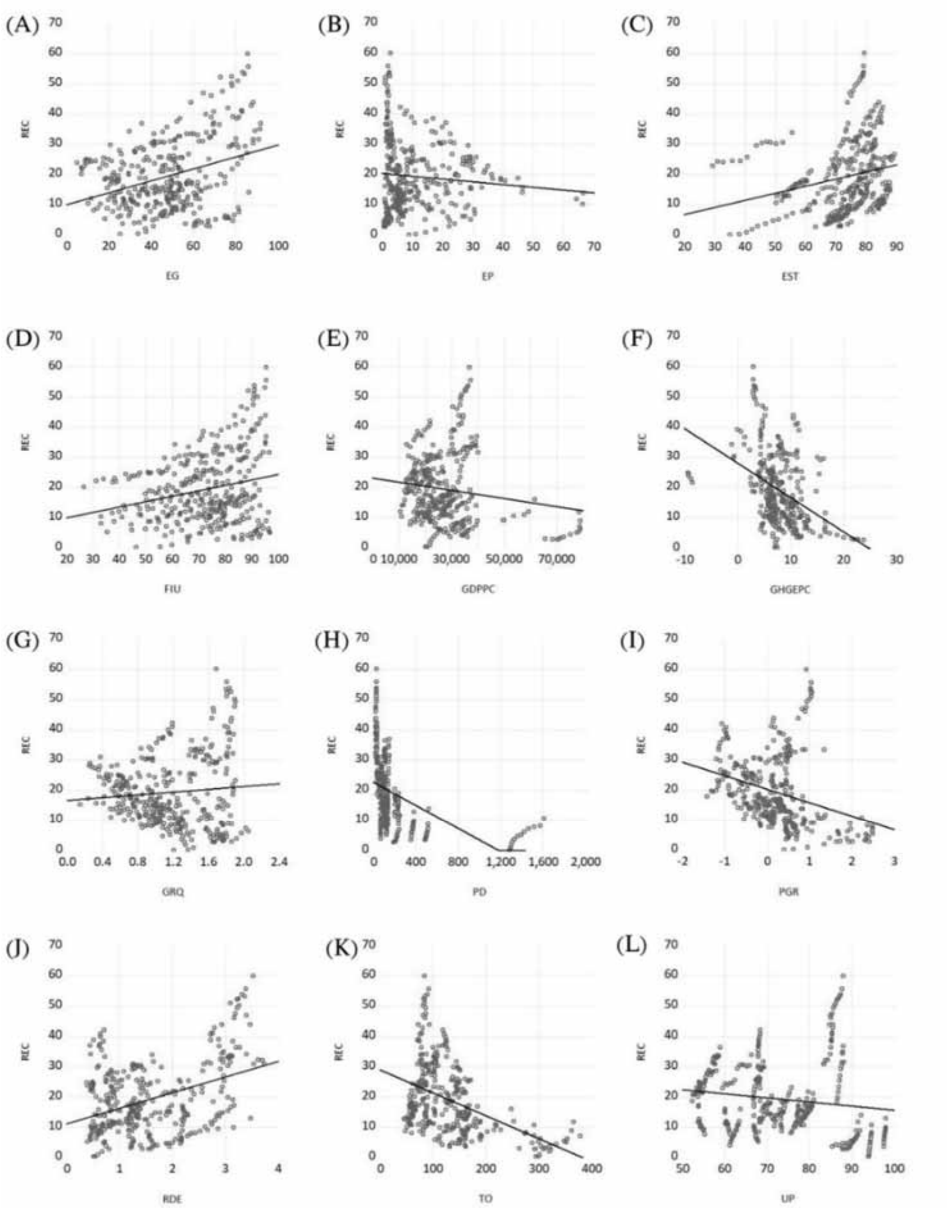
Table 2 presents the descriptive statistics of all variables. To improve data quality, a natural logarithm transformation was applied.

Table 2. Descriptive statistics of the variables

Variable	Mean	Median	Maximum	Minimum	St. Dev.	Observations
REC	2.743	2.818	4.096	-1.635	0.746	351
EG	3.749	3.873	4.518	1.595	0.524	351
EP	1.856	1.792	4.197	-1.204	1.048	351
EST	4.282	4.333	4.491	3.374	0.185	351
FIU	4.260	4.314	4.572	3.271	0.237	351
GDPPC	10.141	10.123	11.276	9.259	0.379	351
GHGEPC	2.851	2.863	3.528	0.000	0.371	351
GRQ	0.062	0.132	0.716	-1.935	0.457	351
PD	4.676	4.683	7.384	2.861	0.904	351
PGR	0.923	0.952	1.593	0.000	0.304	351
RDE	0.290	0.283	1.317	-0.963	0.601	351
TO	4.733	4.690	5.934	3.816	0.463	351
UP	4.270	4.259	4.586	3.955	0.177	351

Figure 3 displays scatterplots of renewable energy consumption as a function of each explanatory variable. The visual representations suggest the existence of a positive relationship between: REC and EG; REC and EST; REC and FIU; REC and RDE. A negative relationship is observed between: REC and GHGEPC; REC and PGR; REC and TO. Relationships with the rest of the explanatory variables cannot be clearly inferred from the scatterplots.

Figure 3. Scatterplots of REC as a function of the explanatory variables



(A). REC as a function of EG; (B). REC as a function of EP; (C). REC as a function of EST; (D). REC as a function of FIU; (E). REC as a function of GDPPC; (F). REC as a function of GHGEPC; (G). REC as a function of GRQ; (H). REC as a function of PD; (I). REC as a function of PGR; (J). REC as a function of RDE; (K). REC as a function of TO; (L). REC as a function of UP.

3.2.2. Correlation analysis

Table 3 shows the correlation matrix. There is a moderate correlation between REC and EST, REC and PGR, REC and TO, REC and UP at the 1% significance level. Meanwhile, PD demonstrates a strong negative correlation with the dependent variable. There are also strong correlations between FIU and EG, EP and GDPPC, PGR and GDPPC (above 0.7). EG does not make it to the final models. As for the other two strong correlations, GDPPC and PGR are only used as control variables and are not of particular interest in the current study.

The correlations between some of the explanatory variables may lead to multicollinearity. However, when correlations are moderate they may not be problematic. The current choice of factors is theoretically or practically justified and relationships between such explanatory variables are quite natural and expected as economic, social and environmental determinants are usually interconnected.

Table 3. Correlation matrix

Variable	REC	EG	EP	EST	FIU	GDPPC	GHGEPC	GRQ	PD	PGR	RDE	TO	UP
EG	0.115**	1											
EP	0.022	-0.616***	1										
EST	0.320***	0.207***	-0.279***	1									
FIU	0.136***	0.856***	-0.633***	0.332***	1								
GDPPC	-0.207***	0.620***	-0.719***	-0.020	0.653***	1							
GHGEPC	-0.294***	0.393***	-0.324***	0.026	0.289***	0.429***	1						
GRQ	-0.142***	0.585***	-0.633***	0.073	0.501***	0.650***	0.323***	1					
PD	-0.717***	-0.043	0.060	-0.414***	0.027	0.258***	0.170***	0.058	1				
PGR	-0.428***	0.374***	-0.564***	-0.213***	0.343***	0.722***	0.310***	0.540***	0.447***	1			
RDE	0.264***	0.657***	-0.643***	0.115**	0.588***	0.563***	0.303***	0.524***	-0.066	0.335***	1		
TO	-0.499***	0.241***	-0.264***	0.158***	0.314***	0.308***	0.272***	0.288***	0.352***	0.336***	-0.145***	1	
UP	-0.312***	0.456***	-0.240***	-0.224***	0.417***	0.482***	0.272***	0.489***	0.330***	0.401***	0.363***	0.155***	1

Note: ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively.

3.2.3. Panel unit root and cointegration tests

All tests and estimations were performed using the log-transformed variables. The panel unit root tests revealed that some of the variables were not stationary but became stationary after the first difference, therefore all variables were integrated at I(1). Since stationarity at first difference was confirmed, the Kao cointegration test (Kao, 1999) was performed to check whether variables demonstrated a long-run relationship. The optimal lag length was chosen based on the Schwartz Information Criterion and was set at 2. The cointegration test results rejected the null hypothesis at the 1% significance level suggesting that the variables demonstrated a stable long-run relationship.

3.2.4. Panel causality tests

Table 4 lists the variables that demonstrated a causal relationship with REC in the Dumitrescu and Hurlin causality tests (Dumitrescu, Hurlin, 2012). The results indicate that bidirectional causality runs between: EG and REC; FIU and REC; PD and REC; TO and REC; UP and REC. A unidirectional causal relationship runs from: EP to REC; EST to REC; GDPPC to REC, but it turns out that REC homogeneously causes GHGEPC. No homogeneous causality is revealed between renewable energy consumption and GRQ, PGR and RDE.

Table 4. Panel causality test results

№	Variable	W-statistic	Zbar statistic	P-value	Result	Type of the observed relationship
1	lnEG ⇸ lnREC	4.98	1.98	0.048**	EG ↔ REC	Bidirectional causality
	lnREC ⇸ lnEG	5.351	2.351	0.019**		
2	lnEP ⇸ lnREC	6.06	3.06	0.002***	EP → REC	Unidirectional causality
	lnREC ⇸ lnEP	4.631	1.631	0.103		
3	lnEST ⇸ lnREC	5.47	2.47	0.014**	EST → REC	Unidirectional causality
	lnREC ⇸ lnEST	4.276	1.276	0.202		
4	lnFIU ⇸ lnREC	7.112	4.112	0.000***	FIU ↔ REC	Bidirectional causality
	lnREC ⇸ lnFIU	5.24	2.24	0.025**		
5	lnGDPPC ⇸ lnREC	5.737	2.737	0.006***	GDPPC → REC	Unidirectional causality
	lnREC ⇸ lnGDPPC	3.247	0.247	0.805		
6	lnGHGEPC ⇸ lnREC	2.418	-0.582	0.561	REC → GHGEPC	Unidirectional causality
	lnREC ⇸ lnGHGEPC	6.946	3.946	0.000***		
7	lnPD ⇸ lnREC	8.36	5.36	0.000***	PD ↔ REC	Bidirectional causality
	lnREC ⇸ lnPD	9.305	6.305	0.000***		
8	lnTO ⇸ lnREC	6.455	3.455	0.001***	TO ↔ REC	Bidirectional causality
	lnREC ⇸ lnTO	5.522	2.522	0.012**		
9	lnUP ⇸ lnREC	3.869	5.837	0.000***	UP ↔ REC	Bidirectional causality
	lnREC ⇸ lnUP	8.58	16.479	0.000***		

Note: The null hypothesis assumes no homogeneous causality (denoted by ⇸). →, ↔ and × stand for unidirectional, bidirectional and no causality, respectively. ***, ** and * indicate significance at the 1%, 5% and 10% level, respectively.

3.2.5. Panel model specification

Two methods were used to provide ground for robustness and comparison of the results: fixed effects and fully modified ordinary least squares. All estimation methods followed a forward selection procedure, beginning with a set of explanatory variables identified in the literature and then testing the rest of the variables for significance. The models estimated via FE (1) and FMOLS (2), respectively, were ultimately specified as:

$$\ln(y_{i,t}) = \beta_0 + \alpha_i + \beta_k \ln(x_{k,i,t}) + e_{i,t} \quad (1)$$

$$\ln(y_{i,t}) = \beta_k \ln(x_{k,i,t}) + e_{i,t} \quad (2)$$

where $y_{i,t}$ is the dependent variable renewable energy consumption and $x_{k,i,t}$ are the explanatory variables GDP, PD, PGR, RDE, EST, FIU, EP, GHGE, TO, UP. The constant terms β_0 and α_i represent the intercept and the country-specific fixed effects, respectively. The error term is denoted by $e_{i,t}$. The subscripts relate to the different countries (i), explanatory factors (k) and time periods (t) and they are defined as follows: in the FE model: i = (1, … , 27); k = (1, … , 10); t = (1, … , 13); in the FMOLS model: i = (1, … , 27); k = (1, … , 10); t = (1, … , 12).

Fixed effects account for country-specific characteristics and reduce omitted variable bias by controlling for unobservable factors that may influence renewable energy consumption. This estimation technique potentially provides more precise insights by exploring both the cross-sectional and temporal dimensions of panel data. First, a simple OLS regression was run with four variables identified in previous studies: GDPPC, PD, PGR and RDE. To check for the presence of fixed or random effects, the Hausman test (Hausman, 1978) was performed. The null hypothesis, which considers random effects more appropriate, was rejected at the 1% significance level and fixed effects were selected. The Wooldridge test for serial correlation (Drukker, 2003; Wooldridge, 2011) revealed that errors for cross-sections were serially correlated. The Breusch-Pagan LM, Pesaran scaled LM, Bias-corrected scaled LM and Pesaran CD statistics for cross-sectional dependence rejected its absence at the 1% significance level. Considering heteroscedasticity, cross-sectional and serial correlation, the estimation methods needed to take these issues into account. The White two-way cluster method was then used to provide robust estimators (Wooldridge, 2011).

FMOLS (Pedroni, 2001) are also typically used because they are superior to other regression methods and can overcome the problem of serial correlation and endogeneity of the variables. While the OLS may produce biased estimators, the FMOLS yield better results in the presence of heterogeneity in cointegrated panels and allow for modelling long-term relationships.

Coefficients of the variables of interest remained rather stable throughout the estimations. Additionally, the final models were rerun by including interaction terms of GDP and EP, FIU, GHGEPC, PGR, RDE as well as interaction terms of EP and FIU, RDE. All trials produced insignificant coefficients for both the interaction term and the variable of interest. Therefore, no statistically significant interaction between control variables and those of interest was found and the relatively strong correlations mentioned in Section 3.2.2. should not have substantially influenced the estimation output.

4. Results

4.1. Fixed-effects models

Table 5 shows the results of the FE estimations with White cross-section and period-cluster standard errors and covariances. The six models appear to be correctly specified according to R-squared and adjusted R-squared. Except for PGR, all other coefficients are statistically significant at the 1%, 5% or 10% level.

The variables demonstrate consistency with respect to signs, significance and size of the effects. GDPPC, PD, RDE, EST, FIU and EP enter the models with positive signs, while GHGEPC, TO and UP have a negative effect on renewable energy consumption. Model 6, for example, shows that a 1% increase in GDPPC, PD, RDE, EST, FIU and EP will raise REC by 0,72%, 3.66%, 0.52%, 2.51% and 0.51 %, respectively. On the other hand, an increase in GHGEPC, TO and UP will negatively affect REC by 0.10%, 0.56% and 5.22%, respectively.

Table 5. FE estimations

Coefficient	(1)	(2)	(3)	(4)	(5)	(6)
C	-33.953***	-32.265***	-30.283***	-30.478***	-29.566***	-10.296
	(6.113)	(2.967)	(3.035)	(3.409)	(2.878)	(10.338)
lnGDPPC	0.965***	0.438	0.177	0.377	0.518**	0.724***
	(0.184)	(0.262)	(0.264)	(0.242)	(0.187)	(0.201)
lnPD	5.617***	4.352***	4.555***	4.087***	4.013***	3.662***
	(1.186)	(0.839)	(0.807)	(0.772)	(0.731)	(0.672)
lnPGR	0.472	0.487	0.695	0.649	0.567	0.322
	(0.703)	(0.547)	(0.599)	(0.591)	(0.525)	(0.436)
lnRDE	0.745**	0.603**	0.520**	0.534**	0.580**	0.523**
	(0.307)	(0.212)	(0.189)	(0.191)	(0.201)	(0.190)
lnEST		2.240**	1.690	1.796*	1.803*	2.507***
		(0.972)	(0.965)	(1.000)	(0.935)	(0.827)
lnFIU			0.448**	0.399*	0.524***	0.513**
			(0.191)	(0.190)	(0.171)	(0.197)
lnEP				0.155***	0.200***	0.238***
				(0.051)	(0.062)	(0.074)
lnGHGEPC				-0.052	-0.071**	-0.103***
				(0.029)	(0.027)	(0.029)
lnTO					-0.532**	-0.56***
					(0.206)	(0.166)
lnUP						-5.221*
						(2.434)
R2	0.922	0.946	0.948	0.951	0.953	0.957
Adj. R2	0.914	0.94	0.943	0.946	0.948	0.952
Observations	351	351	351	351	351	351
Periods	13	13	13	13	13	13

*Note: All variables are log-transformed. Standard errors are reported in parentheses. ***, ** and * indicate significance at the 1%, 5% and 10% level, respectively.*

4.2. FMOLS models

Table 6 presents the long-term coefficients from the FMOLS models. The FE and FMOLS yield similar results regarding the statistical significance of the variables. This time even PGR enters most models with a significant coefficient and a positive sign. The FMOLS Model 6 shows that in the long run, a 1% increase in GDPPC, PD, RDE, EST, FIU and EP affect REC positively by 0.84%, 3.73%, 0.54%, 2.45%, 0.42% and 0.28%, respectively. Meanwhile, an increase in GHGEPC, TO and UP will cause a decrease in REC by 0.14%, 0.57% and 5.51%, respectively. All coefficients are significant at the 1% level, except for FIU, which is significant at the 5% level.

Table 6. FMOLS estimations

Coefficient	(1)	(2)	(3)	(4)	(5)	(6)
lnGDPPC	0.853***	0.457***	0.279*	0.516***	0.591***	0.841***
	(0.129)	(0.127)	(0.168)	(0.168)	(0.167)	(0.166)
lnPD	5.697***	4.578***	4.660***	4.081***	4.132***	3.726***
	(0.500)	(0.454)	(0.457)	(0.455)	(0.445)	(0.428)
lnPGR	0.490**	0.453***	0.602***	0.537***	0.476***	0.190
	(0.191)	(0.166)	(0.181)	(0.171)	(0.169)	(0.168)
lnRDE	0.745***	0.581***	0.525***	0.538***	0.603***	0.535***
	(0.113)	(0.099)	(0.102)	(0.096)	(0.096)	(0.091)
lnEST		1.893***	1.604***	1.689***	1.665***	2.453***
		(0.265)	(0.328)	(0.312)	(0.304)	(0.340)
lnFIU			0.284	0.256	0.437**	0.422**
			(0.188)	(0.178)	(0.190)	(0.178)
lnEP				0.186***	0.228***	0.279***
				(0.042)	(0.045)	(0.043)
lnGHGEPC				-0.069	-0.093**	-0.135***
				(0.046)	(0.046)	(0.044)
lnTO					-0.543***	-0.570***
					(0.191)	(0.179)
lnUP						-5.511***
						(1.387)
R^2	0.936	0.952	0.952	0.954	0.956	0.958
Adj. R^2	0.93	0.947	0.947	0.949	0.95	0.953
Observations	324	324	324	324	324	324
Periods	12	12	12	12	12	12

*Note: All variables are log-transformed. Standard errors are reported in parentheses. ***, ** and * indicate significance at the 1%, 5% and 10% level, respectively.*

5. Discussion

Results from the econometric analysis support all five initial hypotheses. Additional factors turn out to be significant drivers of renewable energy consumption as well. Both FE and FMOLS show that urbanisation, population density, education and economic development have the largest impact on renewable energy consumption in terms of magnitude.

Gross domestic product per capita (GDPPC) as an approximation for economic growth enters most models with a positive sign and high statistical significance. These findings and the unidirectional causality established in Table 4, Section 3.2.4, support the hypothesis that economic development exerts a positive influence on renewable energy consumption. The results are in accordance with the direction of causality found in previous studies (Ben Jebli, Ben Youssef, 2015), as well as the positive effect established in extant literature. While developed countries still heavily rely on non-renewable sources to meet their energy needs, they also allow for larger R&D spending to enhance innovation in the renewable energy sector, more environmentally friendly consumer decisions and better funding opportunities for green investment.

Research and development expenditure (RDE) has a significant positive influence on renewable energy consumption in all models. These results also confirm previous findings. R&D is a source of innovation and further improvement of existing green technologies. It helps reduce the input of energy and materials and the associated environmental impact of energy production. Moreover, R&D makes renewable technologies more cost-effective, productive and reliable, raising their competitiveness. An affordable renewable production means more renewable energy consumption as a share of final energy consumption.

The **frequency of internet use** (FIU) is used to approximate digitalisation in the current analysis. According to Hu et al. (2022), the digital economy promotes both renewable energy production and consumption. It facilitates the conduction of environmental protection policies and accelerates research and innovation through knowledge sharing and collaboration. Moreover, digitalisation has great potential for dematerialisation, energy efficiency improvements and better energy management. Frequent internet access makes information disseminate more easily across different channels so that businesses and the population become more aware of the environmental challenges and ways to counteract them.

Education (EST) is another variable that enters the models with a positive sign and unidirectionally causes renewable energy consumption. Education enhances human capital through learning and implementation of the accumulated knowledge (Pfeiffer, Mulder, 2013). This can result in technological innovations, higher environmental awareness and changes in energy consumption patterns (Ackah, Kizys, 2015). Education should be considered a driver of primary importance since it shapes future habits and attitudes, as well as professional capabilities and level of expertise. The renewable sector creates new jobs, but the potential lack of a qualified workforce may raise concerns in the future.

Greenhouse gas emissions per capita (GHGEPC), as expected, influence renewable energy consumption negatively. For example, higher concentrations of greenhouse gases worsen the air quality and reduce the productivity of photovoltaic systems. Meanwhile, countries with high emissions are usually more dependent on fossil fuels whether because they exploit them locally or import them under favourable conditions. The reliability of conventional energy is one of the reasons to use more polluting energy sources. Low public awareness of the importance of renewable energy adoption and its benefits can also produce a similar effect. Such conditions may discourage green investment, impede the adoption of green technologies and keep the share of renewable energy low.

Energy poverty (EP), surprisingly, turns out to have a small but positive statistically significant impact. There also exists a unidirectional causal relationship running from energy poverty to renewable energy consumption. A few possible explanations for this phenomenon can be provided. First, countries with higher levels of energy poverty consume less energy in total. This may lead to a relatively larger renewable share. Second, energy poverty usually stems from a lack of affordable and easily accessible conventional energy sources, a lack of relevant infrastructure, etc. Renewable energy ensures a cheaper and more sustainable alternative, as well as decentralised solutions that can meet the needs of isolated and energy-poor areas or communities. Public and private investment in such projects can reduce the dependence on conventional sources and provide access to more efficient and sustainable energy. The increased renewable energy consumption, as already mentioned, can produce an alleviating effect on energy poverty since communities will no longer rely solely on expensive fossil fuels. This can contribute to higher living standards and local economic growth. Economic development, in turn, allows for larger spending on R&D and sustainability programs, further increasing the share of renewable energy.

Trade openness (TO) shows a moderate negative correlation with the dependent variable and Models 5 and 6 further support that finding. Pfeiffer et al. (2013) discover such an effect as well. In general, trade drives international competition and helps disseminate knowledge and new technologies. In the case of conventional energy exports, however, some countries may loosen regulations or lower their conventional energy prices to make the most of comparative advantages. Trade openness may also make energy-dependent countries import more foreign fossil fuels instead of developing their own renewable energy sources. Akarsu et al. (2019) confirm the hypothesis when income per capita is below a certain threshold level. However, they point out that wealthier countries make use of the spread of innovative technologies and under these circumstances trade openness promotes renewable energy.

Population density (PD) is found to influence renewable energy consumption positively. In the correlation analysis, it displays a strong negative correlation with the dependent variable, as seen in Table 3, Section 3.2.2. The bidirectional causality running between the two variables is a potential source of bias in observational findings. Salim et al. (2014), for example, show that population density has a negative impact on non-renewable energy consumption but they fail to detect any causality or a significant effect of the variable on renewable energy consumption. Morikawa (2012) reveals that higher population density affects energy efficiency positively. Therefore, the improved energy efficiency may reduce overall energy consumption, while the higher population density may decrease non-renewable energy consumption. This, in turn, may increase the relative share of renewable energy. This is a possible explanation of the positive influence of population density on the dependent variable. Densely populated areas also offer better conditions for the development of small-scale renewable energy systems, shared benefits, sustainable public transport and energy economies of scale.

Population growth rate (PGR) does not significantly impact renewable energy consumption at least in the near future. Malik et al. (2014), for example, discover a short-run negative influence of a higher population growth rate on the consumption of renewable energy. This negative impact disappears in the long term. The current study reveals that the population growth rate receives positive long-run coefficients. An increasing population is a prerequisite for rising energy demand. It is important, however, how this demand will be satisfied. Whether it will raise the dependence on fossil fuels or countries will turn it into an opportunity to expand their renewable capacity in the future, is of key importance.

Urbanisation (UP) and its effects on renewable and non-renewable energy consumption have been widely discussed in recent years. Studies reveal different impacts on renewable energy consumption: positive (Malik et al., 2014), negative (Akarsu, Korucu-Gümüşoğlu, 2019; Islam et al., 2022), mixed (Hu et al., 2022) or no impact at all (Salim, Shafiei, 2014). Hu et al. (2022), for example, discover a predominantly negative influence since urbanisation promotes renewable energy consumption but hinders renewable energy production by reducing the space available for renewable energy installations. The current research reveals a statistically significant and large in magnitude negative impact. Cities are the largest energy consumers and CO_2 emitters on a global scale. Faster urbanisation means more energy demand and heavier air pollution resulting from higher energy intensity and more traffic. Another important aspect to consider is that people in large cities usually enjoy an uninterrupted power supply and better living conditions compared to the rural population. Hence, they rarely need to think of the way energy is provided resulting in lower environmental awareness. Despite the negative impacts of urbanisation, cities offer good opportunities for the sharing economy. Local authorities can support carbon neutrality by transitioning away from conventional energy sources and embracing sustainable alternatives.

Social factors turn out to dominate the promotion of renewable energy. Meanwhile, as expected, economic growth and R&D link renewable energy consumption to other circularity indicators. Since common factors influence different fields in the same manner, this underlines the importance of addressing the energy aspect in the EU Circular Economy Monitoring Framework.

The results of this research should be considered in light of some limitations. First, the sample was chosen according to data availability which made it impossible to include observations on some variables earlier than 2008. For the same reason, post-COVID data could not be considered. Second, this study combines factors identified in extant literature with an author's compilation of additional variables. There may be other equally important determinants of renewable energy consumption that have been omitted. These limitations provide an opportunity for future studies to account for the consequences of the COVID-19 pandemic, the Russian-Ukranian conflict, the ongoing recession and the revisited European Green Deal targets. Expanding the sample will provide ground for comparisons between EU and non-EU member countries, Asia or America. Additional economic, social or environmental factors may also be explored, such as the age structure of the population, the share of people living in houses or flats, land use indicators, as well as specific circularity metrics. It can also be useful to consider some policy evaluations to investigate how net metering and green building standards, for example, affect renewable energy consumption.

6. Conclusion

Renewable energy is essential to the green transition. It should be noted, though, that renewables act as a substitute for conventional sources as long as the total amount of energy consumed by an economy remains the same. Otherwise, it only fuels an ever-growing energy demand and yields minimum or no effect on environmental protection, while threatening critical materials availability. Global crises tend to lower final energy consumption and stimulate the renewable energy sector but results are only short-lived. To yield long-term outcomes, governments should focus on prolonging these effects through proper investment and incentive policies. By gaining insight into the determinants of renewable energy consumption, policymakers can accelerate the adoption of renewables and change consumption patterns more easily.

This research adds to existing knowledge by identifying new factors and exploring their relationships with renewable energy. The presence of a unidirectional causal relationship from economic development, education and energy poverty to renewable energy consumption and their positive impacts can guide stakeholders in their efforts to accelerate the green transition. Energy poverty, for example, is a setback for sustainable development but it can be alleviated through renewable installations as a cheaper alternatives, funded by public or private investment. Developed countries, on the other hand, can promote renewable energy through higher R&D spending, energy efficiency programs or various instruments, such as feed-in-tariffs, tax incentives and subsidies or the issue of green bonds.

Since education and digital inclusion favour renewable energy, governments should allocate additional resources to enhance innovation and efficiency, as well as raise environmental awareness among the population. Sustainability concepts should be integrated across all educational stages and various training and professional development programs. This approach will not only develop a better understanding of renewable energy but will also cultivate a skilled workforce to drive the energy transition forward. In addition, information campaigns and partnerships between the industry and research institutions can substantially facilitate knowledge sharing. The utilisation of digital technologies can help disseminate information and further support these efforts.

While population growth and urbanisation continue to drive energy demand, it is surprising that population density, has a positive impact on renewable consumption. Thus, it becomes more economically and ecologically feasible to invest in renewable energy infrastructure, such as distributed energy sources and public transport electrification. To assist the transition, governments can enact urban planning regulations, offer financial incentives for energy efficiency and raise awareness to engage communities. Alternatively, steps to slow down urbanisation by providing incentives for people to live and work in rural areas can also be undertaken. These actions can further reduce greenhouse gas emissions and boost the productivity of renewable sources.

It is important to understand that sustainable energy and the circular economy are complementary. To manage their relationship successfully, stakeholders should target and monitor them alongside, while incorporating circular strategies in the renewable sector. The share of renewable energy consumption appears to be one suitable metric to track. As the study outlines key renewable energy consumption drivers, its findings may prove useful to policymakers, producers, consumers and researchers. Addressing opportunities and challenges through policy changes, educational channels and public awareness campaigns can stimulate the adoption of renewable energy, improve energy efficiency and accelerate the energy transition to meet climate targets.

References

Ackah, I., Kizys, R. (2015). Green growth in oil-producing African countries: A panel data analysis of renewable energy demand. – Renewable and Sustainable Energy Reviews, 50, pp. 1157-1166.

Adedoyin, F.F., Bekun, F.V. and Alola, A.A. (2020). Growth impact of transition from non-renewable to renewable energy in the EU: The role of research and development expenditure. – Renewable Energy, 159, pp. 1139-1145.

Ahmed, A.A., Nazzal, M.A., Darras, B.M. and Deiab, I.M. (2022). A comprehensive multi-level circular economy assessment framework. – Sustainable Production and Consumption, 32, pp. 700-717.

Akarsu, G. and Korucu Gümüşoğlu, N. (2019). What are the Main Determinants of Renewable Energy Consumption? A Panel Threshold Regression Approach. – Anadolu Üniversitesi Sosyal Bilimler Dergisi, 19(2), pp. 1-22.

Alam, M.S., Apergis, N., Paramati, S.R. and Fang, J. (2020). The impacts of R&D investment and stock markets on clean-energy consumption and CO_2 emissions in OECD economies. – International Journal of Finance & Economics, 26(4), pp. 4979-4992.

Apergis, N. and Payne, J.E. (2010). Renewable energy consumption and economic growth: Evidence from a panel of OECD countries. – Energy Policy, 38(1), pp. 656-660.

Apergis, N. and Payne, J.E. (2011). The renewable energy consumption-growth nexus in Central America. – Applied Energy, 88(1), pp. 343-347.

Baker, S.R., Bloom, N., Davis, S.J., Kost, K., Sammon, M. and Viratyosin, T. (2020). The Unprecedented Stock Market Reaction to COVID-19. – The Review of Asset Pricing Studies, 10(4), pp. 742-758.

Ben Jebli, M. and Ben Youssef, S. (2015). The environmental Kuznets curve, economic growth, renewable and non-renewable energy, and trade in Tunisia. – Renewable and Sustainable Energy Reviews, 47, pp. 173-185.

Bersalli, G., Menanteau, p. and El-Methni, J. (2020). Renewable energy policy effectiveness: A panel data analysis across Europe and Latin America. – Renewable and Sustainable Energy Reviews, 133, p. 110351.

Biernat-Jarka, A., Trębska, p. and Jarka, S. (2021). The Role of Renewable Energy Sources in Alleviating Energy Poverty in Households in Poland. – Energies, 14(10), p. 2957.

Cagno, E., Negri, M., Neri, A. and Giambone, M. (2023). One Framework to Rule Them All: An Integrated, Multi-level and Scalable Performance Measurement Framework of Sustainability, Circular Economy and Industrial Symbiosis. – Sustainable Production and Consumption, 35, pp. 55-71.

Chaikumbung, M. (2021). Institutions and consumer preferences for renewable energy: A meta-regression analysis. – Renewable and Sustainable Energy Reviews, 146, p. 111143.

Chang, T., Gupta, R., Inglesi-Lotz, R., Simo-Kengne, B., Smithers, D. and Trembling, A. (2015). Renewable energy and growth: Evidence from heterogeneous panel of G7 countries using Granger causality. – Renewable and Sustainable Energy Reviews, 52, pp. 1405-1412.

Chiaramonti, D. and Maniatis, K. (2020). Security of supply, strategic storage and Covid19: Which lessons learnt for renewable and recycled carbon fuels, and their future role in decarbonizing transport? – Applied Energy, 271, p. 115216.

Climate Watch. (2023). Data explorer: Historical emissions [Database]. Available at: <https://www.climatewatchdata.org/data-explorer/historical-emissions> [Accessed 22 March 2023].

Corona, B., Shen, L., Reike, D., Rosales Carreón, J. and Worrell, E. (2019). Towards sustainable development through the circular economy – A review and critical assessment on current circularity metrics. – Resources, Conservation and Recycling, 151, p. 104498.

De Rosa, M., Gainsford, K., Pallonetto, F. and Finn, D.P. (2022). European Energy Security: Diversification, Concentration and Renewability of Energy Supply. – Energy, 253, p. 124097.

Dehghan Shabani, Z. and Shahnazi, R. (2019). Energy consumption, carbon dioxide emissions, information and communications technology, and gross domestic product in Iranian economic sectors: A panel causality analysis. – Energy, 169, pp. 1064-1078.

Drukker, D.M. (2003). Testing for serial correlation in linear panel-data models. – The Stata Journal: Promoting communications on statistics and Stata, 3(2), pp. 168-77.

Dumitrescu, E.-I., Hurlin, C. (2012). Testing for granger non-causality in heterogeneous panels. – Economic Modelling, 29(4), pp. 1450-1460.

EEA. (2015). Renewable energy consumption – outlook from IEA. Available at: <https://www.eea.europa.eu/data-and-maps/indicators/renewable-energy-consumption-outlook-from-iea> [Accessed 22 March 2023].

EMF. (2023a). The Circular Economy Glossary. Available at: <https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/glossary> [Accessed 22 March 2023].

EMF. (2023b). What is a circular economy? Available at: <https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview> [Accessed 10 January 2024].

EP. (2023). Greenhouse gas emissions by country and sector. Available at: <https://www.europarl.europa.eu/news/en/headlines/society/20180301STO98928/greenhouse-gas-emissions-by-country-and-sector-infographic> [Accessed 23 Oct 2023].

Eurostat. (2023a). Eurostat database [Database]. Available at: <https://ec.europa.eu/eurostat/data/database> [Accessed 22 March 2023].

Eurostat. (2023b). EU imports of energy products – latest developments. Available at: <https://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_production_and_imports> [Accessed 23 Oct 2023].

Fernández-Amador, O., Francois, J. F., Oberdabernig, D. A., Tomberger, p. (2023). Energy footprints and the International Trade Network: A new dataset. Is the European Union doing it better? – Ecological Economics, 204, p. 107635.

Gate C. (2023). For a circular energy transition: Action Plan for Industry, Policymakers and Investors. Commissioned by the Green Purposes Company.

Haldar, A., Sucharita, S., Dash, D. p. , Sethi, N. and Chandra Padhan, p. (2023). The effects of ICT, electricity consumption, innovation and renewable power generation on economic growth: An income level analysis for the emerging economies. – Journal of Cleaner Production 384, pp. 135607-135607.

Hao, Y., Chen, H. and Zhang, Q. (2016). Will income inequality affect environmental quality? Analysis based on China's provincial panel data. – Ecological Indicators, 67, pp. 533-542.

Hausman, J.A. (1978). Specification tests in Econometrics. – Econometrica, 46(6), p. 1251.

Hu, Y., Jiang, W., Dong, H. and Majeed, M.T. (2022). Transmission channels between financial efficiency and renewable energy consumption: Does environmental technology matter in high-polluting economies? – Journal of Cleaner Production, 368, p. 132885.

Ibarra-Yunez, A., Pérez-Henríquez, B.L. (2017). Government effectiveness and regulatory quality and their impact on output growth in renewable energy. – SSRN Electronic Journal. 10.2139/ssrn.2922182.

IEA. (2019). Energy Transitions Indicators. Available at: <https://www.iea.org/articles/energy-transitions-indicators> [Accessed 22 March 2023].

IEA. (2020a). Put clean energy at the heart of stimulus plans to counter the coronavirus crisis. Available at: <https://www.iea.org/commentaries/put-clean-energy-at-the-heart-of-stimulus-plans-to-counter-the-coronavirus-crisis> [Accessed 22 March 2023].

IEA. (2020b) Renewable energy market update. Available at: <https://www.iea.org/reports/renewable-energy-market-update> [Accessed 22 March 2023].

Islam, Md.M., Irfan, M., Shahbaz, M. and Vo, X.V. (2022). Renewable and non-renewable energy consumption in Bangladesh: The relative influencing profiles of economic factors, urbanization, physical infrastructure and institutional quality. – Renewable Energy, 184, pp. 1130-1149.

Kalcher, L. (2023). A new zero-carbon industrial era. Available at: <https://strategicperspectives.eu/a-new-zero-carbon-industrial-era/> [Accessed 23 Oct 2023].

Kao, C., Chiang, M.-H., Chen, B. (1999). International R&D spillovers: An application of estimation and inference in panel cointegration. – Oxford Bulletin of Economics and Statistics, 61(s1), pp. 691-709.

Klemeš, J.J., Fan, Y.V. and Jiang, p. (2021). COVID-19 pandemic facilitating energy transition opportunities. – International Journal of Energy Research, 45(3), pp. 3457-3463.

Klemeš, J.J., Foley, A., You, F., Aviso, K., Su, R., Bokhari, A. (2023). Sustainable energy integration within the circular economy. – Renewable and Sustainable Energy Reviews, 177, p. 113143.

Kocsis, I. and Kiss, J.T. (2015). Renewable energy consumption, R&D and GDP in European Union countries. – Environmental Engineering and Management Journal, 13(11), pp. 2825-2830.

Kostakis, I. and Tsagarakis, K.P. (2021). Social and economic determinants of materials recycling and circularity in Europe: an empirical investigation. – The Annals of Regional Science, 68(2), pp. 263-281.

Kötter, C., Röcken, R., Moloney, p. (2023). Why circularity is key to a sustainable energy transition. Available at: <https://www.ramboll.com/insights/resource-management-and-circular-economy/why-circularity-is-key-to-a-sustainable-energy-transition> [Accessed 10 January 2024].

Kouton, J. (2019). Information Communication Technology development and energy demand in African countries. – Energy, 189, p. 116192.

Li, F., Zhang, J. and Li, X. (2022). Research on supporting developing countries to achieve green development transition: Based on the perspective of renewable energy and foreign direct investment. – Journal of Cleaner Production, 372, p. 133726.

Li, K., Qi, S. and Shi, X. (2022). The COVID-19 pandemic and energy transitions: Evidence from low-carbon power generation in China. – Journal of Cleaner Production, 368, p. 132994.

Li, S., Wang, Q., Jiang, X-ting., Li, R. (2022). The negative impact of the COVID-19 on renewable energy growth in developing countries: Underestimated. – Journal of Cleaner Production, 367, p. 132996.

Llorente-González, L.J. and Vence, X. (2019). Decoupling or 'Decaffing'? The Underlying Conceptualization of Circular Economy in the European Union Monitoring Framework. – Sustainability, 11(18), p. 4898.

Majeed, M.T., Luni, T. (2020). Renewable energy, circular economy indicators and environmental quality: A global evidence of 131 countries with heterogeneous income groups. – Pakistan Journal of Commerce and Social Sciences, 14(4), pp. 866-912.

Malik, I.A., Siyal, G-A., Bin Abdullah, A., Alam, A., Zaman, K., et al. (2014). Turn on the lights: Macroeconomic factors affecting renewable energy in Pakistan. – Renewable and Sustainable Energy Reviews, 38, pp. 277-284.

Marques, A.C., Fuinhas, J.A. and Pires Manso, J.R. (2010). Motivations driving renewable energy in European countries: A panel data approach. – Energy Policy, 38(11), pp. 6877-6885.

Marra, A. and Colantonio, E. (2022). The institutional and socio-technical determinants of renewable energy production in the EU: implications for policy. – Journal of Industrial and Business Economics, 49(2), pp. 267-299.

Mayer, A., Haas, W., Wiedenhofer, D., Krausmann, F., Nuss, p. and Blengini, G.A. (2018). Measuring Progress towards a Circular Economy: A Monitoring Framework for Economy-wide Material Loop Closing in the EU28. – Journal of Industrial Ecology, 23(1), pp. 62-76.

Mishra, R., Naik, B.K.R., Raut, R.D. and Kumar, M. (2022). Internet of Things (IoT) adoption challenges in renewable energy: A case study from a developing economy. – Journal of Cleaner Production, 371, p. 133595.

Moraga, G., Huysveld, S., De Meester, S. and Dewulf, J. (2021). Development of circularity indicators based on the in-use occupation of materials. – Journal of Cleaner Production, 279, p. 123889.

Moraga, G., Huysveld, S., Mathieux, F., Blengini, G.A., Alaerts, L. et al. (2019). Circular economy indicators: What do they measure? – Resources, Conservation and Recycling, 146(1), pp. 452-461.

Morikawa, M. (2012). Population density and efficiency in energy consumption: An empirical analysis of service establishments. – Energy Economics, 34(5), pp. 1617-1622.

Naderipour, A., Abdul-Malek, Z., Ahmad, N.A., Kamyab, H., Ashokkumar, V. et al. (2020). Effect of COVID-19 virus on reducing GHG emission and increasing energy generated by renewable energy sources: A brief study in Malaysian context. – Environmental Technology & Innovation, 20, p. 101151.

Nicola, M., Alsafi, Z., Sohrabi, C., Kerwan, A., Al-Jabir, A., Iosifidis, C., Agha, M. and Agha, R. (2020). The Socio-Economic Implications of the Coronavirus and COVID-19 Pandemic: A Review. – International Journal of Surgery, 78(1), pp. 185-193.

Niu, X., Dong, W.-K., Niu, X. and Muhammad Wasif Zafar (2023). The transition to clean energy and the external balance of goods and services as determinants of energy and environmental sustainability. – Gondwana Research.

Omri, E., Chtourou, N. and Bazin, D. (2022). Technological, economic, institutional, and psychosocial aspects of the transition to renewable energies: A critical literature review of a multidimensional process. – Renewable Energy Focus, 43, pp. 37-49.

Pagliaro, M. and Meneguzzo, F. (2020). Distributed Generation from Renewable Energy Sources: Ending Energy Poverty across the World. – Energy Technology, 8(7), p. 2000126.

Pantcheva, R. (2023). Circular use of materials: Drivers of the circularity rate in the European Union. – Economic Studies (Ikonomicheski Izsledvania), 32(3), pp. 148-161.

Pantcheva, R., Mengov, G. (2022). Recycling Rate in Europe: Econometric Modeling and dART Clustering Analysis. – In: 2022 International Conference Automatics and Informatics (ICAI), Varna, Bulgaria, pp. 179-182.

Papież, M., Śmiech, S. and Frodyma, K. (2018). Determinants of renewable energy development in the EU countries. A 20-year perspective. – Renewable and Sustainable Energy Reviews, 91, pp. 918-934.

Parchomenko, A., Nelen, D., Gillabel, J. and Rechberger, H. (2019). Measuring the circular economy – A Multiple Correspondence Analysis of 63 metrics. – Journal of Cleaner Production, 210, pp. 200-216.

Pedroni, p. (2001). Fully modified OLS for heterogeneous cointegrated panels. – In: Baltagi, B.H., Fomby, T.B., Carter Hill, R. (2001). Nonstationary Panels, Panel Cointegration, and Dynamic Panels (Advances in Econometrics, Vol. 15), Bingley: Emerald Group Publishing Limited, pp. 93-130.

Pereira, p. , Bašić, F., Bogunovic, I. and Barcelo, D. (2022). Russian-Ukrainian War Impacts the Total Environment. – Science of The Total Environment, 837(155865), p. 155865.

Pereira, p. , Zhao, W., Symochko, L., Inacio, M., Bogunovic, I. and Barcelo, D. (2022). The Russian-Ukrainian armed conflict will push back the sustainable development goals. – Geography and Sustainability, 3(3), pp. 277-287.

Pfeiffer, B., Mulder, p. (2013). Explaining the diffusion of renewable energy technology in developing countries. – Energy Economics, 40, pp. 285-96.

Prisecaru, p. (2022). The War in Ukraine and the Overhaul of EU Energy Security. – Global Economic Observer, 10(1), pp. 16-25.

Reich, R. H., Vermeyen, V., Alaerts, L., Van Acker, K. (2023). How to measure a circular economy: A holistic method compiling policy monitors. – Resources, Conservation and Recycling, 188, p. 106707.

Revez, A., Dunphy, N., Harris, C., Mullally, G., Lennon, B. and Gaffney, C. (2020). Beyond Forecasting: Using a Modified Delphi Method to Build Upon Participatory Action Research in Developing Principles for a Just and Inclusive Energy Transition. – International Journal of Qualitative Methods, 19, p. 160940692090321.

Saba, C.S. and Biyase, M. (2022). Determinants of renewable electricity development in Europe: Do Governance indicators and institutional quality matter? – Energy Reports, 8, pp. 13914-13938.

Salim, R.A. and Shafiei, S. (2014). Urbanization and renewable and non-renewable energy consumption in OECD countries: An empirical analysis. – Economic Modelling, 38, pp. 581-591.

Shahbaz, M., Wang, J., Dong, K. and Zhao, J. (2022). The impact of digital economy on energy transition across the globe: The mediating role of government governance. – Renewable and Sustainable Energy Reviews, 166, p. 112620.

Sharma, G.D., Tiwari, A.K., Erkut, B. and Mundi, H.S. (2021). Exploring the nexus between non-renewable and renewable energy consumptions and economic development: Evidence from panel estimations. – Renewable and Sustainable Energy Reviews, 146, p. 111152.

Sheinbaum-Pardo, C., Ruiz-Mendoza, B.J. and Rodríguez-Padilla, V. (2012). Mexican energy policy and sustainability indicators. – Energy Policy, 46, pp. 278-283.

Sidique, S.F., Joshi, S.V. and Lupi, F. (2010). Factors influencing the rate of recycling: An analysis of Minnesota counties. – Resources, Conservation and Recycling, 54(4), pp. 242-249.
The World Bank. (2023a). Worldwide Governance Indicators [Database]. Available at: <http://info.worldbank.org/governance/wgi/> [Accessed 22 March 2023].
The World Bank. (2023b). Databank [Database]. Available at: <https://databank.worldbank.org/home.aspx> [Accessed 22 March 2023].
Tian, J., Yu, L., Xue, R., Zhuang, S. and Shan, Y. (2022). Global low-carbon energy transition in the post-COVID-19 era. – Applied Energy, 307, p. 118205.
Tsao, Y.-C., Thanh, V.-V., Lu, J.-C. and Wei, H-H. (2021). A risk-sharing-based resilient renewable energy supply network model under the COVID-19 pandemic. – Sustainable Production and Consumption, 25, pp. 484-89.
Tu, Y-X., Kubatko, O., Piven, V., Sotnyk, I. and Kurbatova, T. (2022). Determinants of Renewable Energy Development: Evidence from the EU Countries. – Energies, 15(19), p. 7093.
United Nations. (2023). Population Division: Data [Database]. Available at: <https://www.un.org/development/desa/pd/data-landing-page> [Accessed 22 March 2023].
Vera, I. and Langlois, L. (2007). Energy indicators for sustainable development. – Energy, 32(6), pp. 875-882.
Wan, G., Wang, C., Wang, J. and Zhang, X. (2022). The income inequality-CO_2 emissions nexus: Transmission mechanisms. – Ecological Economics, 195, p. 107360.
Wang, J., Dong, X. and Dong, K. (2021). How renewable energy reduces CO_2 emissions? Decoupling and decomposition analysis for 25 countries along the Belt and Road. – Applied Economics, 53(40), pp. 4597-4613.
Wang, Q., Wang, L. and Li, R. (2022). Renewable energy and economic growth revisited: The dual roles of resource dependence and anticorruption regulation. – Journal of Cleaner Production, 337, p. 130514.
Wang, W., Xiao, W. and Bai, C. (2022). Can renewable energy technology innovation alleviate energy poverty? Perspective from the marketization level. – Technology in Society, 68, p. 101933.
Wooldridge, J.M. (2011). Serial Correlation and the Robust Variance Matrix Estimator. – In: Econometric analysis of cross section and panel data. Cambridge, Mass: MIT Press.
Xu, Q., Zhong, M. and Li, X. (2022). How does digitalization affect energy? International evidence. – Energy Economics, 107, p. 105879.
Yildirim, E., Saraç, Ş. and Aslan, A. (2012). Energy consumption and economic growth in the USA: Evidence from renewable energy. – Renewable and Sustainable Energy Reviews, 16(9), pp. 6770-6774.
Yu, L., Xue, B., Stückrad, S., Thomas, H. and Cai, G. (2020). Indicators for energy transition targets in China and Germany: A text analysis. – Ecological Indicators, 111, p. 106012.
Zakeri, B., Paulavets, K., Barreto-Gomez, L., Echeverri, L. G., Pachauri, S. et al. (2022). Pandemic, war, and Global Energy Transitions. – Energies, 15(17), p. 6114.
Zhong, H., Tan, Z., He, Y., Xie, L., Kang, C. (2020). Implications of Covid-19 for the Electricity Industry: A Comprehensive Review. – CSEE Journal of Power and Energy Systems, 6(3), pp. 489-495.