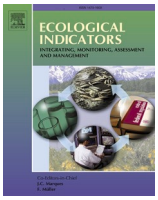
Ecological Indicators 139 (2022) 108912

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



Original Articles

Renewable energy consumption, environmental degradation and economic growth: the greener the richer?

Cosimo Magazzino [a], Pierluigi Toma [b,*], Giulio Fusco [c], Donatella Valente [d,*], Irene Petrosillo [d]

[a] Department of Political Science, Roma Tre University, Roma, Italy
[b] Department of Economics and Management, University of Salento, Lecce, Italy
[c] Regional Institute for Social and Economic Research (IPRES), Bari, Italy
[d] Lab. of Landscape Ecology, Department of Biological and Environmental Sciences and Technologies, University of Salento, Lecce, Italy

ARTICLE INFO

Keywords:
Sustainability
Renewable energy
CO_2 emissions
GDP
Panel data
Scandinavian countries

ABSTRACT

Climate change presents the greatest challenge facing all countries of the world in the new millennium. Among others, objective 13 of the Sustainable Development Goals (SDGs) aims at adopting urgent measures to contrast climate change and its consequences. Part of the decline in the global growth of emissions has been the increase in using renewable energies. In this context, the relationship among GDP, CO_2 emissions, and renewable energy use has been investigated in this study, starting from a systematic review that has noticed the presence of three clusters focused on: CO2 emissions, GDP, and energy consumption. Despite the current level of interest in examining the relationship among these variables, there have been few empirical studies. To fill this knowledge gap, this paper has been focused on the Scandinavian countries, where the use of renewable energies has steadily increased, developing novel panel analysis estimates. Using a dataset of these five economies over a 1990–2018 time period, several panel data tests have been carried out, in order to robustly assess the causality issue among renewable energies, CO_2 emissions, and GDP. The results of the empirical analysis imply that renewable energy consumption is a useful policy instrument to reduce CO_2 emissions without adversely affecting GDP growth. The main implications have been that the decrease of CO_2 emissions, by increasing renewable energy use, can guarantee high levels of energy efficiency and economic growth. These empirical findings help design innovative energy policy roadmaps and accelerate the ecological transition through the promotion of renewable energy and the reduction of GHG emissions.

1. Introduction

In 2015, the United Nations issued 17 Sustainable Development Goals (SDGs) to be achieved by 2030 (UN, 2017) in order to establish a new and concrete agenda for sustainable development. The 17 Goals refer to a set of important development issues that take into account in a balanced way the three dimensions of sustainable development-economic, social, and ecological. Among them, Objective 13 is aimed at Adopting urgent measures to contrast Climate Change and its consequences (UN, 2017). Climate change presents the greatest challenge facing all countries of the world in the new millennium. The need for reducing global CO_2 production represents a global environmental threat that requires a global response to create a real solution, otherwise, the continuous rising trend in CO_2 emissions will become even more problematic (IPCC, 2018).

The steady increase in the global average temperature is making environments increasingly costly and physically difficult to live in, creating a great risk to public health across all countries, developed or developing, and rich or poor (Watts et al., 2021; Gravili et al., 2020).

The sources of excessive carbon emissions are widespread, with the World Health Organization finding that exacerbating outdoor air pollution has caused approximately 4.2 million premature deaths yearly (Shaddick et al., 2020). Moreover, global warming intensifies the negative impact of seawater acidification, thus leading to coral bleaching and irreparable destruction of marine life (Hue et al., 2022).

The ambitious goals to contrast climate change, as set by the Paris Agreement, are unlikely to be achieved if the current speed of action in intervention operations continues to be maintained (United Nations

* Corresponding authors.
E-mail addresses: pierluigi.toma@unisalento.it (P. Toma), giulio.fusco@ipres.it (G. Fusco), pierluigi.toma@unisalento.itdonatella.valent, e@unisalento.it (D. Valente).

https://doi.org/10.1016/j.ecolind.2022.108912
Received 14 March 2022; Received in revised form 19 April 2022; Accepted 22 April 2022
Available online 28 April 2022
1470-160X/© 2022 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Environment Programme, 2020) as highlighted also during the Glasgow COP26 Conference. The reduction in the number of emissions in the decade 2020–2030 has been estimated at least 7.6% per year (United Nations Environment Programme, 2019). To this end, the European Green Deal has set the reduction of Greenhouse Gas (GHG) emissions by at least 55% by 2030 to allow us to achieve net-zero emissions by 2050 (European Commission, 2020), which however appears to be increasingly a chimera.

Over the years, the economic growth has had a negative impact on the quality of life of humans and especially on the environment and on the flux of Ecosystem Service (ES); for instance, in addition to the growth of GHG emissions, we have seen soil, air and water pollution, overexploitation of the soil, disorderly and excessive growth of cities, depletion of natural resources, etc., with enormous problems for global society (Charfeddine and Mrabet, 2017; Canaj et al., 2021).

Ecosystem services are fundamental to human well-being and maintaining the sustainability of such SEs and improving people's livelihoods are critical to global sustainable development. Global climate change has caused significant changes in ES supply (Atkinson et al., 2016; King et al., 2014). ES can represent the true links between nature and society, since they place the foundations of ES (i.e., ecosystem properties) as the basis for the realization of human well-being (Yu et al., 2017).

The International Energy Agency (IEA) has announced that, after two years of growth, global CO_2 emissions from energy sources in 2019 have stabilized at about 33 billion tons, roughly the same as in 2018 (IEA, 2020). However, a one-year freeze in CO_2 emissions does not indicate a world peak in emissions has been reached, as global GDP fell during the shutdowns facing many economies during the COVID-19 pandemic. However, it is a sign that the world's economies can have confidence in the possibilities arising from mitigating global warming to prevent future catastrophic levels of economic output and human wellbeing (Beard et al., 2021).

Part of the decline in the global growth of emissions has been the increase in using green fuel sources for electricity generation. For example, the IEA has found that a decline in the worldwide use of coal to produce electricity in 2019 has reduced global emissions of CO_2 by nearly 200 Mt, as compared to 2018. The most advanced economies (USA, Europe, and Japan) enjoyed an average GDP growth rate of 1.7% despite having reduced their emissions by over 370 Mt of CO_2. This reflects a 3.2% reduction in the electricity generation sector among the most advanced economies, bringing emissions to their lowest level since 1980, back when the electricity consumed was a third lower than in 2019 (IEA, 2020).

The energy transition in Europe passes through the countries of the North. Photovoltaic, wind, biomass, geothermal: these are the rapidly growing renewable sources in Sweden, Denmark, Finland, Iceland, and Norway, which suggest that the energy mix in these countries is increasingly greener. Sweden has reached and surpassed its first GW of photovoltaics, in Finland, the consumption of renewable energy exceeds that of fossil fuels, Denmark has committed to supply 100% renewable energy by 2050, and so on. Therefore, when it comes to energy transition in Europe, the countries of the North are the reference. This is also supported by the recent World Economic Forum report "Fostering Effective Energy Transition 2021". In the ranking, which considers 115 countries, the top three are respectively Sweden, Norway, and Denmark. But Finland (sixth) and Iceland (tenth) also appear in the top ten. Denmark and Finland, in addition to the United Kingdom, are the countries that have shown the most significant improvements in the top 10: they have been able to improve the performance of their energy system and sustainability results thanks to a stable regulatory environment, and energy mix and prices, which reflect the costs.

Nevertheless, different economic growth ambitions across the nations, as well as persistent international imbalances between the levels of economic development across the nations, make the geopolitical challenge of finding an international solution to this global problem exceptionally difficult. Indeed, the vast scientific literature on the relationship between CO_2 emissions and GDP growth, as well as what levels of cooperative actions would be necessary to adequately address the issue, has been growing steadily over the last decade.

Our paper focuses on identifying the relationship between GDP growth and CO_2 emissions over a sufficiently long period of time. This empirical analysis uses an appropriate econometric approach that focuses on data from some states of northern Europe. One of the shortcomings of the literature on this issue is the lack of data from homogeneous clusters of countries. This study investigates the dynamics relating to the relationship between GDP and CO_2 emissions using data collected from a group of states with common geographical proximity and similar economic development. Furthermore, these countries have formally committed to reducing emissions long ago. This allows us to perform a more robust, dynamic analysis in terms of economic impact, and capacity for predicting what may happen in other countries currently at the beginning of this path.

In this context, the present research has made a significant contribution in terms of highlighting how the modification of the structure of energy consumption is a key measure that contributes to sustainable economic growth. The contributions of this study are the simultaneous analysis of economic growth, CO_2 emissions, and the share of renewable energy in total final energy consumption in a single framework. Second, the pool of countries included in our analysis is also unique in that no previous study has studied these countries using econometrics in countries defined as global models for the use of renewable energy and which are comparable from one point of view. economic development. This is an important factor because in general, in countries that are at an early stage of development, economic growth creates a reckless exploitation of environmental resources without suffering the damage of the consequent environmental degradation.

The aim of the following analysis is to fill the existing gap in the literature as it relates to the effectiveness of renewable energy in containing a nation's CO_2 emissions without damping economic growth. We intend to evaluate this relationship robustly using data from advanced economies which are closer to the existing global technological frontier.

The layout of the paper is as follows. Section 2 provides a summary of contemporary research on the growth and CO_2 emissions. Section 3 presents the study area, while Section 4 describes the empirical methodology and data. In Section 5 we apply the proposed approach to the real case study and summarize the main findings. In Section 6 the empirical results are discussed, compared them to previous literature, and some policy recommendations are provided; finally, Section 7 concludes the study.

2. Literature review

Global warming and climate change represent the world's most important issues in the environment-economy nexus. GHG in general, and CO_2 emissions in particular, are the main factors responsible for global warming and climate change (Sari and Soytas, 2009; Esso and Keho, 2016; Magazzino and Falcone, 2022). In this context, many scholars and policymakers have turned their attention to the relationship between climate change, energy production, and sustainable economic growth. Many economists believe that inefficient environmental regulations and policies can limit an economy's production possibilities and hurt long-term economic growth (Ricci, 2007).

These relationships have been analyzed through different analytical approaches. One strand of research in the economics literature investigates the nexus between economic development and environmental pollution. These studies try to verify the Environmental Kuznets Curve (EKC) hypothesis, which postulates an inverted U-shaped relationship exists between different pollutants and per capita income in the economy. That is, environmental degradation in an economy initially increases with a nation's prosperity, but at some point, it eventually decreases as prosperity continues to rise further. Therefore, the EKC

hypothesis expresses a specific relationship between growth and environmental quality (Dinda, 2004; Arouri et al., 2012; Pérez-Suárez and López-Menéndez, 2015; Rüstemoğlu and Andrés, 2016). Other research has focused specifically on the relationship between a nation's energy consumption and its economic growth. The first effort in this direction was the study conducted by Kraft and Kraft (1978), from which the literature on causality emerged (Belloumi, 2009; Bélaïd and Abderrahmani, 2013; Omri, 2013). Other approaches investigated the relationship between energy consumption, economic growth, and pollution emissions (Ang, 2007; Arouri et al., 2012; Kasman and Duman, 2015; Magazzino et al., 2021a, 2021b; Mele et al., 2021a). The results of these studies vary depending on the country analyzed, which reflects several factors that differed across these empirical studies. This included institutional differences between countries, variations in model specifications, and econometric techniques used to examine the data.

In contrast to the popular analytical procedures previously described, the most recent empirical studies explore the relationship between economic growth and renewable energy consumption (Apergis and Payne, 2010a; b; 2011a; b; 2012a; b; Sadorsky, 2009; 2012; Tugcu et al., 2012; Magazzino, 2017; Apergis et al., 2018; Brady and Magazzino, 2018). Some researchers have focused on how renewable energy is enhancing economic growth while contrasting global warming. The new trend in the economic literature investigates the effects of both renewable and non-renewable energy consumption on the economy, but there are a few studies that have focused on the causal relationship between environmental degradation, renewable and/or non-renewable energy, and economic growth (Bélaïd & Ben Youssef, 2017). Chopra et al. (2022) highlighted that CO_2 emissions reduce agricultural productivity in the ASEAN countries. Magazzino et al. (2020) suggested a careful analysis of the process that will lead to the abandonment of nuclear energy in Switzerland to avoid adverse effects on economic growth. Below, we outline some results derived from this field of research (see Table 1).

Thanks to the rapid deployment of renewable energy across multiple countries, a growing number of studies have investigated how the role of renewable energy consumption has affected both environmental quality and economic development at the country, regional, and global levels. For example, Menyah and Wolde-Rufael (2010) used the Toda and Yamamoto (1995) test to explore the causal relationship between CO_2 emissions, nuclear energy, renewable energy, and economic growth in the USA over the period 1960–2007. Their investigation confirms a unidirectional causality from nuclear energy production to lower carbon emissions, finding evidence supporting the theory that non-renewable energy production has had a negative impact on both the environment and the economy. A second important result is a unidirectional causality from CO_2 emissions to renewable energy consumption.

A case study by Shafiei and Salim (2014) explored the relationship between non-renewable and renewable energy consumption and CO2 emissions among OECD countries using the Stochastic Impacts by Regression on Population, Affluence, and Technology model (STIRPAT model) over the period 1980–2011. Their results support the existence of an Environmental Kuznets Curve between CO_2 emissions and urbanization, supporting the theory that renewable energy consumption decreases CO_2 emissions, whereas non-renewable energy consumption increases CO_2 emissions. These results imply that policymakers should design and develop effective support policies to promote investment in new renewable energy technologies.

Jebly and Youssef (2015) investigate the link between GDP, combustible renewables and waste consumption (CWR), and CO_2 emissions across five North African countries during the period 1971–2008. Their findings suggest both short- and long-run unidirectional causalities spanning from CO_2 emissions and CRW consumption to real GDP and a short-run unidirectional causality where CRW decreases CO_2 emissions. Bekhet and Othman (2018) tried to estimate the gap between economic activity and environmental quality in Malaysia. They use the cubic polynomial functional form of EKC by placing renewable energy at the base of the EKC model and find supporting evidence for the relationship between CO_2 emissions and GDP growth for the 1971–2015 period. Their findings show that renewable energy has a negative impact on CO_2 emissions in the long-run perspective.

Finally, Mongo et al. (2021) implied an Auto-Regressive Distributed Lags (ARDL) model to assess the impact of environmental innovations, the consumption of renewable energies, GDP per capita, and the degree of economic openness on CO_2 emissions for 15 European countries over a 23-year span. The results show that, in the long-run, environmental innovations tend to lower CO_2 emissions.

It is really interesting to note that "GDP", "CO_2 emissions" or "ARDL model" are words that also appear in the Network Analysis, carried out with the keywords used in the bibliographic review (see Fig. 1).

Figure 1 shows the results of the network analysis, based on 1,002 keywords. The size of the label and of the node relating to a keyword are proportional to its weight, that is, a greater weight corresponds to a larger label and node. On the other hand, the color of each keyword associates it with the specific cluster, while the lines among the keywords represent the strength of the connections among them (Van Oijstaeijen et al., 2020).

The results have shown three clusters with the following central nodes: CO_2 emissions, GDP, and energy consumption. The most frequent keyword has been "CO_2 emissions" (red cluster), which has been, together with "renewable energy", one of the central topics of the systematic review. "CO_2 emissions" keyword has shown a great weight, evident from the size of the node, and the greatest number of elements (keywords) associated with it. Another important keyword has been "GDP" (blue cluster), a transversal topic associated with several research topics, such as financial development, urbanization, and climate change (Fig. 1). Finally, "energy consumption" has been the last cluster, less important than "CO2 emissions" and "renewable energy", as evident from the size of the node. In particular, "energy consumption" (green cluster) has resulted more linked with "sustainable development", "globalization", and "tourism" (Fig. 2).

Despite the current level of interest in examining the relationship among renewable energy, carbon emissions, and economic growth, there have been few empirical studies. To fill this knowledge gap, this paper has been focused on the Scandinavian countries, where the use of renewable energies has steadily increased, developing novel panel analysis estimates.

3. Study area

The study area is represented by the Scandinavian countries: Denmark, Finland, Iceland, Norway, and Sweden, which have been increasingly recurring to wind and other renewable energies in the last decade, contributing to the EU target of 20% final energy consumption from renewable sources by 2020.

4. Analytical methodology and data

We have selected a panel dataset of the Scandinavian countries over a relatively long period, from a renewable energy study standpoint. Specifically, our analysis has covered the period 1990–2018, with a total of 145 observations ($N = 5$, $T = 29$). The time period has been determined by the data availability from the World Bank (WB) database, which is freely online consultable[1].

The empirical estimation and the methodology applied in this paper are well established in the international literature (Bélaïd and Zrelli, 2019; Aydoğan and Vardar, 2020; Zhang and Zhang, 2021). The variables used in the analysis have included the Real Gross Domestic Product (*RGDP*), renewable energy (*RE*), and CO_2 emissions (*CO2Em*). In particular, in this research, *RGDP* has been used to indicate economic

[1] https://databank.worldbank.org/source/world-development-indicators.

Table 1
Literature review.

Author(s)	Variables	Country	Methods	Causality	Results
Menyah and Wolde-Rufael (2010)	CO_2, renewable energy, GDP, GDP per capita, nuclear energy consumption (NE)	USA	Granger causality	NE → C; RE⇏C	NE reduces CO_2 emission
Apergis and Payne (2014)	GDP, total renewable electricity (RE), CO_2, Oil price (P)	Central America	Panel unit root test, non-linear panel cointegration, Granger causality, FMOLS	RE, Y ↔ C	GDP, CO_2 and P increase RE
Ben Jebli and Ben Youssef (2015)	GDP per capita, combustible renewables and waste consumption per capita (CRW), CO_2 emissions per capita, population	North Africa	Granger causality, FMOLS, DOLS	LR: C, CWR → Y SR: CWR → C	CO_2 and CRW increase GDP; CWR increase CO_2 emission
Ben Jebli and Ben Youssef (2017)	CO_2, GDP per capita, agricultural value added per capita (AGR), renewable energy consumption per capita	North Africa	Panel unit root test, cointegration, Granger causality, FMOLS, and DMOLS	LR and SR: C ↔ A	AGR increases CO_2
Dogan and Ozturk (2017)	CO_2, GDP, RE, NRE (nonrenewable energy)	USA	ARDL	–	RE reduces CO_2, NRE increases CO_2
Bakhsh et al. (2017)	GDP, GDP per capita, FDI, Population, CO_2, renewable energy, Capital stock, Labor force	Pakistan	Three-Stage Last Square estimates	–	FDI, Labor force, Capital Stock increase GDP; GDP increases CO_2
Bekhet and Othman (2018)	CO_2, GDP, RE, (renewable energy), WR (waste resources)	Malaysian	VECM, Granger causality, CUSUM, CUSUMSQ	C → RE	RE reduces CO_2
Dong et al. (2018)	CO_2, GDP, NE, (Nuclear energy), FC (fossil consumption), RE (renewable energy)	China	ARDL, cointegration, unit root test, FMOLS, DOLS, VECM	SR: NE, RE, FC ↔ C LR: Y → RE, NE, FCE	NE, RE reduce CO_2 (S. Run); NE, RE reduce CO_2 (L. Run)
Cheng et al. (2019)	CO_2, RE (renewable energy), environmental development, related technologies, GDP, EX (exports), FDI, DCP (domestic credit to private sector).	BRIICS countries	Panel quantile, OLS regression	–	FDI, RE reduce CO_2, EX increases CO_2;
Bélaïd and Zrelli (2019)	EC (energy consumption), RE (renewable energy), NRE (non-renewable energy), GDP per capita, CO_2	Mediterranean countries	Panel cointegration	Y ↔ C, RE (SR); NRE ↔ Y, RE (SR); NRE ↔ C (LR); Y → C, NRE (LR)	NRE, GDP increase CO_2; RE reduces CO_2
Uzar (2020)	Renewable energy, Gini Index, GDP, Trade openness, CO_2, Corruption	World	Panel ARDL model	–	Gini Index increases RE; RE reduces CO_2
Usman et al. (2021)	CO_2, CE (Clean energy consumption), (CET) clean energy technologies, GDP, globalization, IQ (Institutional quality),	Europe	Panel cointegration, tests elasticities for long-run associations, tests for non-causality of heterogeneity	QI ↔ CE	CO_2, CET, GDP increase CE; IQ reduces CE
Salari et al. (2021)	CO_2, RE (renewable energy), NRE (non-renewable energy), TE (Total energy), IE (Industrial energy), (RHE) Residential energy, GDP per capita	USA	Panel dynamic (GMM AB, GMM BB)	–	NRE, IE, RHE increase CO_2; RE reduces CO_2
Mongo et al. (2021)	CO_2, (EIN) Innovation, renewable energies consumption, GDP, Economic openness	Europe	ARDL	–	EIN reduces CO_2
Nosheen et al. (2021)	DG (Degradation), GDP, GDP square, EN, TU (tourism), FD, TL (trade liberalization), URB (urbanization)	Asia	FMOLS, DOLS	–	TU, TL, URB increase DG

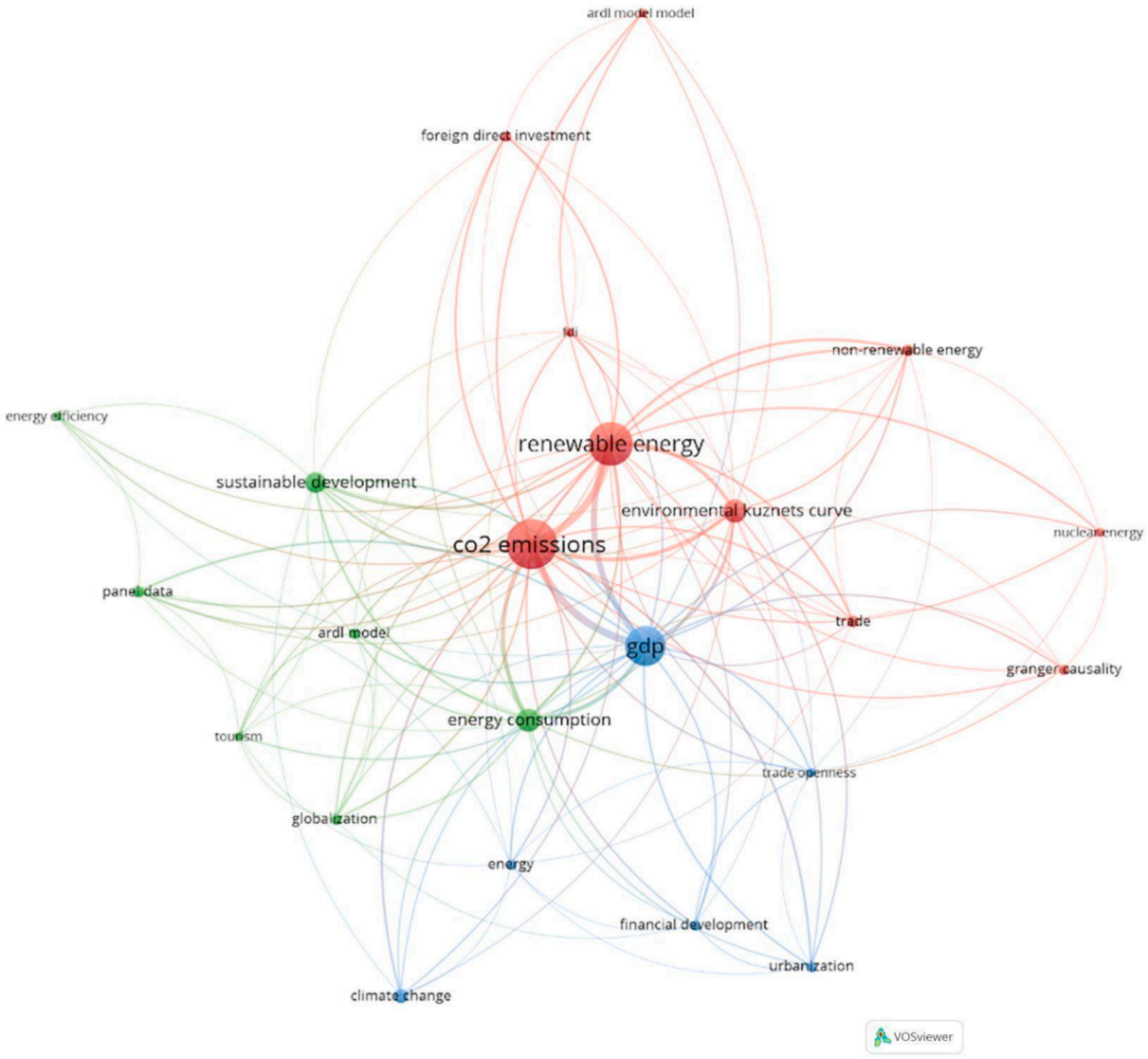
Notes: LR: Long-Run; SR: Short-Run; NE: nuclear energy; CWR: waste consumption; P: oil price; NRE: non-renewable energy; RE: renewable energy; A: agricultural value added; FC: fossil consumption; QI: quality of the institution; Y: economic growth; C: CO_2 emissions. ⇏ indicates no causal link between the variables.→indicates the existence of a unidirectional causality. ↔indicates the existence of bidirectional causality between the variables.

growth and is expressed in constant LCU (Local Currency Unit). *CO_2Em* is measured in metric tons per capita and it has been used as a proxy for environmental pollution as an indicator of the level of GHG emissions. Finally, *RE* is the share of renewable energy in total final energy consumption. All variables used in the analysis have been transformed into a logarithmic scale in order to make them comparable.

The empirical estimation of the model has been structured as follows (Fig. 3):

i) The first step tests for the presence of cross-sectional dependence across the sample using various Cross-sectional Dependence tests (CDs): the cross-section dependence is one of the main diagnostics to be performed before conducting panel data econometric procedures. Indeed, panel data might be affected by influential cross-sectional dependence, through which all units in the same cross-section are correlated, due to some unobserved common factors, or to spatial or spillover effects.
ii) In the second step employs a panel unit root test to determine the stationarity properties of all variable series.
iii) The third step investigates whether these variables present a cointegrating relationship by using different panel cointegration tests, including the Pedroni (1999) and Kao (1999) cointegration tests.
iv) The fourth step corrects the problems of serial correlation and endogeneity by using a Fully Modified OLS (FMOLS) methodology.
v) The fifth step applies the Dumitrescu and Hurlin (2012) panel pairwise causality tests to identify whether a causal link exists among variables.

All the previously described steps are necessary to apply a robust and appropriate procedure to analyze longitudinal data avoiding problems due to the common and specific (for our case) threats to the validity of the model.



Source: our elaborations in VOSviewer.

Fig. 1. Network analysis map.

5. Results

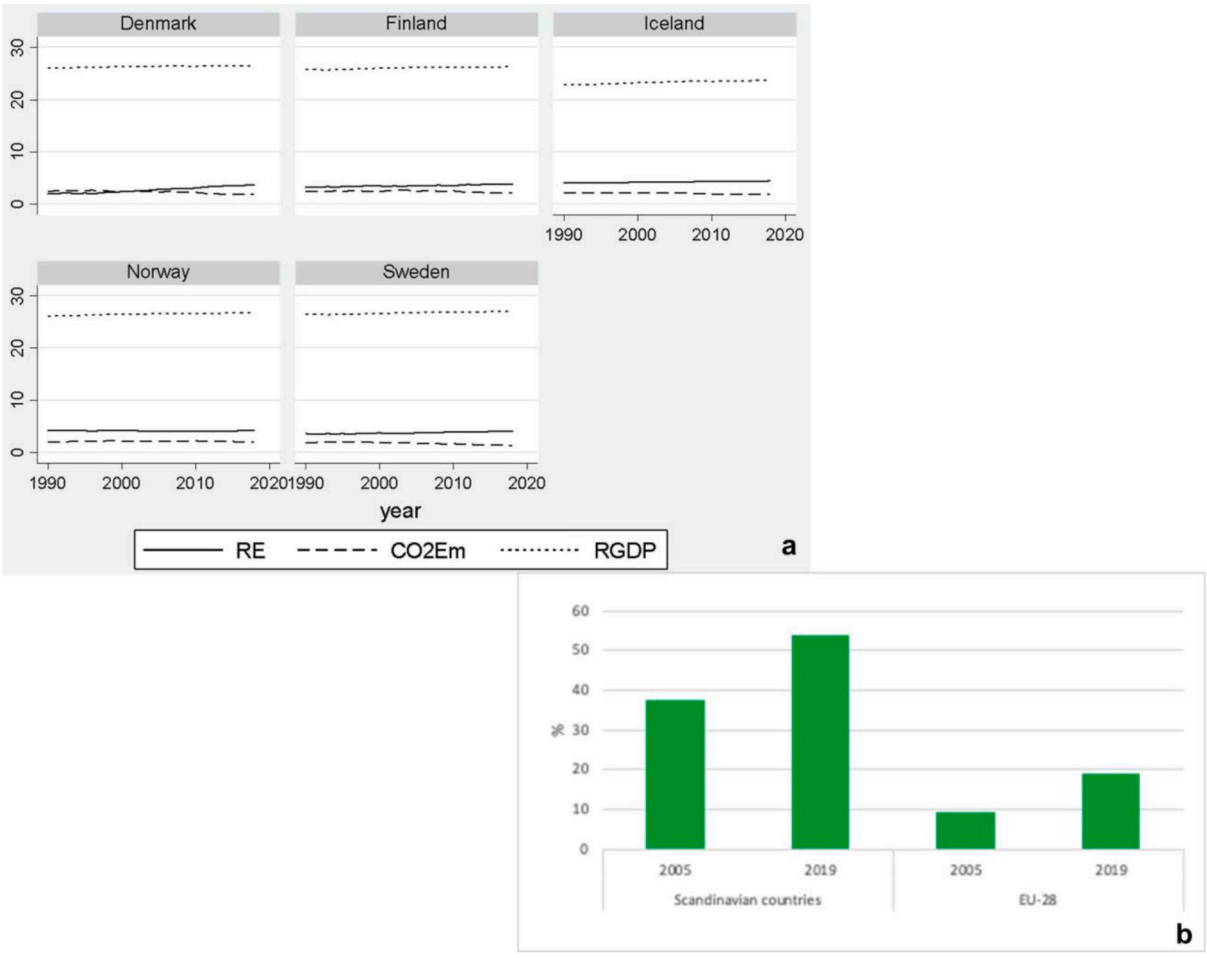
The descriptive statistics have highlighted that the mean and median values have been very similar for each variable in the sample, and the Inter-Quartile Range (IQR) generally has relatively low values. Together, these mean that the series under study have tended to exhibit a Gaussian distribution (Table 2). This is a fundamental condition allowing us to assess the correctness of the analysis for longitudinal data. The correlation matrix (Table 3) completes the descriptive statistics framework.

The North European countries under study could show some possible cross-country dependence due to similar economic policy measures, coupled with analogous fiscal behaviors that are linked to the macro-economic shocks of integrated economies. The scatterplot matrices of these variables are presented in Fig. 4.

We show the results of panel cross-section dependence tests for the selected sample in Table 4. The null hypothesis (H_0) of these tests is the absence of any cross-sectional dependence. The results in Table 4 have revealed that we could clearly reject the null hypothesis for all variables and at any traditional level of significance. Therefore, the cross-section dependence has been taken into account in the ongoing analysis.

On the basis of this cross-section dependence, the analysis has gone ahead with running the so-called second generation panel unit root tests (or panel unit root tests in presence of cross-section dependence), where the presence of cross-section dependence among the residuals is allowed within the panel. Generally speaking, the results in Table 5 have shown that we have failed to reject the non-stationarity hypothesis, with both deterministic specifications (with both a constant and a constant with a trend). Thus, we could assume that all variables in the dataset share cross-section dependence and are non-stationary.

The next step concerns the cointegration analysis. With this type of analysis, it is possible to establish a linear stationary relationship between non-stationary stochastic processes, in order to identify a stable relationship over time between variables that, taken individually, are not stable. The results of Kao's residual cointegration test and Pedroni's test for cointegration are shown in Table 6. Strong evidence has been found to reject the null hypothesis of no cointegration at the 1% level of significance in both the Pedroni and the Kao tests results. Therefore, it has been possible to conclude that a long-run cointegration relationship has emerged among the variables for the multi-country panel. These results have been consistent with both Lee (2005) and Sadorsky (2009) empirical findings.



Source of data: Nordic Co-operation (2021).

Fig. 2. (a) Renewable energy, CO_2 emissions, and real GDP in Scandinavian countries. (b) Comparison between Scandinavian countries and EU-28 countries in terms of renewable energy share (%).

Fig. 3. Steps followed to structure the empirical estimation of the model.

Therefore, assuming that renewable energy consumption, CO_2 emissions, and RGDP are all cointegrated, the long-run coefficients have been estimated by applying the FMOLS estimator (Pedroni, 2001). In general, the results have indicated a long-run negative co-movement for all relationships examined. Analyzing each country individually has revealed statistically significant coefficients at the 1% level for Denmark across the three estimated models. This means, for example, that a 1% increase in Denmark's real GDP leads to a 0.69% decrease in renewable energy consumption. Regarding the relationship between renewable energy consumption and CO_2 emissions, the magnitude of the estimated coefficient has varied from 0.9872 for Sweden to 0.2795 for Iceland. However, the coefficient has not been statistically significant for Finland and Norway. Table 6 shows a negative coefficient of renewable energy consumption on CO_2 emissions, indicating that increasing renewable energy consumption leads to falling CO_2 emissions.

The results in Table 7 indicate that the Scandinavian countries are converging towards a more sustainable economy that is focused on renewable energy with far less GHG production. The abundance of renewable sources (e.g., wind, solar, hydropower, photovoltaic waste, biomass, and geothermal) in most of these countries has likely stimulated the efficient development of renewable energy technologies as well as the investment in this type of energy. This positively affected their economic growth as well as reduced their GHG emissions (Fuinhas et al., 2017; Dinda, 2004; Brock and Taylor, 2005; Nowotny et al., 2018; Kahia et al., 2019; Magazzino et al., 2021d; Usman et al., 2021).

A positive and significant relationship between clean energy consumption and clean energy technology could justify incentivizing the development of environmentally friendly technologies based on sustainable energy use to effectively control and reduce environmental degradation through GHG production. The spread of this type of energy use could promote technology that enables a nation to enjoy an economic growth rate with less environmental impact (Tugcu et al., 2012;

Table 2
Descriptive statistics.

RE								
Country	Mean	Median	Std. Dev.	Skewness	Kurtosis	Range	IQR	CV
Denmark	2.6713	2.6684	0.5692	0.1920	1.6096	1.6179	1.0779	0.2131
Finland	3.4640	3.4421	0.1846	0.3566	2.1318	0.6158	0.2182	0.0533
Iceland	4.1689	4.1290	0.1436	0.0865	1.4344	0.4033	0.3157	0.0344
Norway	4.0731	4.0748	0.0271	−0.0162	1.7434	0.0872	0.0453	00,067
Sweden	3.6954	3.6891	0.1753	0.2200	1.6098	0.5229	0.2953	0.0474
Total	3.6145	3.7531	0.6075	−1.2592	3.9883	2.4076	0.6598	0.1681
CO2Em								
Country	Mean	Median	Std. Dev.	Skewness	Kurtosis	Range	IQR	CV
Denmark	2.2205	2.2997	0.2540	−0.6098	2.2082	0.8826	0.3543	0.1144
Finland	2.3584	2.3924	0.1548	−0.5837	2.4891	0.5663	0.1489	0.0656
Iceland	1.9648	2.0159	0.1108	−0.5130	1.7235	0.3754	0.2077	0.0564
Norway	2.0384	2.0484	0.0693	−0.4097	3.3706	0.3217	0.0803	0.0340
Sweden	1.6830	1.7752	0.2053	−0.5619	1.9912	0.7104	0.3379	0.1220
Total	2.0530	2.0458	0.2869	−0.2665	2.9149	1.3703	0.4332	0.1398
RGDP								
Country	Mean	Median	Std. Dev.	Skewness	Kurtosis	Range	IQR	CV
Denmark	26.2999	26.3400	0.1400	−0.5492	2.2020	0.4847	0.1920	0.0053
Finland	26.0250	26.1032	0.1985	−0.5990	1.8227	0.5807	0.3314	0.0076
Iceland	23.2808	23.3377	0.2972	−0.3355	1.8154	0.9463	0.4891	0.0128
Norway	26.4693	26.5193	0.1940	−0.6331	2.2223	0.6471	0.2457	0.0073
Sweden	26.6928	26.7247	0.2073	−0.1571	1.6791	0.6445	0.3737	0.0078
Total	25.7536	26.2567	1.2773	−1.3710	3.2084	4.2231	0.6691	0.0496

Notes: Std. Dev.: Standard Deviation; IQR: Interquartile Range; CV: Coefficient of Variation.
Sources: our elaborations on WDI data.

Table 3
Correlation matrix.

Variable	RE	CO2Em	RGDP
RE	1.0000		
CO2Em	−0.5660*** (0.0000)	1.0000	
RGDP	−0.3513*** (0.0000)	−0.0327 (0.9719)	1.0000

Notes: Sidak's correction has been applied, P-Values in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

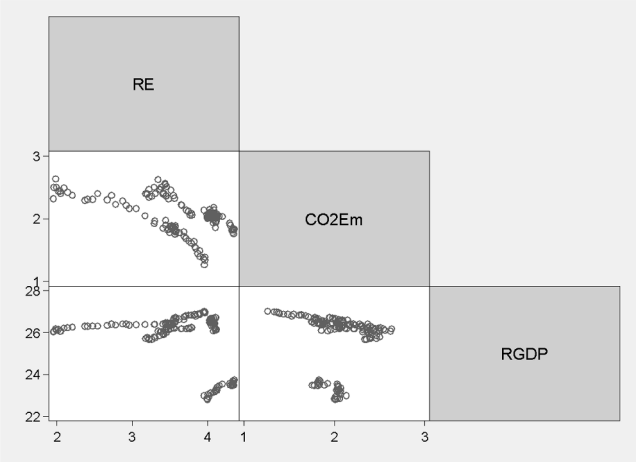


Fig. 4. Scatterplot matrices.

Table 4
Panel cross-section dependence tests.

Test	RE	CO2Em	RGDP
1. Pesaran (2004)	6.486***	6.808***	10.240***
	(0.0032)	(0.0000)	(0.0000)
2. Friedman (1937)	64.597***	68.965***	77.422***
	(0.0000)	(0.0000)	(0.0000)
3. Frees (1995)	0.628***	0.902***	1.166***
	(0.0000)	(0.0000)	(0.0000)
4. Chudik and	3.5637***	6.3247***	5.0375***
Pesaran (2015)	(0.0004)	(0.0000)	(0.0000)
5. Pesaran (2004)	7.6135***	10.6405***	16.6740***
CD	(0.0000)	(0.0000)	(0.0000)
6. Breusch-Pagan	170.7596***	138.1543***	278.0445***
(1980)	(0.0000)	(0.0000)	(0.0000)
7. Pesaran (2004)	35.9469***	28.6562***	59.9366***
LM	(0.0000)	(0.0000)	(0.0000)
8. Baltagi *et al.*	35.8577***	28.5669***	59.8473***
(2012)	(0.0000)	(0.0000)	(0.0000)

Notes: 1: Pesaran (2004) cross-sectional dependence in panel data models test;
2: Friedman (1937) test for cross-sectional dependence by using Friedman's $\chi 2$ distributed statistic;
3: Frees (1995) for cross-sectional dependence by using Frees' Q distribution (*T*-asymptotically distributed);
4: Chudik and Pesaran (2015) test for weak cross-sectional dependence;
5: Pesaran (2004) CD test for cross-section dependence in panel time-series data;
6: Breusch-Pagan (1980) LM test of independence;
7: Pesaran (2004) scaled LM test;
8. Baltagi *et al.* (2012) bias-corrected scaled LM test.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Ben Jebli et al., 2016; Yu et al, 2020).

In the last step of the analysis, the causality relationship between renewable energy consumption and CO_2 emissions has been assessed. In modern econometrics, this possibility is given only by using suitable estimators. Addressing in a proper way the causality means reinforcing the quality of results from an environmental and economic perspective and therefore the ecological policy implications that are discussed below.

The panel pairwise causality test results that appear in Table 8 have highlighted a bidirectional causal relationship between renewable energy consumption and CO_2 emissions. They also have revealed a causal

Table 5
Panel unit root tests in presence of cross-section dependence.

Variable	Specification	
	Constant	Constant and trend
Pesaran CADF test		
RE	0.355 (0.639)	0.614 (0.730)
CO2Em	0.525 (0.700)	−0.065 (0.474)
RGDP	0.350 (0.637)	−1.126 (0.130)
Pesaran (2007) test		
RE	−1.697	−2.096
CO2Em	−1.628	−3.303**
RGDP	−2.512**	−2.607

Notes: for Pesaran (2003) test, *Z-t*-bar statistics are reported; P-Values in parentheses. For both tests, deterministic chosen: constant: Critical Values: −2.210 (10%), −2.330 (5%), −2.570 (1%); deterministic chosen: constant and trend: Critical Values: −2.730 (10%), −2.860 (5%), −3.100 (1%).
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Table 6
Panel cointegration tests.

Pedroni's residual cointegration test			
	Relation	Individual intercept	Individual intercept and trend
Within-dimension	Panel *v*	1.7073** (0.0439)	0.8723 (0.1915)
	Panel *ρ*	−1.1435 (0.1264)	0.3522 (0.6377)
	Panel PP	−1.8323** (0.0335)	−0.9074 (0.1821)
	Panel ADF	−2.2550** (0.0121)	−1.0486 (0.1472)
Between-dimension	Group *ρ*	−0.4087 (0.3414)	1.0983 (0.8640)
	Group PP	−1.6539** (0.0491)	−3.6523*** (0.0001)
	Group ADF	−2.5842*** (0.0049)	−3.1878*** (0.0007)

Pedroni test for cointegration		
Statistic	**Constant**	**Constant and trend**
Modified Phillips-Perron *t*	−1.2608 (0.1037)	0.8685 (0.1926)
Phillips-Perron *t*	−3.6564*** (0.0001)	−0.1813 (0.4281)
Augmented Dickey-Fuller *t*	−2.0985** (0.0179)	−0.4288 (0.3341)
Kao's residual cointegration test		
ADF	−2.0217** (0.0216)	

Notes: Variance calculation: d.f. corrected Dickey-Fuller residual variances; automatic lag length selection based on SIC; spectral estimation: Bartlett kernel; bandwidth selection: Newey-West automatic.
P-Values in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Table 7
Panel estimates of the cointegrating relationship (FMOLS).

Country	CO2Em, RE	RE, RGDP	CO2Em, RGDP
Denmark	−0.6567*** (0.1907)	−0.6944*** (0.2165)	−0.6453*** (0.1534)
Finland	−0.9278 (0.6229)	−0.4686*** (0.1605)	−0.9257*** (0.1922)
Iceland	−0.2795*** (0.0864)	−0.9922*** (0.2400)	−0.1026 (0.1015)
Norway	−0.9752 (0.9159)	−0.2166*** (0.0752)	−0.3227 (0.2843)
Sweden	−0.9872*** (0.1565)	−0.4845 (0.3296)	−0.7478 (0.4864)

Notes: Robust Standard Errors in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

Table 8
Dumitrescu-Hurlin panel pairwise causality tests.

$RE_{it} \nRightarrow CO2Em_{it}$	$RE_{it} \nRightarrow RGDP_{it}$	$CO2Em_{it} \nRightarrow RGDP_{it}$
2.3369** (0.0194)	2.6810*** (0.0073)	−0.0356 (0.9716)
$CO2Em_{it} \nRightarrow RE_{it}$	$RGDP_{it} \nRightarrow RE_{it}$	$RGDP_{it} \nRightarrow CO2Em_{it}$
2.0469** (0.0407)	2.7388*** (0.0062)	4.2047*** (0.0000)

Notes: for Dumitrescu-Hurlin's tests the *Z*-bar statistics are reported. ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

relationship between renewable energy consumption and economic growth, while there is a unidirectional flow running from economic growth to CO_2 emissions.

A graphical synthesis of these relationships is shown in Fig. 5.

6. Discussion

The present study has aimed at inquiring about a central theme in sustainable development research based on the promotion of renewable energy production systems to mitigate CO_2 and GHG emissions, with positive effects on the GDP trends. The study area represented by the Scandinavian countries has been selected because they represent a virtuous example of a developed economy able to switch to a low carbon economy with the proper attitude and commitment towards global challenges.

The results have been in line with the international literature, coping with controversial statements of experts and scholars, and behaviors of different countries. Basically, developing and developed countries differently act to contrast global warming issues considering their pay-off deriving from the twofold opportunity of putting effort or not into decarbonization.

The question is: can the European nations generally be considered the front runners in achieving a sustainable environment with legible developmental milestones? This paper has presented a tentative to address this intriguing question by considering the methodologies deployed by developed economies (Usman et al., 2021), but by applying a different panel estimation to a very homogeneous group of European countries that represent the first to invest in reducing emissions. The analysis of the positive effects of investing in renewable energies on the reduction of COs emissions, and increasing real GDP can help guide the transition of other countries.

In general, this study has demonstrated the existence of a causal relationship between greater renewable energy consumption and lower CO_2 emissions, which is consistent with the previous empirical studies by Silva et al. (2012), Ito (2017), and Saidi and Omri (2020). The results of this analysis imply that renewable energy consumption can help other nations to reduce CO_2 emissions without suffering the loss of GDP growth that has been historically feared.

The policy implications arising from these empirical results could regard the increased renewable energy use with positive effects on the global environmental quality by reducing global environmental pollutants. On the other hand, the study of these Nordic countries can help in analyzing the reciprocal effects of renewable energies, energy efficiency, GDP, and sustainability. These empirical findings can help policymakers design innovative energy policy roadmaps aiming at promoting the use of renewable energy consumption and reducing GHG emissions.

A bidirectional causality between renewable energy consumption and CO_2 emissions is in line with empirical findings by Koengkan et al. (2020), Chen et al. (2019), Apergis et al. (2018), and Salim and Rafiq (2012). This causality flow implies a sort of interdependence among the consumption of renewable energy sources, economic activity, and CO_2 emissions. Further, Azam et al. (2021), Koengkan et al. (2020), Ismail et al. (2017), Kahia et al. (2017), Kocak and Sarkgunesi (2017), Rafindadi and Ozturk (2017), Shakouri and Yazdi (2017), Bildirici and Ersin (2015), Bloch et al. (2015), Shahbaz et al. (2015; 2012), Al-mulali et al.

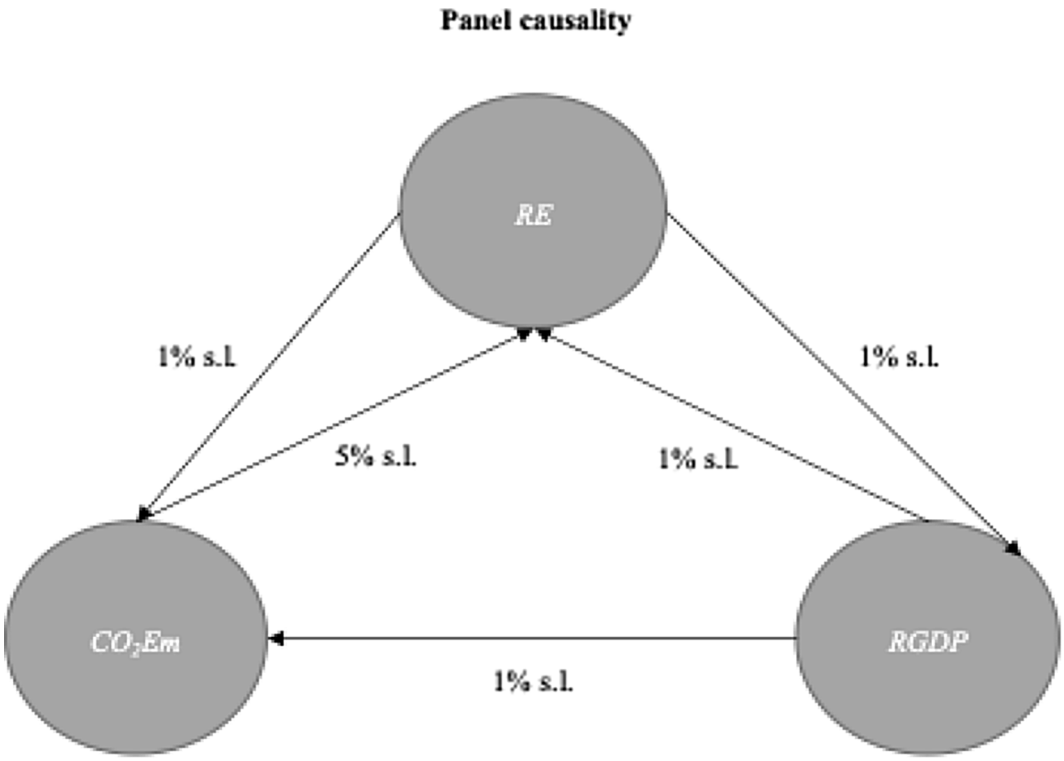


Fig. 5. Summary of causality results.

(2014), Ohler and Fetters (2014), Sebri and Ben-Salha (2014), Apergis and Payne (2010a; b; 2011a; b; 2012a; b), Salim and Rafiq (2012), and Tugcu et al. (2012) found bidirectional causality between renewable energy and economic growth, which support the feedback hypothesis. As per this hypothesis, renewable energy consumption and economic growth are interdependent. Moreover, Apergis et al. (2018), Ben Jebli et al. (2016), Farhani et al. (2014), Shahbaz et al. (2014), Govindaraju and Tang (2013), Niu et al. (2011), Wang et al. (2011), Chang (2010), and Jalil and Mahmud (2009) also provided empirical support to the existence of a unidirectional causality from economic growth to CO_2 emissions.

Here, the important finding is the existence of feedback hypothesis between renewable energy consumption and economic growth. This indicates that economic growth in the Scandinavian countries contributes to the renewable energy investment, and this in turn facilitates production and economic growth. This is a positive sign for taking initiatives for increasing renewable energy investments for sustainable economic growth (Ahmed and Shimada, 2019).

The results indicate that Scandinavian countries might still be following an energy-driven and environment-consuming development path. Therefore, it is urgent for these countries to facilitate energy-efficient emissions reduction technologies and to enhance environmental governance efforts when accelerating economic growth.

In fact, the impact that GDP can exert on emissions is evident. On the one hand, a more advanced economy can afford to use more advanced technologies, which allow a reduced environmental impact with a reduction in the level of emissions (and this is the case of the sample countries here analyzed). On the other hand, more backward economies – making use of more obsolete technologies – tend to pollute more.

This leads to interesting policy implications. In recent years, these five Scandinavian countries have all committed to using renewable energy to achieve very high percentages of their energy needs in their respective Energy Agreements. Policymakers could pay closer attention to these measures, as they indicate their nation's ability to increase the production of renewable energy.

Thus, the findings of this study show that for three of the five countries in the sample, renewable energy consumption negatively affects the amount of carbon dioxide emissions. Similarly, Khan *et al.* (2021a) and Bilgili et al. (2016) found that renewable energy consumption has a negative and significant impact on the proportion of CO_2 emissions. Also, Shafiei and Salim (2014) and Bélaïd and Zrelli (2019) provided similar results for OECD countries and Mediterranean Countries, demonstrating a negative relationship between renewable energy and the increase in CO_2 emissions.

These findings may indicate that the consumption of renewable energy could significantly reduce carbon dioxide emissions for any nation. This means an increase in the consumption of renewable energy can be expected to reduce a nation's dependence on fossil energy consumption, and thereby reduce carbon dioxide emissions. Support for such an argument was found in Thailand by Kusumadewi et al. (2017). Similarly, Salim and Rafiq (2012) find that the use of renewable energy tends to reduce the problem of environmental pollution in Brazil, China, India, and Indonesia.

The interaction between renewables and GDP per capita may mean that affluent nations with high levels of fossil fuels and renewables tend to squeeze out nuclear power, which is an electricity source that is not captured by either category (renewables or fossil fuels). In this case, high levels of renewables make economic growth dependent on fossil fuels in place of nuclear power, and conversely, in affluent nations with nuclear power, growth in renewables tends to substitute more for nuclear power than for fossil fuels (York and McGee, 2017). A similar result has been found by Sovacool et al. (2020), whose analysis used a multiple regressions specification on global datasets of national carbon emissions and renewable and nuclear electricity production across 123 countries over a period of 25 years. The empirical results revealed that large use of nuclear energy could not be associated with a direct reduction of CO_2 emissions, where a nation's attachment to nuclear and renewable fuel sources tends to crowd each other out.

From a short-term perspective, policymakers can create several measures, such as tax incentives and subsidies for low GHG-emitting energy sources (Galinato and Yoder, 2010), sectoral subsidies to increase the production/usage of biomass energy fuels (Bilgili, 2012), a system of fair and affordable access to the electricity from renewable sources (Reiche and Bechberger, 2004), feed-in tariffs (Kalkuhl et al., 2013), and green certificate trading. In the long-term, policymakers can subsidize renewable energy technologies, promote private investment grant policies, and create investment subsidies (Bilgili et al., 2016). Ultimately, countries must make use of properly defined rules and policies that promote lower GHG emission concentrations and sustainable economic development, such as proper carbon pricing, and GHG emissions taxation, and motivate the development of technologies that require less carbon utilization.

However, it is important to underline that our empirical results should be considered as "total" (=direct + indirect) effects, and not – strictly speaking – pure direct effects.

Ultimately, three policy implications emerge from the results. First, there is now no doubt that renewable energies improve environmental well-being. Secondly, the Nordic countries have high energy efficiencies. Technological innovation plays an effective role in the link between energy and growth, and in addition, it represents a significant indicator to reveal the connection between economic growth and the use of renewable energies. Finally, the Scandinavian countries can be one of the most virtuous examples of the use of renewable energy with a view to reducing CO_2 emissions and therefore environmental sustainability, however, greater political, financial, and scientific research support is needed to activate processes of low-carbon energy transitions in various fields.

7. Conclusions

The 2030 Agenda for Sustainable Development is an action program for people, the planet, and prosperity that takes into account the need to support universal peace and freedom, to eradicate poverty in all its forms and dimensions. However, there is a need to propose an economic system based on well-being (Fioramonti et al., 2022) that would make a great contribution to human and ecological well-being, by including costs and benefits linked not only to the market but to society as a whole in the system.

The interconnection between carbon dioxide emissions, economic growth, and GHG is perhaps the most researched term in environmental economics. A nation's efforts to reduce GHG emissions with a minimal negative impact on economic development is a major milestone in attaining future sustainable economic growth (Khan et al., 2021b). Economists usually refer to relative decoupling as the condition when a nation's increases in carbon emissions fall behind increases in economic development. Achieving this goal requires an empirical analysis of emissions, which is also commonly referred to as the GDP relationship. This connection is of vital importance for the developing (and developed) regions of the global economy, as those regions are considered the major contributors to the increased global warming (Song et al., 2019).

Investing in renewable energies can represent an economic insurance for the future, since it could be one strategy to reduce risks and uncertainties towards climate change (Valente et al., 2019). Ecological insurance, the assessment of economic and ecological vulnerability and/or resilience, and the adaptive management of socio-ecological systems can represent key and interacting elements able to mitigate the risk of damages due to meteorological disasters.

The results of this study are timely and significant in shaping global climate policy because they are ambitious CO_2 reduction targets, such as controlling global warming to 2 °C, as in the agreement entered into in the 2015 Paris Agreement (COP 21) which requires understanding primarily the links between energy consumption, economic growth, use of renewable resources and CO_2 emissions. This, in turn, makes it possible to define effective CO_2 mitigation and reduction policies in the fight against the harmful impacts of climate change and thus contributing to global sustainability.

The income elasticity of carbon dioxide emissions, as a measure of the response of GHG emissions to growth in the economy, is another way to examine the issue of decoupling. However, the Granger causality test indicated no evidence that shows the existence of a positive causal relationship running from renewable energy consumption to economic growth that was expected. This may be due to Scandinavian Countries having relatively low levels of both energy intensity and CO_2 emissions (Irandoust, 2016; 2018; Ducoing, 2021). Future research might explore this topic for Scandinavian countries with a different approach, for example by applying Artificial Intelligence (AI) techniques (Magazzino et al., 2020, 2021c, 2021e, 2022; Mele et al., 2021b) and the contribution of renewable energies in terms of human well-being. Moreover, another possibility for future works may involve a proper structural approach, entailing the estimation of these relationships jointly, also disentangling direct and indirect effects, through the estimation of a Structural Equation Model (SEM).

CRediT authorship contribution statement

Cosimo Magazzino: Conceptualization, Formal analysis, Methodology, Supervision. **Pierluigi Toma:** Conceptualization, Formal analysis, Methodology. **Giulio Fusco:** Data curation, Investigation. **Donatella Valente:** Validation, Writing – review & editing. **Irene Petrosillo:** Supervision, 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.

Acknowledgements

Pierluigi Toma received research support from the Italian Ministry of University, Project PON Attraction and International Mobility, n. AIM1823220

References

Ahmed, M.M., Shimada, K., 2019. The effect of renewable energy consumption on sustainable economic development: evidence from emerging and developing economies. Energies 12, 2954.
Al-mulali, U., Fereidouni, H.G., Lee, J.Y.M., 2014. Electricity consumption from renewable and non-renewable sources and economic growth: evidence from Latin American countries. Renew. Sustain. Energy Rev. 30, 290–298.
Ang, J.B., 2007. CO_2 emissions, energy consumption, and output in France. Energy Policy 35 (10), 4772–4778.
Apergis, N., Ben Jebli, M., Ben Youssef, S., 2018. Does renewable energy consumption and health expenditures decrease carbon dioxide emissions? Evidence for sub-Saharan Africa countries. Renewable Energy 127, 1011–1016.
Apergis, N., Payne, J.E., 2010a. Renewable energy consumption and economic growth: evidence from a panel of OECD countries. Energy Policy 38 (1), 656–660.
Apergis, N., Payne, J.E., 2010b. Renewable energy consumption and growth in Eurasia. Energy Econ. 32 (6), 1392–1397.
Apergis, N., Payne, J.E., 2011a. Renewable and non-renewable electricity consumption–growth nexus: evidence from emerging market economies. Appl. Energy 88 (12), 5226–5230.
Apergis, N., Payne, J.E., 2011b. The renewable energy consumption–growth nexus in Central America. Appl. Energy 88 (1), 343–347.
Apergis, N., Payne, J.E., 2012a. Renewable and non-renewable energy consumption-growth nexus: evidence from a panel error correction model. Energy Econ. 34 (3), 733–738.
Apergis, N., Payne, J.E., 2012b. The Electricity consumption-growth nexus: renewable versus non-renewable electricity in central America. Energy Sources Part B 7 (4), 423–431.
Apergis, N., Payne, J.E., 2014. Renewable energy, output, CO_2 emissions, and fossil fuel prices in Central America: evidence from a nonlinear panel smooth transition vector error correction model. Energy Econ. 42, 226–232.
Atkinson, S., Fuller, S., Painter, J., 2016. Wellbeing and Place. Routledge, London/New-York.

Aydoğan, B., Vardar, G., 2020. Evaluating the role of renewable energy, economic growth and agriculture on CO_2 emission in E7 countries. Int. J. Sustain. Energ. 39 (4), 335–348.
Azam, A., Rafiq, M., Shafique, M., Zhang, H., Ateeq, M., Yuan, J., 2021. Analyzing the relationship between economic growth and electricity consumption from renewable and non-renewable sources: fresh evidence from newly industrialized countries. Sustainable Energy Technol. Assess. 44, 100991.
Arouri, M.E.H., Ben Youssef, A., M'henni, H., Rault, C., 2012. Energy consumption, economic growth and CO_2 emissions in Middle East and North African countries. Energy Policy 45, 342–349.
Bakhsh, K., Rose, S., Ali, M.F., Ahmad, N., Shahbaz, M., 2017. Economic growth, CO_2 emissions, renewable waste and FDI relation in Pakistan: New evidences from 3SLS. J. Environ. Manage. 196, 627–632.
Beard, S.J., Holt, L., Tzachor, A., Kemp, L., Avin, S., Torres, P., Belfield, H., 2021. Assessing climate change's contribution to global catastrophic risk. Futures 127, 102673.
Bekhet, H.A., Othman, N.S., 2018. The role of renewable energy to validate dynamic interaction between CO_2 emissions and GDP toward sustainable development in Malaysia. Energy Econ. 72, 47–61.
Bélaïd, F., Abderrahmani, F., 2013. Electricity consumption and economic growth in Algeria: a multivariate causality analysis in the presence of structural change. Energy Policy 55, 286–295.
Bélaïd, F., Ben Youssef, M., 2017. Environmental degradation, renewable and non-renewable electricity consumption, and economic growth: assessing the evidence from Algeria. Energy Policy 102, 277–287.
Bélaïd, F., Zrelli, M.H., 2019. Renewable and non-renewable electricity consumption, environmental degradation and economic development: evidence from Mediterranean countries. Energy Policy 133, 110929.
Belloumi, M., 2009. Energy consumption and GDP in Tunisia: Cointegration and causality analysis. Energy Policy 37 (7), 2745–2753.
Ben Jebli, M., Ben Youssef, S., 2015. Economic growth, combustible renewables and waste consumption, and CO_2 emissions in North Africa. Environ. Sci. Pollut. Res. 22 (20), 16022–16030.
Ben Jebli, M., Ben Youssef, S., Ozturk, I., 2016. Testing environmental Kuznets curve hypothesis: The role of renewable and non-renewable energy consumption and trade in OECD countries. Ecol. Ind. 60, 824–831.
Bildirici, M., Ersin, O., 2015. An investigation of the relationship between the biomass energy consumption, economic growth and oil prices. Procedia Soc. Behav. Sci. 210, 203–212.
Bilgili, F., 2012. Linear and nonlinear TAR panel unit root analyses for solid biomass energy supply of European countries. Renew. Sustain. Energy Rev. 16 (9), 6775–6781.
Bilgili, F., Koçak, E., Bulut, Ü., 2016. The dynamic impact of renewable energy consumption on CO_2 emissions: A revisited Environmental Kuznets Curve approach. Renew. Sustain. Energy Rev. 54, 838–845.
Bloch, H., Rafiq, S., Salim, R., 2015. Economic growth with coal, oil and renewable energy consumption in China: Prospects for fuel substitution. Econ. Model. 44, 104–115.
Brady, G.L., Magazzino, C., 2018. The relationship among renewable energy, economic growth, labor and capital formation in Italy. Rivista di Studi sulla Sostenibilità 1, 35–48.
Brock, W.A., Taylor, M.S., 2005. Economic growth and the environment: a review of theory and empirics. Handb. Econ. Growth 1, 1749–1821.
Canaj, K., Mehmeti, A., Morrone, D., Toma, P., Todorović, M., 2021. Life cycle-based evaluation of environmental impacts and external costs of treated wastewater reuse for irrigation: a case study in southern Italy. J. Cleaner Prod. 293, 126142.
Charfeddine, L., Mrabet, Z., 2017. The impact of economic development and social-political factors on ecological footprint: a panel data analysis for 15 MENA countries. Renew. Sustain. Energy Rev. 76, 138–154.
Chang, C.-C., 2010. A multivariate causality test of carbon dioxide emissions, energy consumption and economic growth in China. Appl. Energy 87 (11), 3533–3537.
Chen, Y., Wang, Z., Zhong, Z., 2019. CO_2 emissions, economic growth, renewable and non-renewable energy production and foreign trade in China. Renewable Energy 131, 208–216.
Cheng, C., Ren, X., Wang, Z., Yan, C., 2019. Heterogeneous impacts of renewable energy and environmental patents on CO_2 emission-Evidence from the BRIICS. Sci. Total Environ. 668, 1328–1338.
Chopra, R., Magazzino, C., Shah, M.I., Sharma, G.D., Rao, A., Shahzad, U., 2022. The role of renewable energy and natural resources for sustainable agriculture in ASEAN countries: do carbon emissions and deforestation affect agriculture productivity? Resour. Policy 76, 102578.
Dinda, S., 2004. Environmental Kuznets curve hypothesis: a survey. Ecol. Econ. 49 (4), 431–455.
Dong, K., Sun, R., Jiang, H., Zeng, X., 2018. CO_2 emissions, economic growth, and the environmental Kuznets curve in China: what roles can nuclear energy and renewable energy play? J. Cleaner Prod. 196, 51–63.
Dogan, E., Ozturk, I., 2017. The influence of renewable and non-renewable energy consumption and real income on CO_2 emissions in the USA: evidence from structural break tests. Environ. Sci. Pollut. Res. 24 (11), 10846–10854.
Ducoing, C., 2021. Weak Sustainability Trends in the Andean and Nordic Countries: A Historical Perspective. In: Natural Resources and Divergence. Palgrave Macmillan, Cham, pp. 257–278.
Dumitrescu, E.-I., Hurlin, C., 2012. Testing for Granger non-causality in heterogeneous panels. Econ. Model. 29 (4), 1450–1460.
Esso, L.J., Keho, Y., 2016. Energy consumption, economic growth and carbon emissions: cointegration and causality evidence from selected African countries. Energy 114, 492–497.
European Commission. 2020. State of the Union: Commission raises climate ambition and proposes 55% cut in emissions by 2030. https://ec.europa.eu/commission/presscorner/detail/en/IP_20_1599.
Farhani, S., Chaibi, A., Rault, C., 2014. CO_2 emissions, output, energy consumption, and trade in Tunisia. Econ. Model. 38, 426–434.
Fioramonti, L., Coscieme, L., Costanza, R., Kubiszewski, I., Trebeck, K., Wallis, S., Roberts, D., Mortensen, L.F., Pickett, K.E., Wilkinson, R., Ragnarsdottír, K.V., McGlade, J., Lovins, H., De Vogli, R., 2022. Wellbeing economy: An effective paradigm to mainstream post-growth policies? Ecol. Econ. 192, 107261.
Fuinhas, J.A., Marques, A.C., Koengkan, M., 2017. Are Renewable Energy Policies Upsetting Carbon Dioxide Emissions? The Case of Latin America Countries. Environ. Sci. Pollut. Res. 24 (17), 15044–15054.
Galinato, G.I., Yoder, J.K., 2010. An integrated tax-subsidy policy for carbon emission reduction. Resour. Energy Econ. 32 (3), 310–326.
Govindaraju, V.C., Tang, C.F., 2013. The dynamic links between CO_2 emissions, economic growth and coal consumption in China and India. Appl. Energy 104, 310–318.
Gravili, G., Manta, F., Cristofaro, C.L., Reina, R., Toma, P., 2020. Value that matters: intellectual capital and big data to assess performance in healthcare. An empirical analysis on the European context. J. Intellectual Capital.
Hue, T., Chateau, O., Lecellier, G., Marin, C., Coulombier, N., Le Dean, L., Gossuin, H., Adjeroud, M., Dumas, P., 2022. Impact of near-future ocean warming and acidification on the larval development of coral-eating starfish Acanthaster cf. Solaris after parental exposure. J. Exp. Mar. Biol. Ecol. 548, 151685.
Intergovernmental Panel on Climate Change (IPCC), 2018. Summary for policymakers. In: Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. https://www.ipcc. ch/sr15/.
Irandoust, M., 2016. The renewable energy-growth nexus with carbon emissions and technological innovation: Evidence from the Nordic countries. Ecol. Ind. 69, 118–125.
Irandoust, M., 2018. Innovations and renewables in the Nordic countries: a panel causality approach. Technol. Soc. 54, 87–92.
Ismail, A.G., Rashid, A.A., Hanif, A., 2017. Electricity consumption and economic growth in ASEAN. J. Emerg. Econ. Islamic Res. 5 (2), 16–27.
Ito, K., 2017. CO_2 emissions, renewable and non-renewable energy consumption, and economic growth: evidence from panel data for developing countries. Int. Econ. 151, 1–6.
Jalil, A., Mahmud, S.F., 2009. Environment Kuznets curve for CO_2 emissions: a cointegration analysis for China. Energy Policy 37 (12), 5167–5172.
Jebli, M.B., Youssef, S.B., 2015. The environmental Kuznets curve, economic growth, renewable and non-renewable energy, and trade in Tunisia. Renew. Sustain. Energy Rev. 47, 173–185.
Kahia, M., Aissa, M., Lanouar, C., 2017. Renewable and non-renewable energy use – economic growth nexus: the case of MENA Net Oil Importing Countries. Renew. Sustain. Energy Rev. 71, 127–140.
Kahia, M., Ben Jebli, M., Belloumi, M., 2019. Analysis of the impact of renewable energy consumption and economic growth on carbon dioxide emissions in 12 MENA countries. Clean Technol. Environ. Policy 21 (4), 871–885.
Kalkuhl, M., Edenhofer, O., Lessmann, K., 2013. Renewable energy subsidies: second-best policy or fatal aberration for mitigation? Resour. Energy Econ. 35 (3), 217–234.
Kao, C., 1999. Spurious regression and residual-based tests for cointegration in panel data. J. Econometrics 90 (1), 1–44.
Kasman, A., Duman, Y.S., 2015. CO_2 emissions, economic growth, energy consumption, trade and urbanization in new EU member and candidate countries: a panel data analysis. Econ. Model. 44, 97–103.
Khan, H., Weili, L., Khan, I., Khamphengxay, S., Kazak, J., 2021a. Renewable energy consumption, trade openness, and environmental degradation: a panel data analysis of developing and developed countries. Math. Probl. Eng. 2021, 1–13.
Khan, I., Hou, F., Zakari, A., Tawiah, V.K., 2021b. The dynamic links among energy transitions, energy consumption, and sustainable economic growth: a novel framework for IEA countries. Energy 222, 119935.
King, M.F., Renò, V.F., Novo, E.M., 2014. The concept, dimensions and methods of assessment of human well-being within a socioecological context: a literature review. Soc. Indic. Res. 116 (3), 681–698.
Kocak, E., Sarkgunesi, A., 2017. The renewable energy and economic growth nexus in black sea and Balkan Countries. Energy Policy 100, 51–57.
Koengkan, M., Fuinhas, J.A., Santiago, R., 2020. The relationship between CO_2 emissions, renewable and non-renewable energy consumption, economic growth, and urbanization in the Southern Common Market. J. Environ. Econ. Policy 9, 4.
Kraft, J., Kraft, A., 1978. On the relationship between energy and GNP. J. Energy Dev. 401–403.
Kusumadewi, T.V., Winyuchakrit, P., Limmeechokchai, B., 2017. Long-term CO_2 emission reduction from renewable energy in power sector: the case of Thailand in 2050. Energy Procedia 138, 961–966.
Lee, C.-C., 2005. Energy consumption and GDP in developing countries: a cointegrated panel analysis. Energy Econ. 27 (3), 415–427.
Magazzino, C., 2017. Renewable energy consumption-economic growth nexus in Italy. Int. J. Energy Econ. Policy 7 (6), 119–127.
Magazzino, C., Falcone, P.M., 2022. Assessing the relationship among waste generation, wealth, and GHG emissions in Switzerland: some policy proposals for the

optimization of the municipal solid waste in a circular economy perspective. J. Cleaner Prod. 351, 131555.
Magazzino, C., Mele, M., Morelli, G., 2021a. The relationship between renewable energy and economic growth in a time of Covid-19: a Machine Learning experiment on the Brazilian economy. Sustainability 13 (3), 1285.
Magazzino, C., Mele, M., Schneider, N., 2021b. A Machine Learning approach on the relationship among solar and wind energy production, coal consumption, GDP, and CO_2 emissions. Renewable Energy 167, 99–115.
Magazzino, C., Mele, M., Schneider, N., 2021c. A D2C algorithm on the natural gas consumption and economic growth: challenges faced by Germany and Japan. Energy 219, 19586.
Magazzino, C., Mele, M., Schneider, N., Sarkodie, S.A., 2021d. Waste generation, wealth and GHG emissions from the waste sector: is Denmark on the path towards Circular Economy? Sci. Total Environ. 755 (1), 142510.
Magazzino, C., Mele, M., Schneider, N., Shahbaz, M., 2021e. Can Biomass energy curtail environmental pollution? A quantum model approach to Germany. J. Environ. Manage. 287, 112293.
Magazzino, C., Mele, M., Schneider, N., Shahzad, U., 2022. Does export product diversification spur energy demand in the APEC region? Application of a new neural networks experiment and a decision tree model. Energy Build. 258, 111820.
Magazzino, C., Mele, M., Schneider, N., Vallet, G., 2020. The relationship between nuclear energy consumption and economic growth: evidence from Switzerland. Environ. Res. Lett. 15 (9), 0940a5.
Mele, M., Gurrieri, A.R., Morelli, G., Magazzino, C., 2021a. Nature and climate change effects on economic growth: an LSTM experiment on renewable energy resources. Environ. Sci. Pollut. Res. 28 (30), 41127–41134.
Mele, M., Magazzino, C., Schneider, N., Nicolai, F., 2021b. Revisiting the dynamic interactions between economic growth and environmental pollution in Italy: evidence from a gradient descent algorithm. Environ. Sci. Pollut. Res. 28 (37), 52188–52201.
Menyah, K., Wolde-Rufael, Y., 2010. CO_2 emissions, nuclear energy, renewable energy and economic growth in the US. Energy Policy 38 (6), 2911–2915.
Mongo, M., Belaïd, F., Ramdani, B., 2021. The effects of environmental innovations on CO_2 emissions: empirical evidence from Europe. Environ. Sci. Policy 118, 1–9.
Niu, S., Ding, Y., Niu, Y., Li, Y., Luo, G., 2011. Economic growth, energy conservation and emissions reduction: a comparative analysis based on panel data for 8 Asian-Pacific countries. Energy Policy 39 (4), 2121–2131.
Nosheen, M., Iqbal, J., Khan, H.U., 2021. Analyzing the linkage among CO_2 emissions, economic growth, tourism, and energy consumption in the Asian economies. Environ. Sci. Pollut. Res. 28 (13), 16707–16719.
Nowotny, J., Dodson, J., Fiechter, S., Gür, T.M., Kennedy, B., Macyk, W., Bak, T., Sigmund, W., Yamawaki, M., Rahman, K.A., 2018. Towards global sustainability: education on environmentally clean energy technologies. Renew. Sustain. Energy Rev. 81, 2541–2551.
Ohler, A., Fetters, I., 2014. The causal relationship between renewable electricity generation and GDP growth: a study of energy sources. Energy Econ. 43, 125–139.
Omri, A., 2013. CO_2 emissions, energy consumption and economic growth nexus in MENA countries: Evidence from simultaneous equations models. Energy Econ. 40, 657–664.
Pedroni, P., 1999. Critical values for cointegration tests in heterogeneous panels with multiple regressors. Oxford Bull. Econ. Stat. 61 (s1), 653–670.
Pedroni, P., 2001. Fully modified OLS for heterogeneous cointegrated panels. In: Nonstationary panels, panel cointegration, and dynamic panels. Emerald Group Publishing Limited.
Pérez-Suárez, R., López-Menéndez, A.J., 2015. Growing green? Forecasting CO_2 emissions with environmental Kuznets curves and logistic growth models. Environ. Sci. Policy 54, 428–437.
Rafindadi, A., Ozturk, I., 2017. Impacts of renewable energy consumption on the German economic growth: evidence from combined cointegration test. Renew. Sustain. Energy Rev. 75, 1130–1141.
Reiche, D., Bechberger, M., 2004. Policy differences in the promotion of renewable energies in the EU member states. Energy Policy 32 (7), 843–849.
Ricci, F., 2007. Channels of transmission of environmental policy to economic growth: a survey of the theory. Ecol. Econ. 60 (4), 688–699.
Rüstemoğlu, H., Andrés, A.R., 2016. Determinants of CO_2 emissions in Brazil and Russia between 1992 and 2011: a decomposition analysis. Environ. Sci. Policy 58, 95–106.
Sadorsky, P., 2009. Renewable energy consumption and income in emerging economies. Energy Policy 37, 4021–4028.
Sadorsky, P., 2012. Energy consumption, output and trade in South America. Energy Econ. 34, 476–488.
Saidi, K., Omri, A., 2020. The impact of renewable energy on carbon emissions and economic growth in 15 major renewable energy-consuming countries. Environ. Res. 186, 109567.
Salari, M., Javid, R.J., Noghanibehambari, H., 2021. The nexus between CO_2 emissions, energy consumption, and economic growth in the US. Econ. Anal. Policy 69, 182–194.
Salim, R.A., Rafiq, S., 2012. Why do some emerging economies proactively accelerate the adoption of renewable energy? Energy Econ. 34, 1051–1057.
Sari, R., Soytas, U., 2009. Are global warming and economic growth compatible? Evidence from five OPEC countries? Appl. Energy 86 (10), 1887–1893.
Sebri, M., Ben-Salha, O., 2014. On the causal dynamics between economic growth, renewable energy consumption, CO_2 emissions and trade openness: fresh evidence from BRICS countries. Renew. Sustain. Energy Rev. 39, 14–23.
Shaddick, G., Thomas, M.L., Mudu, P., Ruggeri, G., Gumy, S., 2020. Half the world's population are exposed to increasing air pollution. NPJ Clim. Atmos. Sci. 3 (1), 1–5.
Shafiei, S., Salim, R.A., 2014. Non-renewable and renewable energy consumption and CO_2 emissions in OECD countries: a comparative analysis. Energy Policy 66, 547–556.
Shahbaz, M., Loganathan, N., Zeshan, M., Zaman, K., 2015. Does renewable energy consumption add in economic growth? An application of auto-regressive distributed lag model in Pakistan. Renew. Sustain. Energy Rev. 44, 576–585.
Shahbaz, M., Sbia, R., Hamdi, H., Ozturk, I., 2014. Economic growth, electricity consumption, urbanization and environmental degradation relationship in United Arab Emirates. Ecol. Ind. 45, 622–631.
Shahbaz, M., Zeshan, M., Afza, T., 2012. Is energy consumption effective to spur economic growth in Pakistan? New evidence from bounds test to level relationships and Granger causality tests. Econ. Model. 29, 2310–2319.
Shakouri, B., Yazdi, S.K., 2017. Causality between renewable energy, energy consumption, and economic growth. Energy Sources Part B 12, 9.
Silva, S., Soares, I., Pinho, C., 2012. The impact of renewable energy sources on economic growth and CO_2 emissions: a SVAR approach. Eur. Res. Stud. J. 15 (4), 133–144.
Song, Y., Zhang, M., Zhou, M., 2019. Study on the decoupling relationship between CO_2 emissions and economic development based on two-dimensional decoupling theory: a case between China and the United States. Ecol. Ind. 102, 230–236.
Sovacool, B.K., Schmid, P., Stirling, A., Walter, G., MacKerron, G., 2020. Differences in carbon emissions reduction between countries pursuing renewable electricity versus nuclear power. Nat. Energy 5 (11), 928–935.
Toda, H.Y., Yamamoto, T., 1995. Statistical inference in vector autoregressions with possibly integrated processes. J. Econom. 66 (1–2), 225–250.
Tugcu, C.T., Ozturk, I., Aslan, A., 2012. Renewable and non-renewable energy consumption and economic growth relationship revisited: evidence from G7 countries. Energy Econ. 34, 1942–1950.
UN, 2017. United Nations - Resolution adopted by the General Assembly on 6 July 2017, Work of the Statistical Commission pertaining to the 2030 Agenda for Sustainable Development.
United Nations Environment Programme. 2019. Emissions Gap Report 2019. https://wedocs.unep.org/bitstream/handle/20.500.11822/30797/EGR2019.pdf?sequence=1&isAllowed=y.
United Nations Environment Programme. 2020. Emissions Gap Report 2020. https://wedocs.unep.org/bitstream/handle/20.500.11822/34438/EGR20ESE.pdf?sequence=25.
Usman, M., Ma, Z., Zafar, M.W., Waheed, A., Li, M., 2021. Analyzing the determinants of clean energy consumption in a sustainability strategy: evidence from EU-28 countries. Environ. Sci. Pollut. Res. 1–14.
Uzar, U., 2020. Is income inequality a driver for renewable energy consumption? J. Cleaner Prod. 255, 120287.
Valente, D., Miglietta, P.P., Porrini, D., Pasimeni, M.R., Zurlini, G., Petrosillo, I., 2019. A first analysis on the need to integrate ecological aspects into financial insurance. Ecol. Model. 392, 117–127.
Van Oijstaeijen, W., Van Passel, S., Cools, J., 2020. Urban green infrastructure: A review on valuation toolkits from an urban planning perspective. J. Environ. Manage. 267, 110603.
Wang, S.S., Zhou, D.Q., Zhou, P., Wang, Q.W., 2011. CO_2 emissions, energy consumption and economic growth in China: a panel data analysis. Energy Policy 39, 4870–4875.
Watts, N., Amann, M., Arnell, N., Costello, A., 2021. The 2020 report of the Lancet Countdown on health and climate change: responding to converging crises. Lancet 397, 129–179.
York, R., McGee, J.A., 2017. Does renewable energy development decouple economic growth from CO_2 emissions? Socius 3, 1–6.
Yu, D., Fu, B., Lu, N., 2017. Establishment of a comprehensive indicator system for the assessment of biodiversity and ecosystem services. Landscape Ecol. 32, 1563–1579.
Yu, L., Xue, B., Stückrad, S., Thomas, H., Cai, G., 2020. Indicators for energy transition targets in China and Germany: a text analysis. Ecol. Ind. 111, 106012.
Zhang, X., Zhang, X., 2021. Nexus among economic growth, carbon emissions, and renewable and non-renewable energy in China. Environ. Sci. Pollut. Res. 28 (29), 39708–43972.

Further reading

Hammar, H., Åkerfeldt, S., 2015. CO_2 Taxation in Sweden. Experiences of the Past and Future.
Nordic Co-operation, 2021. Renewable Energy in the Nordics 2021. Available online: https://www.norden.org/en/publication/renewable-energy-nordics-2021.