UNIVERSITÀ DI FOGGIA

Dipartimento di Economia, Management e Territorio

(DEMeT)

Doctoral Thesis in "Economia, Cultura, Ambiente. Scienze Economiche e Umanistiche per la valorizzazione dei Territori"

– XXXVII cycle –

Essays on Energy Issues

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Author's Declaration

I, **Maria Shabir** hereby declare that the contents of the thesis ***Essays on energy issues*** are the product of my own research and no part has been copied from any publication source (except the references, standard mathematical models/ equations/ protocols, etc.). I further declare that this work has not been submitted by me for the award of any other diploma/degree.

This thesis contains three research articles.

The first article, titled "*Energy innovation and ecological footprint: Evidence from OECD countries during 1990–2018*" (with Pazienza, P. and De Lucia, C.) has been published in 2023 in the international peer review journal *Technological Forecasting and Social Change, 196*, 122836. https://doi.org/10.1016/j.techfore.2023.122836.

The second article, titled "*Investigating a new energy justice index on carbon emissions: A global study of 95 economies during 1996-2021*" (with De Lucia, C., and Pazienza, P.) is currently under review in the *Journal of Environmental Management*.

The third article, titled *"Green growth and spillover effects: From micro- to macro perspectives of the PESTLE framework in 30 European economies"* (with Ahmad, S., Hine, D., De Lucia, C., Pazienza, P., Matarrese, M. M.) has been presented at the latest Regional Studies Association Winter Conference 2024, London, 7-8 November, 2024. An updated version, which considered the feedback from the participants of the conference, has been submitted to the international peer reviewed journal *Global Environmental Change*.

In addition, I declare the following publication as paper in conference proceedings.

Shabir, M., Basile, G., Pazienza, P., & De Lucia, C. (2023). Does energy democracy affect economic growth? early evidence from high income countries during 1997–2020. Proceedings of the 13th International Scientific Conference "Business and Management 2023", Vilnius Gediminas Technical University, Lithuania. https://doi.org/10.3846/bm.2023.1070. https://etalpykla.vilniustech.lt/handle/123456789/154005



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Maria Shabir

Acknowledgement

I would like to express my sincere gratitude and indebtedness to all who guided and facilitated me during my journey of doctoral study. First, this study was made possible by the generous support from the University of Foggia, Italy and Ministry of Education, University and Research (MIUR). Secondly, I would like to extend my heartfelt gratitude to my supervisors, Professor Dr. Pasquale Pazienza, and my co-supervisor, Professor Dr. Caterina De Lucia for their unwavering support throughout my PhD journey and related research. The patience, kindness and friendship I received from my supervisors made my PhD experience an enjoyable one. Although I faced many challenges during this journey, my supervisory committee was always a source of inspiration for me. Because of their encouragement and sincere advice, I remained committed and motivated throughout my doctoral study. I will always remember their indefatigable assistance with the completion of this dissertation. I could not have imagined having better advisors and mentors.

Beside my supervisors, I would like to thank Prof. Alessandro Muscio and Prof. Antonio Lopolito, and my external co-supervisor, Dr. Shabbir Ahmad, from the University of Queensland, Australia, and Prof. Damian Hine from the same institution, for their insightful comments and encouragement, as well as for the challenging questions that motivated me to broaden my research from various perspectives. I really acknowledge their assistance and value their suggestions to improve this dissertation.

I owe many thanks to the current coordinator of the department, Antonio Corvino, for his timely support and guidance. I also want to thank the endless encouragement and advice of Dr Marco Maria Matarrese, and my colleagues Fabeha, Nazgul, Giuseppe Basile and Angelo Porcaro for their keen interest in my studies, research endeavors, personal well-being and for all the fun we had in the last three years (coffee and lunch gathering). I also want to thank all DEMeT staff for the encouragement, support and friendship I received from all of them. I will forever cherish the friendship you have shown me.

Finally, I want to express my sincerest gratitude to my lovely father, uncles, sisters and cousins for their unwavering moral support and best wishes.

Maria Shabir

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Abstract

In this era of economic advancements, global economies are suffering with significant energy issues, from fulfilling growing energy demand to protecting environmental health. The main objective of this PhD Dissertation is to highlight the energy challenges and explore how energy innovations, energy justice and environmentally friendly energy sources influence green growth processes.

The first paper of this PhD Dissertation is titled *Energy innovation and ecological footprint: Evidence from OECD countries during 1990–2018*" and addresses the issue on the relationship among technological innovations in energy markets and environmental damage, which still receives contrasting views from the international debate. On the one hand, technological advancements in energy markets are seen as 'solitary steps' to tackle green growth; on the other hand, massive investments in research and development (R&D), as well as other financial mechanisms, are needed. The paper advances and contributes to the current literature because actual facts and figures motivate us to investigate the effects of ad-hoc socio-economic co-variates on a proxy of environmental degradation such as the ecological footprint, thus extending the majority of literature focusing on CO2 emissions. Second, the literature lacks in expoloring these relationships from the perspective of the sampled OECD countries. Lastly, to test the above relationships, the paper uses advanced econometric procedures.

The second paper of this PhD Dissertation focuses on energy justice, which has emerged as a contemporary research agenda that pursues the integration of justice principles into energy policy. However, its role in achieving carbon neutrality goals remains undiscovered in academic literature. To address this gap, the paper builds a new energy justice index with the use of the entropy-based method and is aligned with the Sustainable Development Goals (SDGs) 7 (equitable clean energy access), 10 (inequality reduction), and 13 (climate action), thus extending the 2015 work of Sovacool & Dworkin. Second, together with other socio-economic covariates, it infers CO2 emissions in 95 different income groups economies such as high-income, upper-middle-income, lower-middle-income, and low-income countries from 1996 to 2021. Finally, to test the above relationships, this second paper uses advanced econometric techniques such as the novel Method of Moments Quantile Regression.

Although energy justice promotes fairness in the energy and socio-economic system, it does not address the growth aspects of societies. Green growth is a comprehensive approach that stimulates economic progress with ecosystem conservation. The third paper of this PhD Dissertation addresses the issue of green growth according to a spatial perspective. The novelty

of this work is to extend the microeconomic firm-related PESTLE (political, economic, social, technological, legal, and environmental) framework (Francis Aguilar, 1967) to a macroeconomic perspective of green growth in 30 European economies from 1996 to 2021. The study also tests spatial dependencies and spillover effects through a Spatial Durbin Model. Main findings suggest that improvements in the home country's institutional quality, financial development, human development, technological innovation, and environmental policy favour green growth in adjacent countries. The need of national regulations for energy infrastructures and cross-border collaborations for a renowned European industrial and energy policy are highly encouraged to favour green growth.

Chapter 1

General Introduction

1.1. Environmental Crisis Causes and Consequences

"The greatest threat to our planet is the belief that someone else will save it"

Robert Swan, Author

This Doctoral Dissertation, titled "*Essays on energy issues*" is an extensive collection of three scholarly articles that explore the complex relationship between energy economics and environmental sustainability. My PhD journey began in January 2022 at the Department of Economics, Management, and Territory (DEMeT) at the University of Foggia, Italy, under the supervision of Professor Dr. Pasquale Pazienza and Professor Dr. Caterina De Lucia. During my doctoral experience, I had the opportunity to publish my work in a notable academic journal. My article titled "Energy innovation and ecological footprint: Evidence from OECD countries during 1990–2018" has been published in *Technological Forecasting and Social Change*. During the third year of my PhD, I joined the university of Queensland as a visiting researcher where I spent six months and learned spatial econometrics. During this period, I employed spatial econometrics techniques and investigated the spatial spillover impacts of green growth across 30 European economies. This experience not only enhanced my research skills, but gave me valuable international exposure in terms of culture. Upon my returning from Australia in September 2024, I had the opportunity to present my work at the Regional Studies Association Winter Conference in London.

The world is experiencing a trade-off between profit-driven economic growth and environmental sustainability (Sinha et al., 2023). The drive towards sustainability is one of the biggest challenges of the 21st century. Many anthropogenic activities such as burning fossil fuels, population growth, rapid urbanization, and industrialization, are the sources of greenhouse gas (GHG) emissions (Shahbaz, et al., 2023). These issues exacerbate various economic and social problems, such as low GDP growth, reduced productivity, increased healthcare costs, price volatility, income disparities, poverty, and inflation (Wen et al., 2023). Numerous anthropogenic activities, including deforestation (the clearing of forests and vegetation for urbanization and agriculture), electricity generation (causing water usage, methane leakage, and air pollution), excessive transportation use, oil and gas extraction, and the establishment of industries in urban areas, are major contributors to climate change (Nguyen 2023;Olaniyi et al., 2023;Shabir et al., 2023). Recent research by Radmehr et al., (2023), Khurshid et al., (2024) argued that environmental degradation directly affects the

energy supply and demand gap; indirectly, it accelerates geopolitical uncertainty, and border conflicts with oil -producing and importing nations(Sinha et al., 2023). The growth patterns of nations are continually amplifying the ecological deficit while diminishing the Earth's carrying capacity (Zhao et al., 2022). A report published by IEA, claimed greenhouse gas emissions rose by 46.7% from 1990 to 2016 (International Energy Agency, 2022).

In this capitalist world, every country attempts to become economically stronger without prioritizing environmental quality (Kongbuamai et al., 2020). Economic growth and environmental quality are complementary goods and there exists a reciprocal relationship between them (Khan et al., 2021; Ahmed et al., 2022; Brubacher et al., 2024; Paleari, 2024). This relationship was firstly explored by Grossman et al., (1991) who found an inverted U-shape association between economic progress and environmental degradation in Mexico. Inverted-U shape correlation shows that, in the earlier stages of economic development, economies pay more attention to economic growth over environmental quality, thus demanding more energy and production of electricity from non-renewable energy sources and leading to increase CO2 emissions (Khan et al., 2022). During the composition effect, numerous structural changes occur where the countries shift from agriculture to industry. This sectoral transformation increases industrial processes, which, in turn, affects energy demand and put a pressure on natural resource extraction(Saqib et al., 2023). However, after reaching a income threshold, further increases in income leads to an income/technological substitution effect which reduces the ecological burden.

In literature scholars have used various environmental indicators to measure the environmental wellbeing of societies. Earlier studies by Mensah et al. (2018), Yirong (2022),Lin and Ullah (2024) utilized CO2 emissions as a metric for environmental degradation (Naseem et al., 2020). In contrast, Wackernagel and Rees (1996) introduced a more comprehensive environmental indicator, known as the ecological footprint (EF). In contrast to CO2 emissions, which focus solely on GHG emissions and provide a limited perspective of environmental damage, EF offers a more comprehensive view by quantifying emissions from cropland, grazing land, forests, fishing grounds, and built-up land. The identification of the EF can steer policymakers in shaping more rigorous environmental regulation frameworks and sustainability practices. Figure1 describes main environmental indicators used in the literature.

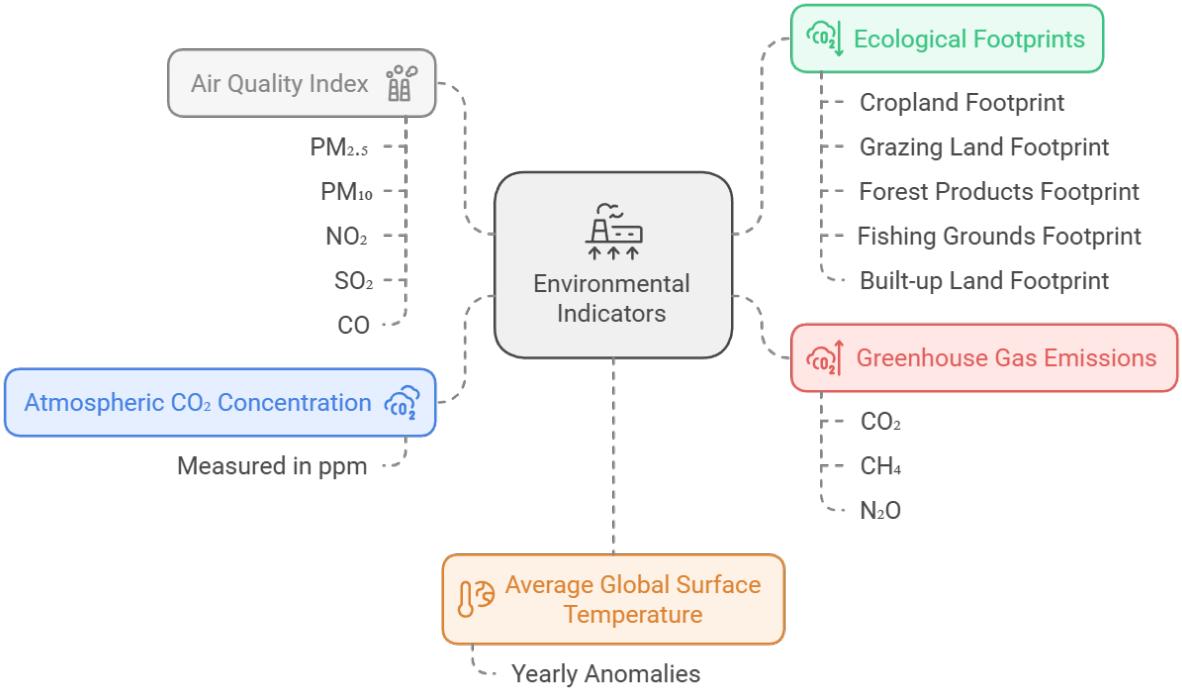


Figure1. Environmental indicators in the current international debate.Source: Authors' owns elaboration

According to the *ecological framework* given by global footprint network (GFN, 2014), when human demand for natural resources exceeds the ecosystem's biocapacity to absorb waste, it creates an ecological imbalance and called *ecological deficit*. Conversely, when biocapacity exceeds the human demand for natural resources, it is referred to as *ecological surplus*. Recent studies documented by Paleari (2024), Brubacher et al. (2024); Ahmad et al. (2021), and Javed et al. (2023) declare that macroeconomic activities, urbanization, globalization, trade, government spending, financial development and population growth rate drive EF. Figure 2 illustrates the trends of ecological deficit and ecological surplus in world economies.

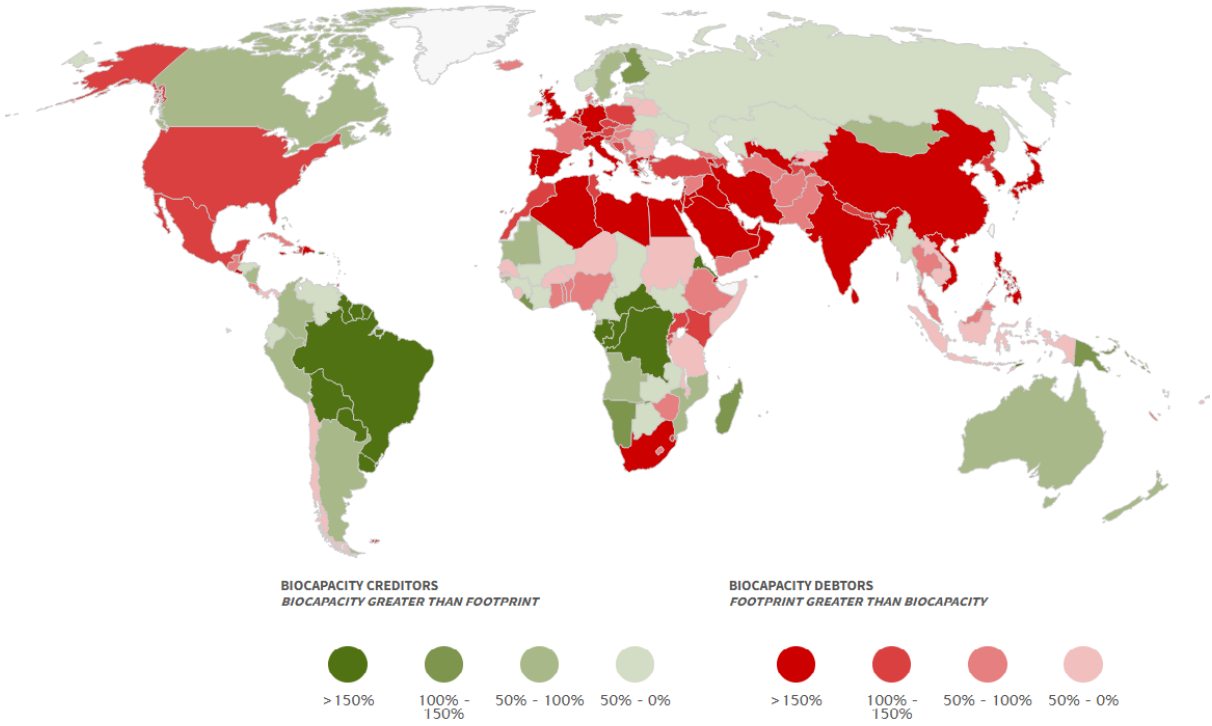


Fig.2. Ecological surplus and deficit trends

Source: Authors Elaboration on Ecological footprints and Biocapacity Data https://www.footprintnetwork.org/

Figure 1 illustrates the ecological *surplus* and *deficit* scenarios across global economies. The green color indicates *surplus areas,* while red denotes *deficits.* Countries with high ecological footprints, such as the United States, France, Italy, Spain, China, India, United Kingdom, Germany, and Saudi Arabia, often fall into the >150% and 100% - 150% categories of biocapacity debtors. Their elevated footprints are primarily the result of industrialization, high energy consumption, and urban lifestyles that place significant demands on resources. In contrast, nations like Brazil, Australia, Canada, Sweden, Norway, and Finland, classified as 50% - 100% or even >150% biocapacity creditors, maintain lower ecological footprints. This is due to their abundant natural resources, lower population densities, and their emphasis on sustainable practices. Carbon footprints are directly and indirectly affecting the economic and social progress of human beings. For instance, high world temperatures reduce labor productivity and increase health issues; low productivity ultimately declines economic output (Radmehr et al., 2023; Hao et al., 2021).

To overcome the ecological deficit, various efforts have been made by international organizations. Such as the Paris Agreement, endorsed by 195 nations in 2015, with the aim to

limit the world temperature at 1.5 °C and mitigate the detrimental effects of climate change. The UN Climate Change Conferences COP26, COP27 and sustainable development goals 7(affordable and clean energy) and 13(climate actions) highlighted importance of investment in green energy market to achieve global net-zero emissions goals by mid-century(Paleari, 2024). After the Eurozone economic crisis, the Russia-Ukraine war, and the COVID pandemic, European economies are actively working to reduce their dependence on coal and gas . They are phasing out imported carbon-intensive energy sources and increasing their reliance on renewable energy. In July 2021, the European Union put forth the "Fit for 55" package promising at least a 55% cut in greenhouse gas emissions by 2030, compared to 1990, highlighting the importance of renewable energy. Due to the instability in global energy prices and widespread supply concerns, the European Commission introduced the "REPower EU" energy plan . This plan aims to raise the share of renewable energy from 40% to 45% by 2030 to urgently reduce reliance on imported energy sources. The United Nations emphasizes the significance of both adaptive and mitigative strategies to tackle the challenges posed by extreme climate events. All international bodies concluded that the key solutions lie in the transformation of energy production and consumption strategies from polluted energy sources to clean and environmentally friendly energy sources (IEA, 2023).

One of the anticipated solutions to overcome the climate crisis is the utilization of environmental friendly energy sources (wind, solar, and hydroelectric) in a total energy mix (Cooray & Özmen, 2024). It is a debatable question in literature whether renewable energy is public good, or a private one. A research study by Zhang et al.(2022) claimed that renewable energy is a public good—non-rival and non-excludable. Its consumption does not reduce the availability of energy for others. Few studies explained the economic importance of renewable energy sources. Madriz-vargas et al. (2018) stated that green energy sources reduce the economic cost of production. Radmehr et al. (2023) asserted that renewable energy sources raise the economies of scale by reducing the long run average cost. Mercedes & Cantarero (2020) and Zhang et al.(2022) argued that environmental -friendly energy sources reduce energy poverty by giving energy production rights to the local individuals. On the other hand, a few scholars define the environmental significance of renewable energy and argue that green energy sources mitigate ecological deterioration, reduce energy prices, minimize energy waste, and enhance energy accessibility (Bashir et al., 2024). Fakher et al., (2022) argue that renewable energy sources promote environmental sustainability and diminish the ecological deficit.

Technological innovations play a vital role in energy transition process (Lorente, 2021a). The effectiveness of environmentally friendly innovation is rooted in the idea of "creative destruction," as presented by Schumpeter (1942), which posits that the creative ideas of stakeholders enhance economic productivity and improve the sectors efficiency. The findings of the endogenous growth model (Romar, 1986) highlight that continuous investment in research and development leads to combat CO2 emissions (Alvarez-Herranz et al., 2017). Unlike traditional technology that focuses on prioritizing economic growth at the expense of environmental preservation, green technological innovation (GTI) emphasizes the integration of technological benefits with environmental well-being. Developed countries use modern technology to enhance environmental quality (Usman & Hammar, 2021). The effectiveness of eco-innovation depends on robust fiscal policies. For instance, carbon prices can encourage industries to the adoption of environmentally friendly products (Sandberg et al., 2019).

To address present and future climate challenges we cannot solely rely on market forces. As a result, the importance of rigorous environmental regulations has been raised significantly to protect environmental quality (Yirong, 2022). To achieve the carbon neutrality objectives, nations around the world are increasingly adopting a policy instrument like the enforcement of environmental taxes on the energy industry and transportation, as well as implementing sustainable strategies to foster the generation and consumption of renewable energy(Wei et al., 2024a). For Asia and Europe, Lee et al., (2024) argue that stringent environmental regulations can mitigate the negative effects of carbon emissions by encouraging sustainable technologies and discouraging environmentally harmful practices. Taxes can be imposed on products that are energy-intensive and produce a significant amount of carbon emissions, which encourages market stakeholders to shift towards sustainable products that have a lower environmental impact (Maiti, 2022). Two schools of thought have offered differing perspectives on the relationship between environmental regulations and environmental quality. The first argues that strict environmental policies, such as environmental taxes, carbon pricing, and subsidies, directly and indirectly influence stakeholders' behavior toward sustainability (Ganda, 2022; Ibrahim & Ajide, 2021b;Sinha et al., 2020). The second school of thought argues that at the initial phase of policy execution, strict environmental policies decline economic productivity and raise the economic cost of production (Albulescu et al., 2022;Lin & Huang, 2022). Policymakers should create robust environmental laws and policies to tackle ecological issues and minimize carbon emissions from governmental bodies, companies, and the general population.

Institutional quality is another important driver of environmental sustainability. The foundation of institutional quality is based on various favorable and unfavorable political factors such as government effectiveness, rule of law, regulatory quality, control of corruption, political instability, and corruption, which significantly influence a country's environmental and economic policies. A variety of studies in the literature have established an inverse relationship between IQ and EFs (Cooray & Özmen, 2024) and argued that strong governance typically fosters the establishment and execution of rigorous environmental regulations, which alleviate environmental degradation. Strong institutional quality plays a vital role in achieving sustainable developmental goals. Nations with robust regulations can effectively overcome their economic hurdles and environmental footprints(Jahanger et al., 2022). Additionally, Nguyen & Su (2022) concluded that effective government policies increase stakeholder confidence in investments in stable green energy projects. High institutional quality reduces market uncertainties and encourages people to follow environmental regulations in the production and consumption process. Lower levels of corruption, transparency, and efficient government policies provide an excellent foundation to achieve 2030 SDGs (Byaro et al., 2024). Few studies (López & Mitra, 2000;Fakher et al., 2022) have examined the effect of corruption and rent-seeking activities on environmental sustainability and they found that corruption reduces economic development, and promotes negative environmental externalities.

Finance is the main driver of green economic growth. Financial institutions provide money and physical capital to investors for investment in infrastructural development, and research and development (R&D), leading to an increase the technological progress. Integration of technological advancement in the financial sector reduces the financial accessibility barriers and accelerates economic growth (Zhang et al., 2023). Additionally, technological advancement boosts eco-innovations in the renewable energy market, improves energy efficiency, reduces the dependence on polluted energy sources, and helps to mitigate climate challenges. Multiple studies in the current scholarly work assess the linear relationship between financial development (FD) and the environment, originating from two distinct school of thoughts. The first school of thought, argues that financial development (FD) plays a positive role in improving environmental quality by fostering R&D in areas like sustainability and renewable energy (Jianguo et al., 2022; Yang & Ni, 2022;Ullah et al., 2023). FD not only enhances R&D investments, but also attracts foreign direct investment (FDI), which together spur economic growth, reduce environmental degradation, and would help nations to achieve their carbon neutrality goals by 2050 (Bashir et al., 2022).

1.2 Problem statement

In light of the above discussion, we found that the global dependence on carbon intensive energy sources (oil, coal and gas) generates numerous economic, social, environmental and technological challenges. For instance, the continuous extraction of natural resources produces two major challenges: it exacerbates resource scarcity (where demand for resources exceeds supply), increases countries' reliance on imported energy, and contributes to trade deficits. Secondly, fossil fuel consumption drives climate change. Climate change adversely affects human health and reduces labor productivity. Additionally, it creates economic challenges, increases production costs, lowers economic output, and exacerbates income inequalities within and between societies. This, in turn, diminishes individual access to energy and contributes to energy poverty issue. Figure 3 describes the environmental sustainability challenges.

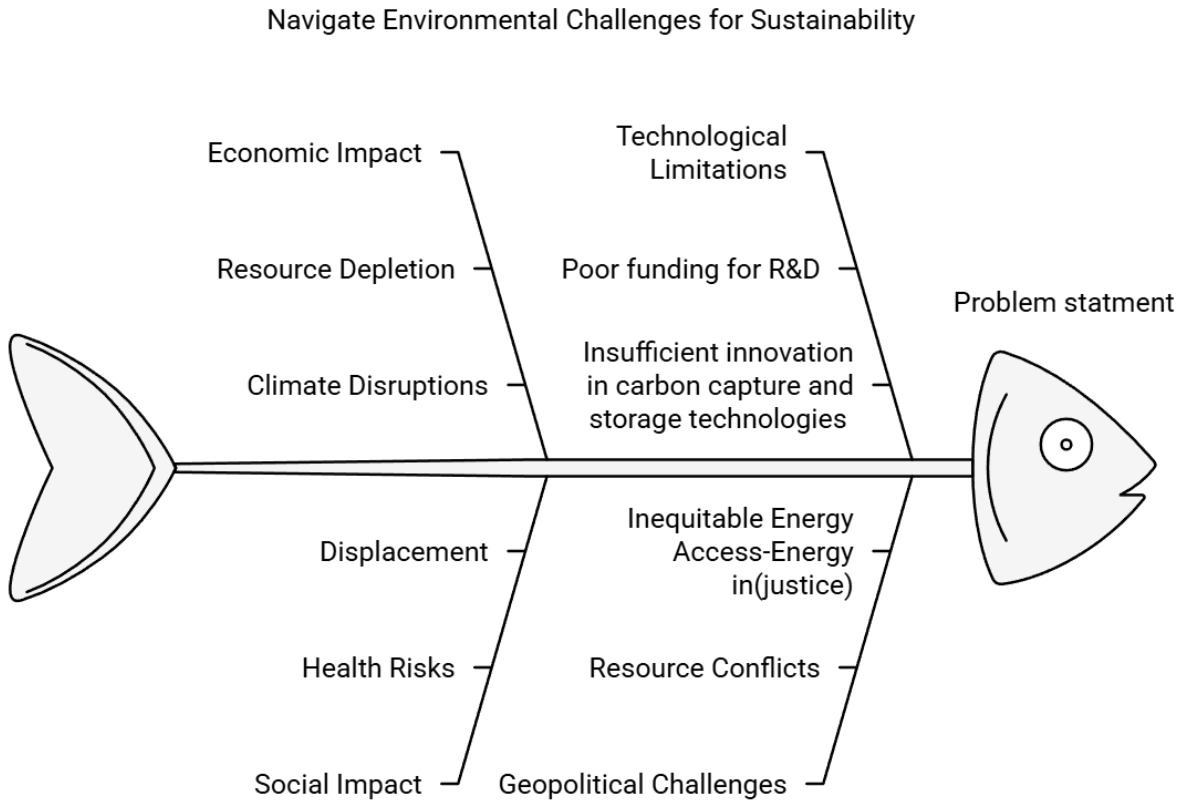


Figure 3. Thesis problem statement.

Source: Author's own elaboration on international literature

The above-mentioned issues motivate us to find alternative ways to reduce them and we found that in energy economics literature, earlier studies have explored the determinants of traditional economic growth, which comes at the expense of environmental quality (Albulescu et al., 2022;Lin & Huang, 2022). Many studies explained the economic importance of renewable

energy sources and energy innovations by using traditional econometric models (Bashir et al., 2024' Fakher et al., 2022). Moreover, the majority of studies overlooked the environmental effects of , energy justice (Sustainable Energy for All (SE4ALL) agenda), and green economic growth. By addressing the theoretical, and empirical gap, this doctoral study contributes to the existing body of literature in numerous ways.

1.3 Research objectives

The general objective of this doctoral study is to explore energy challenges. We declined this broader objective into three *research questions* and produced three research articles.

1. How do energy innovations, renewable energy sources, research and development, energy intensity, and GDP growth contribute to improving environmental quality in OECD economies?
2. What role does energy justice play to overcome ecological inequalities? How do exports, financial development, technological innovations and natural resources influence CO2 in low-income countries (LICs), lower-middle-income countries (LMICs), high-income countries (HICs), and upper-middle-income countries (UMICs)?
3. How do PESTLE factors (Political, Economic, Social, Technological, Legal, and Environmental) drive green growth in developed economies? Additionally, how do PESTLE indicators originating in neighboring spatial units influence green growth in the home country?

To empirically and theoretically answer the above questions, this study used advanced econometric models. A short summary of each research article is explained below.

The remainder of the Thesis includes three research chapters (Chapters 2-4), each designed to meet the research questions outlined earlier and followed by a final chapter presenting a general conclusion and highlighting main policy implications.

Chapter 2 explored the first research question, and investigates how energy innovations, renewable energy sources, and energy intensity influence the environmental quality in OECD economies.

Chapter 3 concentrates on the second goal, stressing the critical role of energy justice to reduce environmental inequalities in various income group economies.

Chapter 4 addresses the third research question and examines the spatial influence of PESTLE indicators on green economic growth in 30 European economies.

Chapter 5 offers overall conclusions and draws some policy implications deriving from this research study.

Figure 4 shows the thesis outline

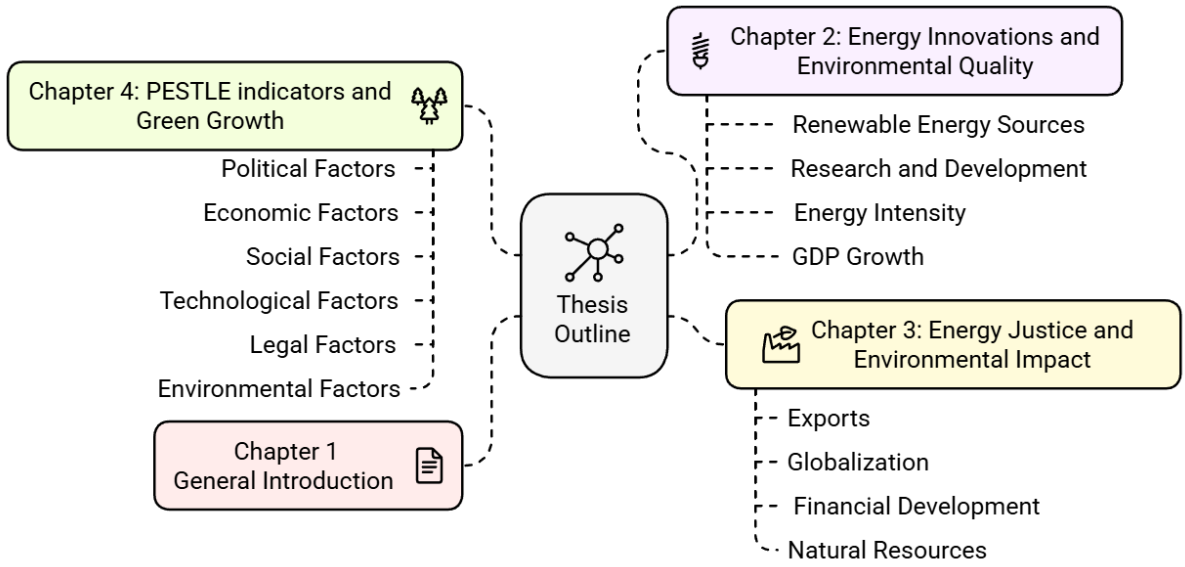


Figure 4. Thesis outline. *Source*: Author's own elaboration.

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Chapter 2

Energy innovation and ecological footprint: Evidence from OECD countries during 1990-2018

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https://www.sciencedirect.com/science/article/pii/S0040162523005218

Abstract

The recent developments in energy engineering and state of art technologies to increase eco-friendly energy production are receiving increasing attention from the scientific debate as an engine of growth. Although the energy-growth-environment nexus has extensively been studied, the ecological implications of innovative technologies in energy production are to be adequately addressed to provide ad-hoc social changes and policy perspectives. To bridge these gaps, the present study investigates the relationship between energy innovation (EIN), renewable energy production (REP), non-renewable energy production (NREP), energy intensity (EI), research and development (R&D) expenditures, GDP, and ecological footprint (EF) in 21 OECD economies during the period 1990-2018. This study applies advanced, rigorous, and robust econometric methodologies. The empirical outcomes reveal that REP, EIN, and EI, decline the ecological footprints while NREP, GDP, and R&D accelerate the ecological deficit. This study advances the empirically proven validity of the Environmental Kuznets Curve hypothesis for OECD countries and provides valuable policy insights in terms of intensification of government budget spending on R&D, and boosting technological energy innovations and non-polluting energy projects. Of particular importance to trace green energy growth, is the development of comprehensive economic and energy policies with a specific focus on ecological wellbeing.

Keywords: Energy innovation, energy intensity, ecological footprint, economic growth, OECD.

1. Introduction

Since the industrial revolution, environmental degradation has gained more importance to researchers and policymakers, as it has been seen – especially over the last thirty years – among the main problems to be tackled to achieve sustainable economic growth. Environmental degradation itself contains various ecological challenges at global level such as air and water pollution, deforestation, food shortage, and extreme weather conditions (Bashir et al., 2022; Karimi Alavijeh et al. 2022). In spite of that, the growth trajectory of nations is continuously enhancing the ecological deficit and reducing the carrying capacity of the Earth (Ahmed et al. 2020). Ecological degradation intensifies the level of poisonous gases (CO_2, SO_2, NO_2 and NO_X) to the environment and deteriorate air quality. After the recovery of COVID-19 pandemic, the world temperature is unexpectedly extreme and changes abruptly. Earlier scholars (Shahbaz et al. 2015; Hashmi & Alam 2019; Khan et al. 2019; Espoir et al. 2022) used CO_2 emission as an indicator of environmental damage to capture air pollution, although carbon emissions generally ignore other degradations occurring in lands, grasslands, water, and forests. In the early work of Wackernagel and Rees (1996) a common indicator for the quantification of the overall ecological deficit has been established as ecological footprint (https://www.footprintnetwork.org/). However, the ecological deficit arises due to human endeavours and excessive utilization of exhaustible resources (Shabaz et al.,2015; Dauda et al., 2019; Ramzan et al., 2023).

A year before the publication of Wackernagel and Rees' work, the pioneering study on the Environmental Kuznets Curve (EKC) by Grossman & Krueger (1995) explained the existence of an inverted U-shaped relationship occurring between economic growth and environmental quality (particularly medium range pollutants such as SO_2 and NO_X) in Mexico, as a consequence of the country's entry to the North American Free Trade Agreement (NAFTA).

The subsequent EKC literature developed since then, compared, tested and contrasted the *one-size-fits-all* GDP variable used to measure a country's growth. The latter depends on a specific economic structure, and this needs a sufficient supply of energy to function. According to the International Energy Agency - IEA (2022), 80% of the world economies are producing electricity from conventional energy sources (74%) (International Energy Agency - IEA, 2022) (Figure 1). Thus, the energy sector alone contributes towards the increase of global greenhouse gas emissions (GHGs).

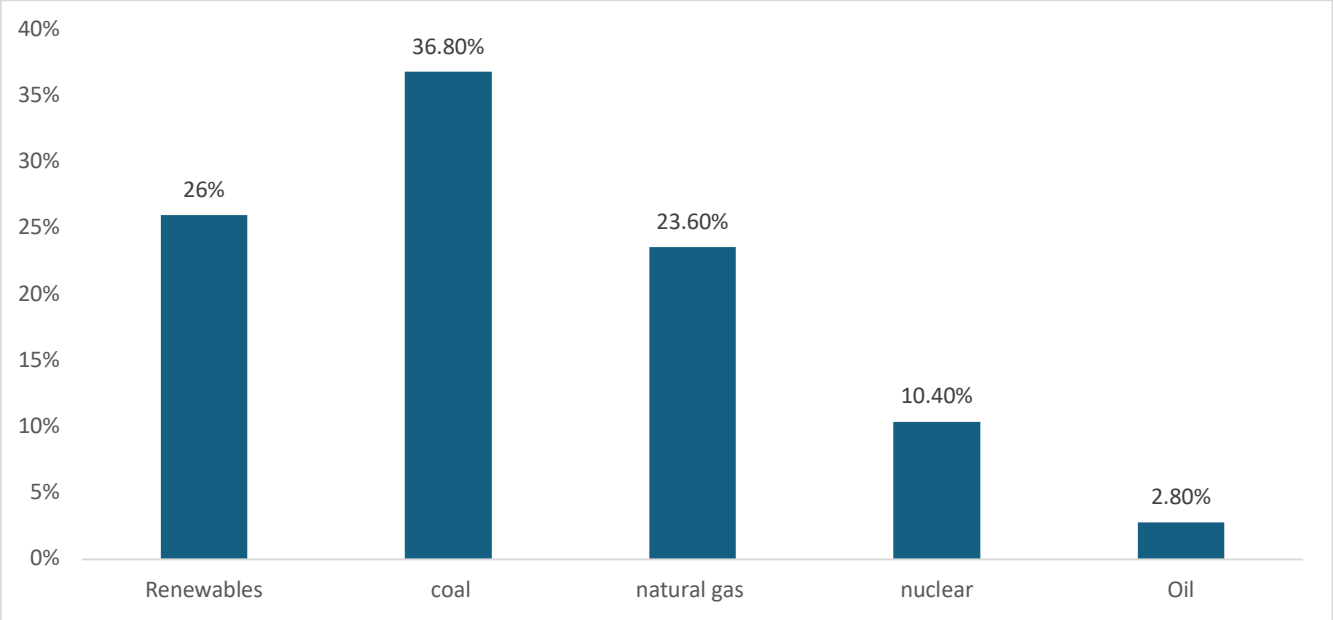


Figure 1. Worldwide sources of energy production (in %).

Source: World Energy Outlook (2021)

One of the foreseen remedies is to overcome the consumption of hard-to-abate polluting sources (oil, coal and gas) with renewables such as solar, wind, hydroelectric, and biomass energy (Álvarez-Herránz et al., 2017; Carvalho et al., 2018; Usman et al., 2021). A number of studies also address the issue that renewable energy sources are significantly reducing the ecological burden and upholding green standards (Karimi, et al., 2022). In accordance with the Kyoto protocol, economies are legally enforced to minizine their ecological footprints to foster the adoption of clean energy sources.

To embrace this green growth path, technological advancements and energy innovation are key towards a resilient society against climate change. Over the last years, the issue on the relationship among technological innovations in energy markets and environmental damage has received major attention from the scientific community and society at large. The ecological aftermath of energy innovations has been a subject of debate since 1960s. Contrasting scientific opinions emerge. On one hand, technological advancements in energy markets are seen as 'solitary steps' to tackle green growth, such to provide negative effects on the environment and ecosystems (Shahbaz et al, 2019; Ganda 2019; Charfeddine & Kahia, 2019; Danish et al., 2020; Huang et al., 2022). On the other hand, to gain full benefits from technological advancements of renewable energy sources, massive investments in R&D (Danish et al 2018; Sarkodie & Strezov, 2019; Sherif et al.,2022) together with other (public and private) economic and financial mechanisms are needed.

By virtue of technological innovations in energy markets, OECD countries in particular are experiencing a downward trend of energy production from non-renewable sources (Bronselaer & Zanna, 2020) (Figure 2). This trend is notably relevant for coal and oil. Correspondingly, the replacement effect induced a sharp increase in the use of wind and solar energy sources.

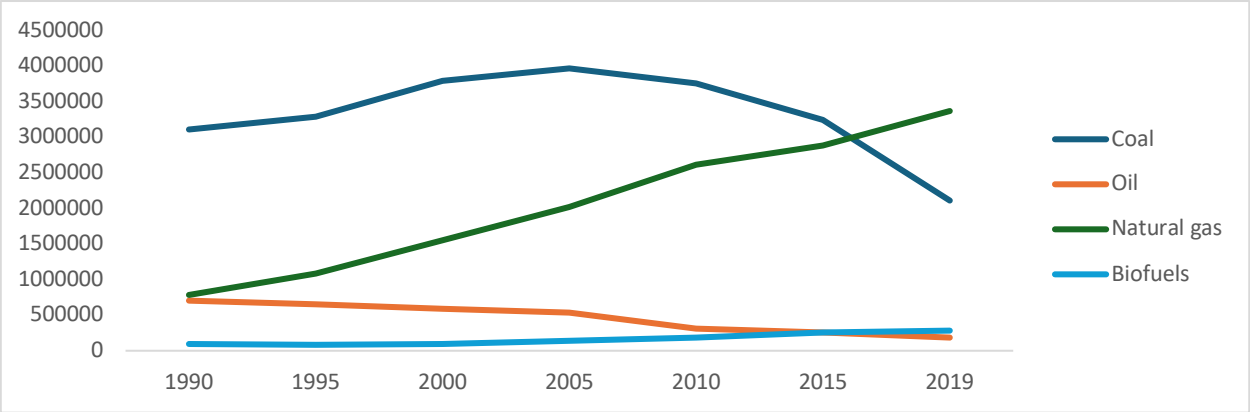


Figure 2-Energy Production from non-renewable energy sources (Gwh).

Source: Authors' own computations based on OECD data.

Fig 3

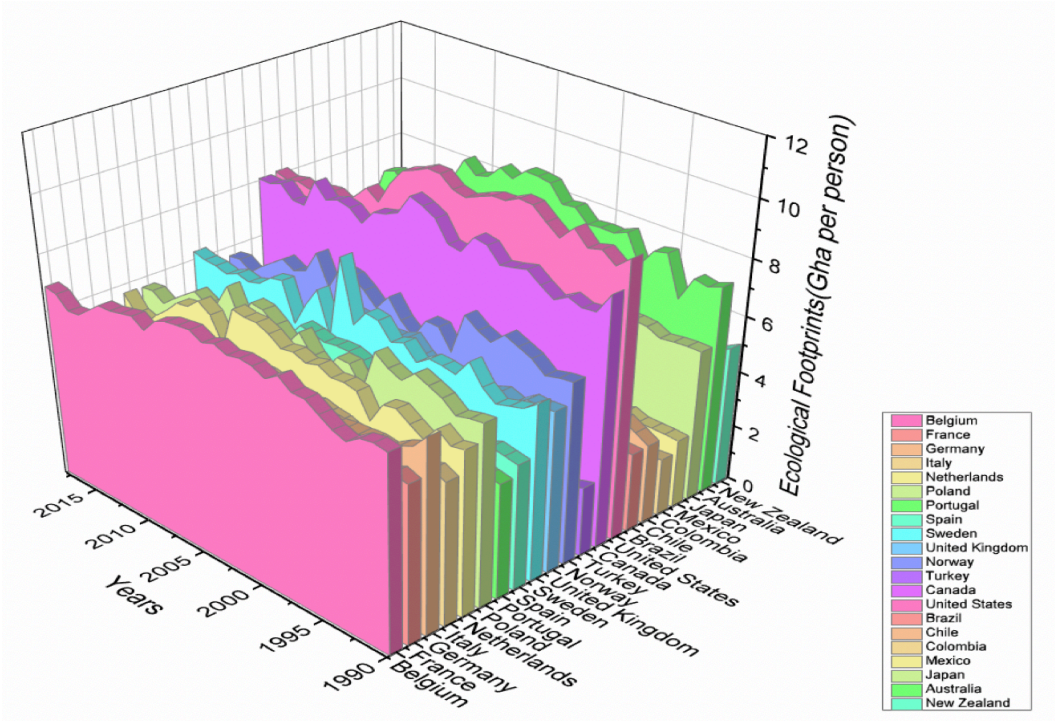


Figure 3. Glimpse of ecological footprints in the sampled OECD countries (in Gha/person).

Source: Authors' own computations based on OECD data.

The diminishing reliance of these nations on fossil fuels can lead to better environmental quality (EQ) in their territories and induced green growth (Liu et al., 2022; Razzaq et al., 2023). Within the thematic context of the above considerations, the current study aims at deepening the investigation of the relationship between EI, EIN and EF.

In the following aspects, our study advances and contributes to the current literature. Firstly, the above-mentioned facts and figures motivate us to investigate the effect of REP, NREP, EI, EIN, R&D, and GDP on EF, which very few studies have not examined from the perspective of the sampled OECD countries. Secondly, the choice of this group of countries is supported by high levels of per capita EFs (Figure 4), particularly due to high industrial growth and technological advancements in the last three decades.

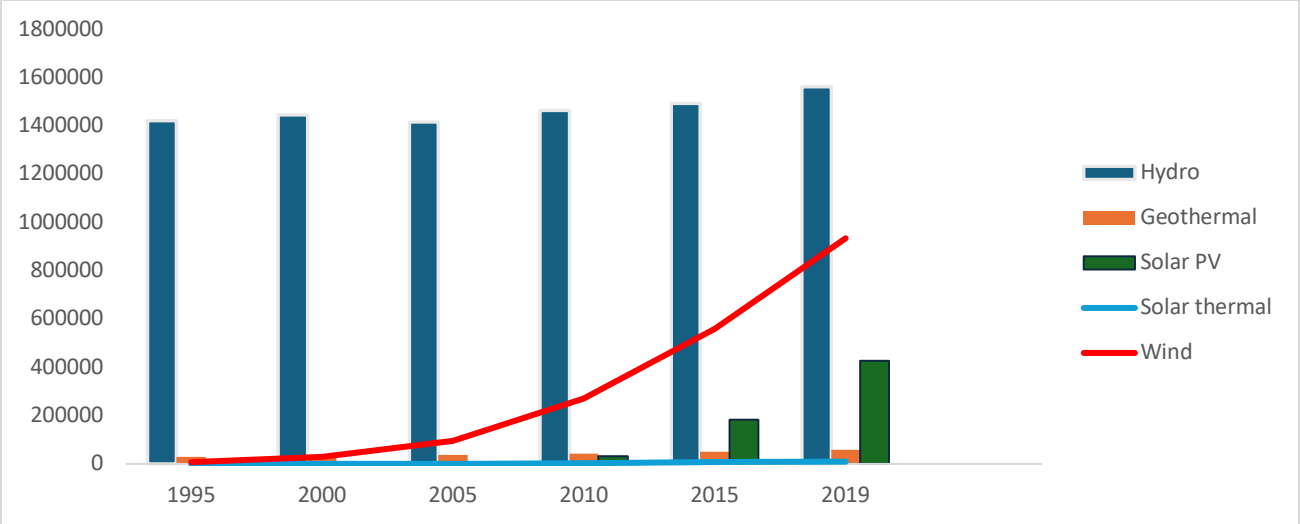


Figure 4. Energy production from renewable energy sources (Gwh).

Source: Authors' own computations on OECD data.

Thirdly, a more comprehensive environmental indicator as the EF (which covers the human consumption placed on the biosphere) is used as a proxy for EQ and extends the majority of research which mainly focuses on CO_2 emissions. Fourthly, this study uses more recent data and modern econometric techniques (see section 3). We explore a panel of twenty-one OECD countries over the period 1990-2018. Earlier investigations (Ulucak and Khan 2020; Ahmed et al. 2020) ignored the problems of cross-sectional dependence (CSD) and heterogeneity, thus providing biased policy indications for green growth. Given the above gaps, the novelty of the present work aims to explore the potential of current supply-side energy production in growth processes expressed by technological advancements of energy markets to mitigate the ecological footprint of nations, thus providing new strength to the EKC hypothesis in OECD countries.

The remainder of the paper is arranged as follows. Section 2 shows a background of the relevant literature; Section 3 discusses materials and econometric techniques; Section 4 depicts the empirical outcomes and discussion. Finally, section 5 draws main policy implications and concludes.

2. Literature Review

2.1 Main theoretical background

The theoretical foundations of our study can be traced in the following classical macro-economic models:

1. Optimal growth models, á la Ramsey (1928), Koopmans (1965) and Cass (1966);

2. Endogenous growth models, built on Romer's work (1990);

3. Schumpeterian models of innovation, developed upon Schumpeter's mainstream work in early 1900s (Schumpeter, 1934);

4. Ecological modernization models, based on Hajer (1995).

Optimal growth models. These are dynamic optimization models, where optimal control theory solves consumer's utility maximization problems. Koopmans (1965) and Cass (1966) build optimal growth models based on Ramsey (1928)'s framework. The latter replaces labour, in the utility function, with environmental or ecological degradation. As a consequence, Koopmans (1965), deals with a suitable mathematical experiment on optimal economic growth path by comparing different mathematical forms of optimality with a simple model of technological progress and population growth by using the concept of 'preference ordering of growth path'[1]. Koopmans argues against the complete separation of an objective function from the set of technologically feasible paths. This intuition suggests that an optimal growth path is determined using technological advancements. Cass (1965), on the other hand, emphasises an optimal growth path with a model of capital accumulation and discusses the same conclusions as Koopmans (1965), Ramsey (1928), Uzawa (1964) and Srinivasan (1964).

Soon after the euphoria of the Club of Rome in the 1970s, main literature extended the Ramsey framework to models adopting a trade-off between the dis-utility to pollute and the utility to consumption. On this regard, the literature considers models with optimal growth path and pollution (Keeler et al. 1971; d'Arge & Kogiku, 1973; Gruver, 1976; Tahvonen &

[1] For each pair of alternative growth paths, it is discussed whether these differ from the optimum. In the latter case, an ordering preference is also expressed.

Kuuluvainen, 1993; Stokey, 1998), in which abatement strategies provide a solution to the social planner' optimal consumption possibilities; and models of optimal growth and resource depletion (Dasgupta & Heal, 1980; Stiglitz, 1974), in which the social planner opts for extraction or extinction of natural resources according to an applicable social discount rate.

As for the former sub-type of models, these are an extended version of dynamic optimization models of Ramsey (1928), Cass (1965) and Koopmans (1965). Keeler et al. (1971), treat pollution as a state variable in the framework of control theory. d'Arge & Kogiku (1973), deal with an optimal control theory model built upon conservation-mass energy principles. Major conclusions argue that at early stages of production a substantial undiscounted price is applied to the stock of polluted resources. Relaxing the assumptions of constant technology and capital investments in the long run, advancements in technological progress allow for changing (technological or investment) prices to the shadow price of the polluted resource, thus allowing green long-run adjustments in growth paths. Similarly, Gruver (1976), uses a neo-classical growth model to investigate the optimal allocation between pollution control and investment and allows for saving rates to vary over time. The model assumes an index flow of all-important pollutants and studies how optimal investment is allocated between pollution control and productive capital over time. Therefore, pollution is increasing function of GDP and decreasing in pollution control capital. Further comparisons can be made with the analysis of Keeler et al. (1971) and d'Arge & Kogiku (1973). The former assumes that the output is employed in pollution control policy, while the latter uses capital investments in mature stages of the growth process, when recycling is present. Tahvonen & Kuuluvainen (1993), analyse an optimal economic growth model with pollution control strategies and extend it to renewable resources. The latter version yields to higher steady state capital stocks than the traditional version of the model, meaning that long run mechanisms of green paths need extensive capital investments to achieve sustainable growth. Stokey (1998), through simple static models of growth and pollution, argues that technology plays a key role in optimal allocation of inputs for production processes.

As for models of optimal growth and resource depletion, Dasgupta & Heal (1979), analyse an inter-temporal optimal growth path with exhaustible resources, where the elasticity of substitution between man-made capital and exhaustible resources is a key element for depletion policies. Advancements in technology and ad-hoc intertemporal discount rate allow for cost-effective substitutions to take place. Stiglitz (1974) argue that natural resources are considered as capital goods exhibiting the same uncertainty as capital markets. Therefore, in the long-run,

these can be exploited to quickly or too slowly, and increases in the expected rate of natural resource prices might result in disturbance for other markets.

Endogenous growth models. Endogenous growth models relax the assumption of conventional production functions assumed in optimal growth models and allow for the investigation of spillover effects. Gradus and Smulders (1993), Lightart and Van der Ploeg (1994), Bovenberg and Smulders (1995, 1996), and Barbier (1999) employ models of endogenous growth with environmental quality all built on earlier works by Romer (1986, 1990), Lucas (1988), Barro (1990) and Rebelo (1991). Gradus and Smulders (1993), conclude their work with two main interesting views. The first one considers endogenous growth models providing long-run growth rates to remain unchanged, if the productivity of growth is not affected by any changes in pollution activities. The second one assumes a 'crowding out' effect between a lower growth rate and investments in abatement strategies. The authors argue that the 'crowding out' effect can be offset by substituting hard-to-abate technologies with less polluting production processes, thus allowing for long-run sustainable growth paths. Lightart & Van der Ploeg (1994), extend the work of Romer (1986) and Barro (1990) to investigate the effects of public expenditures on environmental quality. Optimal policy (i.e. second best policy) is determined by applying the Keynes-Ramsey rule for optimal allocation of resources between current and future consumption. Therefore, an economy shift towards environmental concerns result in additional taxation, which turns public consumption to be relatively less expensive compared to private demand. Bovenberg and Smulders (1995, 1996), as well as Lucas (1988) argue that pollution abatement induce the adoption of new technologies allowing a change in the structure of the economy. The latter favours new demand and intensive consumption for less polluting goods. Barbier (1998) considers technological innovation as an endogenous factor in the growth process. Assuming a simple Romer-Stiglitz model with resource scarcity and population growth, an optimal balanced growth depends on resource availability and technology innovation. If resource scarcity is not a constraint for technological advancements, then this latter allows a country to grow towards green paths.

Schumpeterian models of innovation. According to Howitt & Aghion (1998) and Aghion (2004), the Schumpeterian approach is a variant of endogenous growth models in which innovation (particularly radical innovation) plays a crucial role in growth processes, where the 'creative destruction', by breaking with past approaches, technologies, markets and behaviours, produces beneficial effects in the long run, where more efficient technologies displace old ones (Godin, 2015; Godin & Schubert, 2021;). This is particular evident in countries (i.e. OECD) in which technological innovations in the energy sector are taking place (cfr. Figure 4) such to

translate innovative ways of producing and consuming, into all other aspects of social and economic life thus rising energy efficiency (Ibrahim & Ajide 2021), reducing energy intensity (Xia et al., 2022), and upgrading environmental excellence from ad-hoc institutional frameworks (Jahanger et al. 2022; Sahoo and Sethi 2022; Tomiwa et al. 2023; Karimi Alavijeh et al. 2023).

Ecological modernization models. According to early insights by Hajer (1995), ecological modernization suggests that political, economic, and social institutions have the ability to internalize and address current environmental challenges, ensuring sustainability. In the growth context, the concept of 'ecological modernization' asserts that economic growth and the resolution of ecological issues are not necessarily at odds; rather, the discourse on environmental sustainability follows a utilitarian rationale, seeking to find ways to harmonize both aspects. In the context of innovation, ecological modernization models posit that the achievement of optimal environmental outcomes relies on the interplay between economic activity, technological innovation, and interventions from the nation-state and civil society. Huber (1991, 2010) highlights the significant role of the state within the ecological modernization theory, emphasizing the absolute necessity of legal frameworks in environmental policy and regulation. These structures, in the energy context, provide stability, which is crucial for businesses to make informed decisions and foster growth and innovation.

2.2. Empirical literature review

The environmental deficit is a global challenge, and it needs consistent effort. Over the last few years, researchers are investigating the causes beyond environmental deficit (Ahmad, et al., 2020; Bronselaer & Zanna, 2020; Kocak & Ulucak¸ 2019; Shabaz et al.,2015). Numerous studies have examined the relationship between REP, NREP, EI, EIN, GDP, and EQ. Table 1 illustrates a summary of the literature considered in the present work, whereas below we deepen the discussion presented from previous studies.

REP and EQ/EF. Environmental sustainability is essential for the well-being and prosperity of the world. For this purpose, several scholars have analysed the correlation between renewable energy and different environmental indicators. Ibrahim & Ajide (2021) investigate the impact of REP, NREP, and Trade Openness (TO) on EQ for G-7 countries from 1990 to 2019. The authors applied second-generation tests and concluded that REP significantly enhances EQ. To support this argument, Omri & Saidi (2022) use data from 15 major renewable energy consuming countries and applied fully modified ordinary least square (FMOLS) approach and argued that REP is considerably boosting GDP and reducing CO_2 emissions. Similarly, the

work by Karimi Alavijeh et al (2023), use a quantile approach to explore the roles of renewable energy consumption, institutional quality, technological innovation, and GDP on CO_2 emissions in 14 EU countries. In addition, the authors check for robustness by employing FMOLS, dynamic ordinary least squares (DOLS), and fixed effect ordinary least square (FE-OLS). Main findings reveal that renewable energy consumption has a notable and positive impact on reducing CO_2 emissions across all quantiles in the studied context. Analogously, the study of Busu & Nedelcu, (2021) explore the impact of solar energy, biofuel, population size, and urbanization process on CO_2 emissions in European Union countries. Results of a panel data multiple regression model demonstrate that biofuel and REP reduce CO_2 emissions. Whereas population and urbanization accelerate pollution. An influential study by Zafar et al. (2020) reveal that renewable energy consumption lessens CO_2 emissions and the EKC holds in OECD countries. For BISCS economies (Ulucak & Khan, 2020) applied fully modified ordinary least square (FMOLS) approach and detected that renewable energy production declines the ecological deficit. As a part of another major investigation, Khan et al. (2020) explore the relationship between renewable energy, terms of trade, and environmental quality in Nordic countries from 2001 to 2015. The outcomes of a Pooled Mean Group (PMG) model depict that REP favours a better environmental quality. Likewise, Yu et al., (2018) and Kasperowicz et al. (2020) argue that inexhaustible resources improve ecological impacts. By using panel quantile regression model (Cheng et al. 2019) scrutinized a positive correlation between the utilization renewable energy sources and environmental quality. Furthermore, Mbarek & Rahman (2018) uses time series data for Australia and detected the similar results. The detailed literature review confirmed the existence of a positive correlation between renewable energy and environmental quality[2].

NREP sources and EQ/EF. With reference to recent empirical documentation on the relationship between NREP and EQ, many scholars, for instance Sherif et al. (2022), Khan et al., (2019); Hassan et al. (2019), Destek & Sinha (2020), Shahzad et al. (2017), Dehdar et al (2022), Chu et al. (2023), Usman et al. (2021), Zhang et al. (2022) report that NREP contribute to increase the environmental damage.

EI and EQ/EF. The literature about the relationship between EI and EQ seems contrasting. Few researchers observe that EI negatively affects EQ. For instance, Shokoohi, et al. (2022) investigate the effect of EI on EQ in the Middle East region over the period 1971-2015. The empirical estimates reveal, also in this case, that EI has a negative impact on EQ. Similarly,

[2] In terms of EF, since this is measured as the availability of land and sea needed to capture pollution and waste in a given territory (https://www.footprintnetwork.org/our-work/ecological-footprint/), an improvement provided by REP has a negative sign on EF.

Shahbaz et al., (2015), Namahoro et al. (2021), and Chu & Le (2022) argue that EI increases CO_2 emissions in African and G7 countries. Whereas Danish et al (2020) and Aydin & Turan (2020) find similar outcomes in USA and BRICS countries. In contrast, the study by Nasir et al., (2021) argues that EI considerably decreases CO_2 emissions and improves environmental quality in Australia.

EI and EQ/EF. Several researchers found that energy innovation enhance EQ. As an illustration, Baloch et al. (2021) examine the association between financial development, EI, and EQ in OECD countries. The empirical outcomes reveal that financial development accelerates EI and in turn it improves environmental quality. An Auto Regressive Distributive Lag model used by Shahbaz et al. (2018) conclude that EI cuts down CO_2 emissions in France. In supporting this view, Dauda et al. (2021) and Lorente et al (2021) illustrate that technological innovations curb carbon emissions in African and EU countries, respectively. Similarly, Balsalobre et al., (2021) and Li et al. (2022) illustrate that EI strengthen environmental quality. Correspondingly, for OECD economies (Ganda, 2019) employed Generalized method moments (GMM) model and concluded that as economies grow they start investment in technological sector, at the first stage of growth technological innovations rise the ecological deficit and later when economies reach at maturity, technological innovations reduce the carbon emissions and relationship becomes negative. In contrast, FGLS model was applied by Usman and Hammar., (2021) noticed that technological innovations are responsible for ecological degradation in APAC economies. Additionally, Sinha et al. (2020) applied IPAT framework and found that technological innovations increase EF in NEXT Eleven countries[3]. Likewise, Adebayo, (2021) applied a non-linear regression model and concluded that technological innovations also negatively affect environmental quality in Chile.

R&D expenditures and EF/EQ. In terms of R&D effects on environmental quality and/or EF, Koçak & Ulucak (2019) investigate a dynamic link between R&D expenditures and CO_2 emissions in OECD countries from 2003-2015. Their empirical findings show no significant association between R&D expenditures and CO_2 emissions, in contrast to the findings of Godil et al (2021) for the same group of countries. Kahouli (2018) applies a Generalised Method of Moment (GMM) model and finds that R&D expenditures are able to mitigate CO_2 emissions in the long run. In addition, Fernández et al. (2018) apply an OLS approach and estimate the effect of R&D spending on CO_2 emissions in the EU, United States, and China between 1994

[3] According to Goldman Sachs investment bank (https://www.goldmansachs.com/), Next Eleven countries are Bangladesh, Egypt, Indonesia, Iran, Mexico, Nigeria, Pakistan, Philippines, South Korea, Turkey, and Vietnam. These countries are likely to become next BRICS countries in 21st century based on their positive economic performance over the last decades.

and 2013. The authors argue that apart from China, R&D expenditures have a positive effect (i.e. decrease) CO_2 emissions in EU and USA. Similar results for the USA are also in the work by Wu et al. (2021). The above work proposes similar results to the insights of Li et al (2023). In contrast, the study by Mamkhezri & Khezri (2023) which uses a redundant fixed effect model for 53 global economies, find a negative effect (i.e. increase) of R&D on CO_2 emissions.

GDP and EQ/EF. An empirical work by Wang et al. (2011) for 28 provinces of China applied panel vector error correction model and conclude that economic growth accelerate the carbon emissions . In the same way, Usman et al. (2022) employed AMG and CCMG model and concluded that that GDP growth promotes energy consumption, and this, in turn, contributes to increase CO_2 emissions. Thus, GDP growth rate increases the EF of a country. In support of this argument, Danish et al. (2018) investigate the impact of GDP and energy production on CO_2 emissions in BRICS countries from 1970 to 2011. The results of their ARDL model reveal that NREP enhance CO_2 emissions. Likewise, Hassan et al. (2019) applied auto regressive distributive lag (ARDL), Ahmed et al. (2020a) applied CUP-FM, Ahmed et al. (2020b) investigated the impact of economic growth, human capital, natural resources, and urbanization, on EF and argue that GDP growth enhances EF and nonlinear GDP growth reduced it. Furthermore, these studies confirm the existence of EKC hypothesis. In Contrast, Khan et al., (2021) explore the relationship between health expenditures, renewable energy consumption, GDP, and EQ in 10 central European countries. The authors apply GLS and GMM methods and find a positive correlation between REP, GDP growth and EQ. Likewise, Dogan et al. (2020) applied panel quantile regression model and confirmed the validation of EKC hypothesis in 68 developed economies. Similarly, *Adam* et al. (2021) and Li et al (2023) disclose that economic growth mitigates EF.

Table 1. Summary of empirical studies

Authors	Duration	Countries	Variables	Econometric Approach	Results
Renewable energy production and Environmental Quality					
Yu et al., (2018)	2004 to 2016	43 Different Countries	FDI, REC, CO2 TGHG, EXP, and IMP	GMM	RE increased EQ.
S. A. R. Khan et al. (2020)	2001 to 2018	Nordic counties	RE, EM, TOP, CO2, and RP	PMG	RE and EM diminished the Co2 emission
Busu & Nedelcu, (2021)	2000 to 2019	(EU) Countries	RE, BF, BE, POP, URB, and CO2.	Panel Regression	UBR and POP increase Co2 emissions while BF and RE reduce it.

Omri and Saidi (2022)	1990 to 2014	15 MRECC	GDP, RE, TO, GFCF, LF,Co2 and URB	FMOLS VECM	RE enhances GDP and slashed Co2.
Ibrahim and Ajide (2021)	1990 to 2019	G-7 Countries	RE, NRE, TO, TECH, and EQ.	PMG	RE and TECH boost the EQ.
Zafar et al. (2020)	1990 to 2015	OECD	RE,ED, NRA, FDI, GDP and Co2	FMLOS	RE improves EQ and FDI destroy the ecosystem.
Kasperowicz, Bilan, and (Štreimikienė 2020)	1995 TO 2016	EU	REC, GFC, and GDP	FMOLS	REC minimized the Co2 emission
Mbarek et al., (2018)	1990 to 2018	Australia	REC, EG, TO, URB and CO2	P-ARDL	GDP surged CO2 emissions & REC reduced it.
Non-renewable energy and Environmental quality					
Destek et al.,(2020)	1980 to 2014	OECD	RE, NRE, TO, GDP, and CO_2	FMOLS, DOLS	NRES reduced the EQ.
Shahzad et al. (2017)	1990 to 2011	Pakistan	FD, CO_2, NRE, TO	ARDL	Tow-way correlation exist among NRES and CO_2.
Khan et al., (2019)	2001 to 2014	35 UMIC	CO_2, FD, NREC, REC, TOP and URB	FMOLS, VECM	An inverse relationship was observed between NREC and EQ.
Usman et al. (2021)	1990 to 2017	15 highest emitting countries	NRE, RE, EF,	AMG	NRE enhanced EF.
Hassan et al. (2019)	1970 TO 2014	Pakistan	NRE, GDP and EF	P-ARDL	Fossil fuel utilization increased EF.
Sharif et al. (2018)	1990 to 2015	74 countries	RE, NRE, EC, and CO_2	FMOL	NRE is increasing environmental deterioration.
Energy intensity and Environmental Quality					
Shokoohi et al.,(2021)	1971 to 2015	Middle east Iran, Iraq, and Turkey	EI, GDP, and EQ	ARDL	Energy intensity reduces the environmental quality
Shahbaz et al.,(2015)	1980 to 2012	African Countries	GDP, CO_2 and EI	VECM granger Causality test	A unidirectional causality was observed between EI and GDP.
Nasir et al. (2021)	1980 to 2014	Australia	GDP, TO, CO_2, EI, and IND	STRIPT	Disclosed a bidirectional causation among GDP and EI.
Namahoro et al.,(2021)	1980 to 2018	Africa	GDP, RES, CO_2 and EI.	PMG, CD, and CCEMG	Unidirectional link was found among Co2 and EI.
Chu and Le.(2021	1997 to 2015	G7 Countries	EPU, ECI, EI , RES,and EQ	FMOLS	EI increased environmental degradation

Danish et al.,(2020)	1980 to 2017	United States	Co2, EI, GDP, and EPU	Dynamic ARDL Approach	EI enhanced the Co2 emission.
(Aydin & Turan, 2020)	1996 to 2016	BRICS	FO,TO, EI and EF	AMG	EI had a significant positive impact on EF.
Energy innovation and Environmental Quality					
Baloch et al.(2020)	1990 to 2017	OECD	FD, GDP, EI, and EP	PMG	FD and globalization boost energy innovations and minimize GHG emissions.
Shahbaz et al. 2017	1995 to 2016	France	FDI, FD,GDP , EC , ERI, and Co_2 emission.	Bootstrap ARDL	Energy innovation improves environmental quality.
Balsalobre et al.,(2019)	1990 to 2012	OECD	GHG, GDP, RD, RES, and NRES	Panel least squares, two-stage least squares.	RES and energy *i*nnovation reduced GHG emission.
Sinha et al.,(2020)	1990 to 2016	Next 11 Countries.	EF, GDP, EI , EIN,	Quantile on Quantile regression.	Energy innovations improve EQ.
Li et al. (2019)	2004 to 2016	30 Chinese provinces	CO_2,GDP, FDI, TI, and POP	STRIPAT-Durbin model	FDI and Population enhance Carbon emissions while High tech industry lessens the emission and improves quality.
Lorente et al.,(2021)	1990 to 2015	5 EU Countries	CO_2, EG, IT, CEP, and TI	IPAT model	To achieve carbon neutrality in the future, the EU is increasing investment in the renewable energy market.
Research and Development Expenditures and Environmental Quality					
Koçak and Ulucak.,(2021)	2003 to 2015	OECD	R&D, GDP, Co_2	PMG GMM	No link was discovered between RNES, R&D spending, and CO2 emissions.
Kahouli (2018)	1990 to 2016	Mediterranean nations	EC, R&D , GDP, and CO_2	3SLS GMM	Unidirectional causality exists between R&D and Co_2.
Fernandez et al. (2018)	1994 to 2013	EU, USA, China	R&D, CO_2, EC, and CO2	OLS	Research and developmental expenditures reduce the Co_2 emission.
Godil et al. (2021)	1995 to 2018	India	FD, R&DE, EC, and EQ	QARDL	FD, R&DE, and IQ increased environmental quality.
Wu et al., (2021)	1990 to 2019	USA	EP, R&DE, GDP, and CO_2	DOLS FMOLS	R&DE increased the co2 emission
Ghanda (2019)	2000 to 2014	OECD	RE, CO_2, R&D, FDI, HC, and GDP	GMM	REC and CO2 are inversely related.
Economic growth and Environmental Quality					
Usman et al.,(2022)	1990 to 2017	Arctic countries	FD, EG, EC, NRR, and EQ	AMG	GDP increases ED
Danish et al.,(2019)	1970 to 2011	BRICS	NREP, URB EG, and Co_2	FMOLS, DOLS	Fossil fuels energy production and economic growth

					decrease the environmental quality.
Ahmed et al. (2020)	1970 to 2016	China	LC, LNA, GDP, URB and EF.	ARDL	Natural resources, urbanization, and GDP enhanced the EF.
Hassan et al. (2019)	1970 to 2014	Pakistan	EF, NR, HC, BIO, and URB	ARDL	A bidirectional relationship is found between EF and URB.

Source: Published Literature

2.3 Keywords networking analysis

Bibliometric analysis has intensively been used by researchers as a tool to measure the scientific research productivity (Zyoud et al, 2017). For several reasons international scholars use bibliometric analysis i.e., articles trending, researchers' collaboration, and keywords for specific domains. Many sources of databases exist, but well known, scientific and internationally recognised databases are Web of Science, Digital Library, Scopus, PubMed, and Google Scholar (Kumar et al., 2022; Kumar and Harichandan 2022; Ho et al, 2023). For keywords bibliometric analysis purpose, the current study uses Scopus and WOS databases. We found a 45% overlap between the above-mentioned databases. Similarly, Chistov et al., (2021) also argue for the existence of a 50% overlap between Scopus and WOS databases[4]. Figure 5 shows main keywords mostly occurring in our research domain. In the context of technological innovations and environmental degradation, networking analysis involves the studying and evaluating the association, interaction, influence, and the connection of different stakeholders, industries, organizations, and policies related to energy production and consumption. Each colour in the network explains the existence of major clusters among the considered literature; while the size of the nodes shows occurrence rate of the keywords, and the links indicate their co-occurrence. The 'red cluster' displays the links, among keywords, related to technological innovations such as eco-innovation, environmental innovations, and energy innovations. Likewise, the 'yellow cluster' includes main keywords explaining the concept of eco-innovations. In the same way, the 'purple cluster' indicates how researchers relate economic growth to environmental sustainability.

[4] The bibliometric analysis is beyond the scope of this research study. Therefore, it should be interpreted as a pure illustrative case.

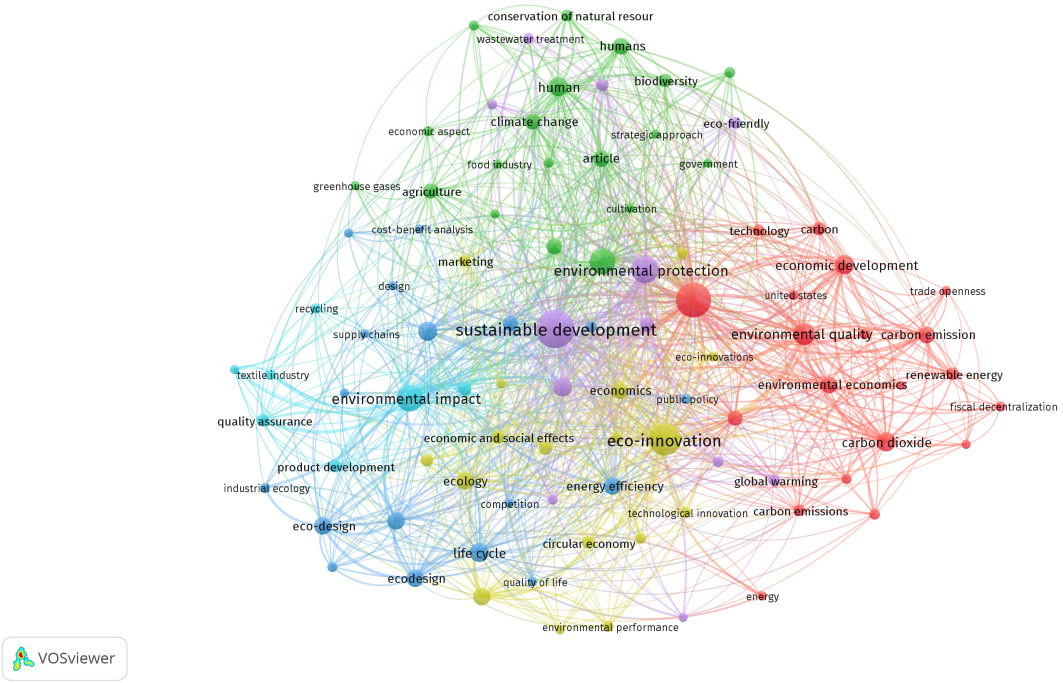


Figure 5. Bibliometric Analysis.

Source: Authors' own computations based on keywords findings from international literature.

2.4 Research gap

The current body of literature does not provide a valuable insight about the correlations emerging between energy, technological advancements, economic growth, and EF. According to the literature cited above, EI generally boost or harm environmental quality (broadly defined mostly in terms of CO_2 emissions) depending on its use, technological advancements, long *vs* short runs, and employed resources. Moreover, an insufficient number of studies examined the above factors on EF in OECD countries. In addition, most studies applied conventional quantitative approaches and found spurious results. To bridge these gaps, the present study applies advanced econometric methodologies and investigates long run and short run associations among EI, REP, R&D expenditures, GDP and EF. Based on the empirical findings (see next sections), the present study contributes to advancements of the EKC hypothesis and provides solid foundations to policymakers in OECD countries to address EF concerns arising from technological innovations, energy and economic growth.

3. Material and methods

3.1 Data sources

The current research uses an annual panel dataset of twenty-one OECD countries such as Belgium, France, Germany, Italy, Netherland, Poland, Portugal, Spain, Sweden, United Kingdom, Norway, Turkey, Canada, United States, Brazil, Chile, Colombia, Mexico, Japan, Australia, and New Zealand during the period from 1990 to 2018. As shown in the introductory section, the choice of the above countries is based on the evidence that OECD countries are currently experiencing a replacement effect from NREP to REP and are suffering from increases in EFs due to industrial growth in the considered time period.

A fundamental environmental indicator such as EF is applied as a proxy variable of environmental quality and quantified in Gha per person (https://www.footprintnetwork.org/). In the same context, data on REP is measured in *kWh*; NREP is gathered as percentage of total energy production. EI is considered in kilograms (kg) per capita oil equivalent; whereas, R&D expenditures are measured as percentage of total GDP. EIN considers the number of patent applications per thousand population. Current literature (Töbelmann & Wendler, 2020; Khan et al., 2020; Cheng et al., 2019; Zhang et al. 2022) uses EI as a proxy variable for patent applications. Per capita GDP is considered in constant 2015 dollars. Table 2 depicts an illustration of measurement units and variable description.

Table 2. Description and sources of data

Variables	Definition	Unit of measures	Data sources
EQ	Environmental Quality	Ecological footprints gha per person	GFN
REP	Renewable energy Production	Renewable Electricity production (kWh	WDI
NREP	Non-renewable energy sources	Energy production from oil, coil and natural gas (% of total)	WDI
EI	Energy intensity	kg of oil equivalent per capita	WDI
EIN	Energy Innovation	Patent applications number per thousand population	WDI
EXPR&D	Research and developmental expenditures	% Of government expenditures on research and development	WDI
GDP	Economic growth	GDP per capita constant 2015$	WDI

Note: GFN- Global footprint network (https://data.footprintnetwork.org/#/.).

WDI-World development indicator((https://data.worldbank.org/indicator.)

3.2 Specified model

Eq. (1) expresses the linear form of the EF function of our empirical investigation as follows:

$$EF = f(REP_{it}, NREP_{it}, IE_{it}, EIN_{it}, R\&D_{it}, GDP_{it}, GDP_{it}^2) \quad (1)$$

To overcome data sharpness and heteroskedasticity, we take the natural log of the selected variables of Eq. (1), in the following notation:

$$LnEQ = \Upsilon_0 + \Upsilon_1 lnREP_{it} + \Upsilon_2 lnNREP_{it} + \Upsilon_3 lnEI_{it} + \Upsilon_4 lnEIN_{it} + \Upsilon_5 R\&D_{it} + \Upsilon_6 \ln GDP_{it} + \Upsilon_7 GDP_{it}^2 + \mu_{it} \quad (2)$$

where GDP_{it}^2 indicates the inverted U-shape according to the EKC hypothesis. In addition, *i* defines the cross-section units, *t* identifies the time units, and μ_{it} is the stochastic error term across countries and time periods. Based on the observed literature and the EKC hypothesis, the current study predicts a positive sign between EF, NREP, EI, and GDP as follows: $\Upsilon_2 = \frac{d(EF)}{d(NREP)} > 0$; $\Upsilon_3 \frac{d(EF)}{d(EI)} > 0$; $\Upsilon_6 \frac{d(EF)}{d(GDP)} > 0$. In contrast, a negative sign is likely to occur between EF, REP, EIN, and GDP^2: $\Upsilon_1 = \frac{d(EF)}{d(REP)} < 0, \Upsilon_4 = \frac{d(EF)}{d(EIN)} < 0$; $\Upsilon_5 = \frac{d(EF)}{d(R\&D)} < 0$; $and\ \Upsilon_7 = \frac{d(EF)}{d(GDP^2)} < 0$.

3.3 Methodological framework

The present study uses an advanced econometrics procedure relying on four steps. In the first step, we check cross-sectional dependency via cross-sectional dependence tests. Subsequently, the stationarity properties of the variables are investigated by Cross-section Augmented Dickey-Fuller (CADF) and Cross-sectional lm, Pesaran and Shin (CIPS) test. After the identification of the integration order of the series. This study will check a long run association between variables via Westerlund panel cointegration test (Westerlund, 2007). Finally, we investigate the magnitude and signs of the estimated coefficients.

Cross-sectional dependency tests. According to Khan et al. (2020) cross sectional dependence (CSD) stands out a significant complication in panel data estimation, which leads to produce a spurious outcome. The issue should be addressed before processing with inferential analysis. Due to economic integration and globalization, economies are dependent on each other. Internal and external shocks effect on the progress of other economies. The significance level(p-value) of cross-sectional dependence tests allow use to choose first-generation or second-generation empirical approaches. This study is based on CSD statistics offered by Pesaran CSD (Pesaran, 2007), Breusch and Pagan (1980), and the Pesaran scaled LM test (Pesaran, 2004). These tests deal with both CSD and heterogeneity issues. The hypothesis of CSD test analysis is the following:

H_0: Cross sectional independent.

H_1: Cross sectional dependent.

Based on probability values, we are able to accept or reject the null hypothesis (H_0). The null hypothesis (H_0) is presented in the following equation:

$$H_0: \eta_{ij} = \text{corr}\left(\varepsilon_{ij}, \varepsilon_{ij}\right) = 0 \quad \forall\, i \neq j \tag{3}$$

and the related mathematical version is as follows:

$$CSD = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{K=i+1}^{N} \beta iK\right) \sim N(0,1) i, K \tag{4}$$

Where CSD = 1,2, 3,4,…N and Bias-corrected Pesaran test presented in equation 8:

$$LM_{BC} = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{K=i+1}^{N} \hat{\beta}_{iK}\right) \left[\frac{(T-K)\hat{\beta}_{iK}^2 - (T-K)\,\hat{\beta}_{iK}^2}{Var(T-K)\hat{\beta}_{iK}^2}\right] \tag{5}$$

Here, N reveals 21 cross-sections, and T shows 28 years sample size (time), respectively.

Panel unit root tests. A second step is to verify the order of the integration among the respective variables. CADF and CIPS tests are more robust and reliable in the presence of CSD (Pesaran, 2007). These tests provide precise information regarding the integration order of the series as compared to first-generation tests (Kabir et al., 2017). CADF panel stationary test is expressed in the following notations(including lag factor) :

$$\Delta Y_{it} = \beta_i + \delta_i y_{i,t-1} + \gamma_i y_{t-1} + \sum_{j=0}^{p} \psi_{ij} \Delta y_{t-j} + \sum_{j=0}^{p} \Theta_{ij} \Delta y_{i,t-j} \tag{6}$$

whereas $\Delta y_{i,t-j}$ and y_{t-j} represent the first change operator for each cross-section, respectively. CIPS is the simple average of augmented CADF and appears in the following notation:

$$CIPS = N^{-1} \sum_{i=1}^{N} \delta(N, T) \tag{7}$$

Here, the factors δ(N, T) can be replaced with the following:

$$CIPS = N^{-1} \sum_{i=1}^{N} CADF_i \tag{8}$$

Westerlund cointegration test. In order to get a long run association among sampled variables this employed Error Correction Model (ECM) based panel cointegration test , proposed by

Westerlund (2007). It has the ability to tackle with CSD and slope of heterogeneity issues. It is based on four tests statistics, two for panel and two for group statistics, respectively.

The following equation shows the formulation of Westerlund cointegration test:

$$\Delta X_{i,t} = \alpha_i \gamma_i + \delta_i \left(Z_{i,t-1} - \delta_i Y_{i,t-1}\right) + \sum_{j=1}^{\theta} \delta_{ij} \Delta Z_{i,t-j} + \sum_{j=0}^{\theta} \varphi_{ij} \Delta Y_{i,t-j} + \mu_{i,t} \quad (9)$$

Here, δ_i shows the speed of adjustment that brings back to the long-run equilibrium.

Long-run estimations. Finally, the last step checks the magnitude and nature of the variables. The current study applies pooled mean group (PMG/ARDL) (Pesaran & Shin, 1995) and mean group (MG) models. These techniques are suitable when some variables are stationary at integrated order one, while some other at level. Subsequently, the Hausman test is applied to check the reliability of the estimated models. Based on this latter test, we argue on the type of model (PMG *vs* MG) resulting in statistically more accurate and reliable. The following notation depicts the PMG model as follows:

$$\Delta Y_{it} = \theta_i + \sum_{j=0}^{z-1} \alpha_{ij} \Delta X_{i,t-j} + \pi_i \tau_t + \sum_{j=1}^{q-1} p_{ij} \Delta Y_{i,t-j} + \mu_{it} \quad (10)$$

Where θ_i is the intercept, Y_{it} and X_{it} represent the dependent and independent variables respectively with (z) an equal number of lags through an individual cross section i units in t, time units. $\pi ECT_{i,t}$demonstrates error correction term, speed of adjustment from short run disequilibrium towards long equilibrium. θshows the long run coefficients. Δ shows the first difference, and μ_{it} is the error term across units and time periods.

4. Results and discussion

Table 3 illustrates the descriptive statistics of our sample. In particular, the sample includes 610 observations over the considered time period. EF has a mean value of 5.34 gha/person (s.d.=1.92), while REP and NREP indicate mean values of 22.45 kWh (s.d.=1.76) and 50.39 % (s.d.=29.97 %), respectively. Therefore, the latter variable presents higher variability than REP. Similar results appear for EIN (mean=12.95 patent application / thousand population; s.d.=15.24) and EI (mean=4.46 kg of oil equivalent per capita; s.d.=1.51). In terms of R&D, this has a mean value of 1.57% on governmental expenditures (s.d.=0.88), while per capita GDP is on average about 27,000 $ expressed in constant 2015 $.

Table 3. Descriptive statistics

Statistics	EQ	REP	NREP	EIN	EI	EXP R&D	GDP	GDP^2
Mean	5.34	22.45	50.39	12.95	4.46	1.57	27047.7	159.62
Maximum	10.34	26.68	98.75	89.79	11.54	3.87	69807.23	264.21
Minimum	1.81	17.75	0.073	0.01	2.14	0.08	4728.30	68.76
Std.Dev.	1.92	1.76	29.97	15.24	1.51	0.88	13578.72	42.48
N. of obs.	610	610	610	610	610	610	610	610

Source: Authors' own computations on OECD data.

4.1 Correlation Matrix

Table 4 shows the bivariate analysis of eight variables prior to the log transformation. The dependent variable EF is positively correlated with REP (=0.17) and negatively associated with NREP (=-0.10). While other variables such as EIN (=0.24), and EI (=0.69) are positively correlated with EF. According to Doğan & Madaleno (2020), the correlation table shows values below the threshold of 0.85. As such, we argue for the absence of no multicollinearity across variables.

Table 4. Correlation Matrix

Series	EQ	REP	NREP	Einnov	EI	R&DE	GDP
EQ	1.00						
REP	0.17*	1.00					
Probability	0.00						
NREP	-0.10***	0.06	1.00				
Probability	0.00	0.13					
EIN	0.24*	0.4915*	-0.09**	1.00			
Probability	0.10	0.00	0.06				
EI	0.69***	-0.04	-0.09***	0.04	1.00		
Probability	0.00	0.34	0.02	0.27			
R&DE	0.54**	0.46*	-0.20*	0.75	0.29***	1.00	
Probability	0.07	0.10	0.00	0.00	0.00		
GDP	0.59***	0.59*	-0.02	0.55	0.10***	0.06	1.00
Probability	0.00	0.00	0.57	0.00	0.01	0.11	

*** indicates a 1% level of significance.

Source: Authors' own computations on OECD data.

4.2 Results of CSD tests

Table 5 shows the obtained results from CSD tests by employing Breusch Pagan LM, Pesaran Scaled CSD, and Pesaran CSD tests (see section 3.3). We can argue that all series are statistically significant, and based on the estimated p-values, we are able to reject H_0 at 1 percent level of significance.

Table 5. Cross-sectional dependency test

Series	Breusch Pagan LM		Pesaran Scaled CSD		Pesaran CSD	
	Statistics	prob	Statistics	prob	Statistics	prob
LnEQ	1410.81	0.00	58.59	0.00	20.22	0.00
LnREP	5226.85	0.00	244.80	0.00	72.13	0.00
LnNREP	1991.87	0.00	86.95	0.00	9.65	0.00
LnEIN	2089.66	0.00	91.72	0.00	15.20	0.00
LnEI	2039.68	0.00	88.29	0.00	12.88	0.00
LnR&D	1472.21	0.00	61.63	0.00	14.87	0.00
LnGDP	5800.60	0.00	272.80	0.00	76.12	0.00
LnGDP^2	5545.24	0.00	260.34	0.00	74.21	0.00

* ,**and *** indicate at 10% ,5% and 1% level of significance, respectively.
Source: Authors' own computations on OECD data.

4.3 Results of panel unit root tests

Table 6 shows the panel unit root tests for the integration order of the series. First-generation tests (like Chu, Hadri, ADF and PP) may fail to detect CSD and can generate spurious outcomes. As such, we consider second-generation tests. As mentioned in section 3.3, the current study uses second-generation CADF and CIPS tests. The estimated outcomes show that lnEF, lnREP, lnNREP, InEI, InEIN, InR&D, and InGDP are not stationary at level integrated order zero I[0]. Yet, all variables present stationarity at first difference I[1]. Hence, we reject H_0 at 1 percent level of significance.

Table 6. Panel unit root tests results

Series	Level		First Difference		Integration Order
	CADF	CIPS	CADF	CIPS	
Ln_EQ	81.33**	-2.71**	348.89***	-18.48***	I(1)
Ln_REP	14.57	7.01	211.47***	-18.97***	I(1)
Ln_nREP	38.80	3.48	292.44***	-14.11***	I(1)
Ln_EI	40.04	4.06	201.51***	-9.54***	I(1)
Ln_EIN	42.06	-4.54*	271.98***	-30.06***	I(1)
Ln_EXPR&D	84.85	-0.26	206.56***	-17.77***	I(1)
Ln_GDP	23.25	2.73	255.28***	-13.97***	I(1)
Ln_GDP^2	14.69	-9.44	187.235**	-13.02%-***	I(1)

*,**and *** indicate at 10% ,5% level and 1% level of significance, respectively.

4.4 Results of Westerlund test

Table 7 shows the estimated results of the Westerlund (2007)'s test. As mentioned in section 3.3, this test is employed to examine the long run association among variables. Table 7 shows that all mean groups (Ga=-2.70 and Gt=-2.65) and panel groups (Pa=-1.93 and Pt=3.26) are

statistically significant at 1 per cent level of significance. Thus, we reject the null hypothesis H_0 and conclude that cointegration exists among series.

Table 7. Westerlund co-integration test outcomes.

Statistics	Z-Values	P-value
Ga	-2.69***	0.03
Gt	-2.65***	0.09
Pa	-1.93**	0.02
Pt	-3.25***	0.03

* ,**and *** indicate at 10% ,5% level and 1% level of significance, respectively.

4.5 Pooled mean group

Table 8 illustrates the estimated results of PMG and MG models. Based on the Hausman test (Hausman, 1978), we are able to reject H_0 and argue that PMG results are more reliable for our analysis. The estimated ECM model shows negative signs, and it is statistically significant at 1 percent level of significance. According to our findings, it shows the conversion speed from short-run equilibrium to long-run stable equilibrium within three years. REP holds a negative and statistically significant effect on EF, showing that an improvement in terms of hectares of land and sea to absorb pollution and waste material is possible through substituting fossil fuels with renewable energy. By just switching these two forms of energy by 1 percent, the estimated change occurs in the same percentage. Other studies support this positive evidence. Particularly, Su et al. (2023) in a paper considering OECD countries and quantile regressions technique, argue that lower quantiles experience reduced GHG emissions due to renewable energy production and stricter environmental policies, whereas higher quantiles are notably influenced by environmental innovation. In similar works, Nan et al. (2022) and Liao et al (2023) using Method of Moment Quantile Regression (MMQR) and panel models argue that renewable energy in OECD countries has a notably stronger and more beneficial effect on reducing carbon emissions, due to advancements of green technologies (Doğan et al., 2021; 2022a). Similar results are obtained by Khalfaoui et al (2023) for MENA region countries and Payne et al (2023) for top-25 energy-use countries. Likewise, in other country contexts such as E7 and G7 (Eyup et al., 2022; Doğan et al., 2022b; Khan et al., 2022), PIIGS economies (Balsalobre-Lorente et al. 2022), Asian Pasific countries (Usman et al., 2021) and SARRC region (Khaizran et al., 2021) energy transition provides, through economies of scales (Eyup e al., 2020), enhancements of environmental quality.

* ,**and *** indicate at 10% ,5% level and 1% level of significance, respectively.

Table 8: Pooled mean group estimations

	Long run estimations			
Variables	PMG		MG	
	Coeff.	Prob	Coeff	Prob
LnREP	-0.10**	0.00	-0.06*	0.09
LnNREP	0.17**	0.00	0.57**	0.02
LnEI	-0.15*	0.10	1.08	0.30
LnEInno	-0.12**	0.00	-0.07	0.92
LnR&DE	0 .08**	0.00	-0.02	0.76
LnGDP	2.20**	0.00	0.29	0.01
LnGDP ^{2}	-4.10**	0.00	0 .02	0.92
Short Run				
ECT	-0.34	0.00	-0.92	0.00
LnREP	0.01	0.36	0.03	0.44
LnNREP	0.11	0.58	0.36	0.07
LnEI	0.25	0.02	0.05	0.38
LnEIN	0.05	0.14	-0.00	0.92
LnR&DE	0.05	0.34	0.16	0.36
LnGDP	0.51	0.00	0.44	0.01
LnGDP ^{2}	-0.08	0.23	-0.18	0.51
Hausman test	Chi test=13.80	Prob. 0.06		

Source: Authors' own computations on OECD data.

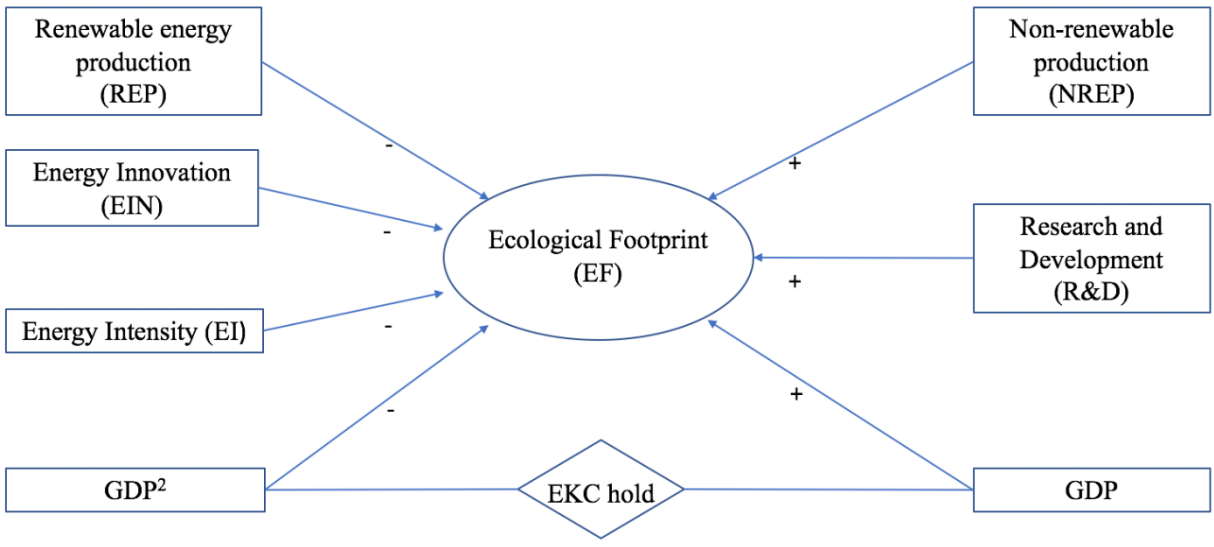


Figure 6. Long run estimations of PMG

On the contrary, the long-run elasticity of NREP still poses negative effects on EF. Our estimates show that, keeping other things constant, a 1 percent increase in the use of traditional energy sources, EF worsen by 0.17 percent. Fossil fuel combustion, used extensively in various economic activities like production, distribution, transportation, and storage, still constitutes a significant contributor to environmental quality. As such, autonomous and induced investment

in renewable energy market must be acknowledged as an important element to ensure long-lasting environmental sustainability. Recent literature also suggest similar results such as Ahmad et al. (2020a); Khan et al. (2022); Mujtaba et al. (2022); Noor et al. (2023). The expected outcome of EI holds a negative and statistically significant impact on EF. The finding reveals that a 1 percent increase in EI, lessens EF by 0.15 percent. We can argue that in the studied period the structure of OECD countries has been changing such to require less energy to produce economic output as it decouples growth dynamics from increased energy consumption. In particular, higher EI encouraged industries and businesses to adopt more efficient technologies and processes, leading to reduced energy waste and lower production costs. In addition, as industries strive to enhance energy efficiency, a surge in demand for skilled workers specializing in sustainable practices, created new job opportunities (OECD, 2023). Similar results for EI, can be found in the works of Shahbaz et al. (2015); Zafar et al. (2019) and Aydin & Turan (2020).

Likewise, mitigation effects on EF also depend on EIN. More precisely, in the long run, a 1 percent increase in EIN reduces EF by 0.12 percent. Other studies also support this evidence such as the recent works of Huang et al., (2022a) and Sahoo & Sethi (2022). Over the past three decades, OECD countries have made significant strides in the realm of energy innovation. These advancements have been driven by the need to address environmental concerns, enhance energy security, and foster sustainable economic growth. From renewable energy technologies to energy efficiency measures, the progress made in this domain has been remarkable (OECD, 2015; 2022). One of the most prominent developments in energy innovation has been the rapid expansion of renewable energy sources (Figure 4). Solar and wind energy technologies have witnessed substantial growth, thanks to favorable policies and declining costs. Wind farms and solar installations now mark the landscapes of many OECD countries, contributing to a substantial share to their energy mix, reducing GHGs, and fostering energy diversification.

Classical estimates of EKC income co-variates such as GDP (GDP^2), hold statistically significant positive (negative) impact on EF. A 1 percent increase in GDP (GDP^2) increases (decreases) EF by 2.20 (-4.10) in the long run. The outcomes of the above estimated EKC income variables are in line with the findings of the recent literature such as Sapkota and Bastola (2017), Kahouli (2018), Hassan et al. (2019), Sefa et al., (2019). In contrast, other studies reveal an N-shaped relationship between EF and GDP (Mrabet et al. 2017; Doğan et al., 2020). Finally, the estimated coefficient of R&D expenditure shows, in contrast with our expectations, a positive impact on EF. More specifically, a 1 percent increase in R&D expenditure intensifies EF by 0.08 percent. R&D expenditures in OECD countries can have

negative effects on the ecological footprint due to several reasons. First, increased R&D spending often leads to higher levels of industrialization and technological advancements. While these developments can bring about positive changes in various sectors, they may also result in greater resource consumption and waste generation in other sectors, contributing to an intensified ecological footprint. Moreover, certain R&D activities may focus on industries that heavily rely on fossil fuels or resource-intensive processes. As a result, the carbon emissions and ecological impact of these industries can increase, further exacerbating the ecological footprint of the countries involved (Alam & Apergis, 2021; Godil et al. 2021). Furthermore, the pursuit of cutting-edge technologies might lead to the extraction and depletion of natural resources at an accelerated pace. Exploitation of minerals, rare earth elements, and other essential materials for research purposes can have significant ecological consequences, including habitat destruction and biodiversity loss (OECD, 2019). Additionally, some R&D projects may lack adequate environmental assessments, leading to unintended negative ecological outcomes. We argue that without proper consideration of ecological impacts, technological advancements might inadvertently contribute to environmental degradation. Notwithstanding, we recognize that not all R&D expenditures have detrimental effects on EF. In fact, a considerable portion of research funding in OECD countries is dedicated to sustainable technologies, renewable energy, and environmental conservation as shown by the estimated outcomes of REP, EI, and EIN. Such investments can result in positive contributions, helping to mitigate ecological footprints and promote eco-friendly practices in the immediate future (Koçak & Ulucak 2019; Charfeddine and Kahia 2019).

5. Conclusion and policy implications

The current environmental situation in OECD countries highlights the need of energy innovations to mitigate the ecological deficit. The role of energy innovations for the reduction of ecological footprints is still cryptic. In the light of these circumstances, the current study investigated the impact of GDP, REP, NREP, EI, EIN, and R&D on EF. To do so, our work applied advanced PMG inferential analysis and offered a contribution to the EKC debate in the light of the relationship between ecological deficit, growth, technological advancements and energy transitions in 21 OECD countries in the last 30 years (1990-2018). While all the estimated co-variates were in accordance with the predicted signs, R&D expenditure contrasted our expectations.

We argue that as OECD countries seek the transition to more sustainable energy sources, policymakers face critical decisions that can significantly impact environmental conservation and ecological well-being in growth processes.

Firstly, governments must prioritize and incentivize the development and deployment of renewable energy technologies. By offering financial incentives (including feed-in tariffs, tax credits, grants, and low-interest loans), tax breaks, and subsidies for renewable energy projects, policymakers can accelerate their implementation and make them more cost-competitive with traditional fossil fuel-based energy sources. By making renewable energy more economically attractive, such measures encourage private investments and consumer participation. Financial support can significantly reduce the payback period for renewable energy investments, making them more accessible to a broader range of stakeholders, including households and businesses. Moreover, setting ambitious renewable energy targets can create a clear roadmap for a low-carbon future, and create a sense of urgency, encouraging investments in clean energy infrastructure and driving technological innovation. Governments can commit to specific and quantifiable goals, such as achieving a certain percentage of renewable energy in the total energy mix by a designated year. Ambitious targets also demonstrate the country's commitment to global climate goals and enhance international cooperation.

In addition, carbon pricing mechanisms, such as carbon taxes or cap-and-trade systems, can create economic incentives for industries and individuals to reduce greenhouse gas emissions. By placing a price on carbon emissions, policymakers internalize the external costs associated with fossil fuel use, making renewable energy more economically competitive. Revenue generated from carbon pricing can be reinvested in renewable energy projects and other sustainability initiatives.

Also, while transitioning to renewable energy is crucial, optimizing energy use through efficiency measures can further diminish EF. Reducing energy consumption through energy-saving measures and technologies or providing incentives or setting efficiency standards for energy-efficient buildings, appliances, transportation and industrial processes can significantly contribute to ecological conservation.

In addition, fostering R&D in renewable energy technologies is crucial. Governments should allocate resources to support innovation and advancements in areas such as solar, wind, hydro, geothermal, and bioenergy to accelerate the deployment of more efficient and cost-effective solutions. According to the International Energy Agency - IEA (2022) (Agency IEA, 2022) the adoption of eco-friendly resources in the national energy mix could mitigate the budgetary

pressure and governments can allocate more budget on R&D in the energy sector. In fact, investments in REP industries, which are more labor intensive than NREP, yields governments with higher multipliers effects ranging from 1.1 to 1.7 times compared to traditional fossil fuel technology projects (Batini et al, 2022).

Furthermore, effective policy implementation requires international cooperation and knowledge sharing. OECD countries can collaborate on research, development, and best practices in renewable energy deployment. Public-private partnerships can facilitate knowledge transfer and help bridging the gap between academia and industry, driving technological advancements to accelerate the global transition to clean energy and collectively reduce the ecological footprint.

Additionally, policymakers must address the intermittency of some renewable energy sources by investing in energy storage technologies and smart grid upgrades (Brouwer et al., 2014). Implementing large-scale energy storage solutions such as battery storage, pumped hydroelectric storage, and advanced and resilient grid management systems can ensure a stable and reliable balance of energy supply and demand. On this issue, governments should actively monitor digital trends and provide support to energy companies in integrating digital technologies into their energy systems. The adoption of digital tools in energy systems has the potential to enable the development of advanced technologies, such as energy storage systems and intelligent grids, within the clean energy sector. The collaboration between digital technologies and clean power-generation technologies holds promise in enhancing energy efficiency, reducing the costs of renewable energy, and promoting environmentally friendly production and consumption practices. The assessment of this interaction aligns with Sustainable Development Goal (SDG) 7 (affordable and clean energy) of the UN Agenda 2030[5].

At country level, within the observed OECD sample, we discern potential drawbacks and advancements that can help governmental bodies to advance towards green growth transitions. According to Diaz-Rainey & Sise (2018), both Australia and New Zealand needs policy stability for market confidence as well as political will and regulatory acceptance of energy transition. This also induce both countries to commit to advancements of reforms of or within their electricity markets. As for Japan, the latest IRENA report (2022) highlights the progress made on the planned energy scenario (PES) of the country and that further measures occur to increase international collaboration and lower domestic carbon taxes in view of a more efficient

[5] https://www.un.org/sustainabledevelopment/development-agenda/).

income distributional policy. Japan is also currently promoting hydrogen energy and several other energy developments such as wind and bioenergy for the green transition of its economy.

International and national financial banks and carbon price mechanisms (i.e. auctions) have been essential for the development of REP industries in Brazil, Chile, Colombia and Mexico. The Brazilian Development Bank (BNDES) is facilitating indirect financing for REP enterprises by partnering with development financial institutions (DFIs) like microfinance banks through public-private partnerships. This approach expedites learning in the financial industry but also improves access to finance for RE ventures.

Chile (Raihan, 2023) has the option to employ several measures, including imposing high carbon taxes, implementing carbon capture and storage technologies, and adopting emission trading schemes, to decrease fossil fuel consumption in electricity generation and industrial activities. Achieving sectoral decoupling, which entails significant transformations in centralized government policies, behaviors, research, and technology, will be essential to accomplish these goals. Colombia benefits from abundant hydric resources, which contributes to the country's electric system being both highly reliable and competitive. Davies & Saygin (2023) argue that in order to reduce the cost of renewable energy technologies, secure greater volumes of private equity and debt, and successfully replace outdated and polluting diesel generation systems, will be crucial for the development of innovative business and financing models. In addition, some incentive mechanisms are needed to increase REP implementation through a well-defining approach to the distribution of renewable energy in the supply chain. The recent decisions made by the Colombian government (Rueda-Bayona et al., 2019) demonstrate a clear interest in promoting and incentivizing the exploitation of renewable energy resources in the immediate future.

In Mexico, the recently launched government package shows promising potential in terms of creating value added, employment opportunities, reducing greenhouse gas (GHG) emissions, and optimizing materials per unit of investment and GWh (gigawatt-hour) produced (Banacloche et al., 2020). Green investments, according to the National Electricity System Development Program (PRODESEN), could increase employment approximately by 0.9% to 2.7% in the next years. Nonetheless, these green investments would also lead to a rise in the Mexican emission footprint, estimated to be around 2.3% to 7.2% (Banacloche et al., 2020). Similarly, according to Pérez-Denicia et al. (2017), promoting domestic industries and reducing reliance on imports would foster continuous economic development within local communities. For the above countries, the future involvement of community-based organizations in financing RE projects, results particularly important for promoting financial

inclusion and contributing to a fair and equitable energy transition is also advisable to promote the already in place energy developments particularly relevant for wind and bioenergy.

As for USA, Canada, Europe, UK and Norway, much is still to be done to achieve full transition to a sustainable growth. In the US, the Department of Energy (DoE)'s Office of Energy Efficiency and Renewable Energy (EERE) is in charge to operate public spending on energy related projects for the government. Hasna (2021) argues that the multiplier effect of a 1$ increase in investment in energy efficiency and renewable energy results in a contemporaneous increase of 1.1$ in local economic activity. At the end of only one year, this increase in public spending may more than double to 2.5$. The same author also argues that the impact is also significant in terms of R&D and patents. Doubling current patents may increase economic growth in the medium run by 3.4 percentage points (Hasna et al. 2021). The most recent US policy act, the Inflation Reduction Act of 2022[6], is actively striving to drive genuine economic growth while also prioritizing energy security and climate change investments. This includes a substantial budget of $369 billion allocated for such initiatives in the next ten years. The fnding will be directed towards various measures, including production tax credits to accelerate the adoption of solar and wind energy, investment tax credits, grants, and subsidies to support clean vehicles, as well as funding for R&D in green technologies.

In Canada, the Pan-Canadian Framework on Clean Growth and Climate Change (PCF)[7] outlines a range of policies aimed at lowering carbon emissions and fulfilling Canada's commitments under the Paris Agreement. Alongside carbon pricing and various other initiatives, it binds federal and provincial governments to a series of actions, such as increased demand for energy related products, redistribution of savings on energy bills, and reduced energy sales, designed to enhance energy efficiency in Canadian homes, buildings, and industries. In particular, these measures will contribute to boost GDP by 1% (7$ GDP multiplier vs 1$ spending), create 118,000 jobs, save 1.4 billion $ to Canadian consumers, and reduce 52M tonnes of CO_2e emissions by 2030.

In Europe, the primary objective of the REPowerEU plan (European Commission, 2022) is to swiftly decrease reliance on Russian fossil fuels by the year 2027. According to the European Commission's estimates, achieving this goal will necessitate substantial growth in the proportion of renewable energy in the electricity, transport, and heating sectors. The expansion of renewable energy in the electricity sector is projected to reach nearly 55% by 2027. However, this falls short of the European Commission's estimated target of 69% required to

[6] Pub. L. No. 117-169, 136 Stat. 1818 (Aug. 16, 2022).
[7] https://publications.gc.ca/collections/collection_2017/eccc/En4-294-2016-eng.pdf

support the REPowerEU plan. To facilitate further increases in renewable energy penetration, governments throughout the European Union must take measures to minimize policy uncertainty, streamline permitting procedures, and expedite upgrades to transmission and distribution networks. The proportion of renewable energy in heating and cooling is projected to grow by 0.9 percentage points each year until 2027, marking a one-third faster pace compared to the previous decade. However, this growth rate falls short of the 2.3-percentage-point annual increase necessary to align with the ambitious goals of the REPowerEU plan. To expedite the deployment of renewable energy in heating and cooling, more assertive policies will be essential for the COP21 commitments (Balsalobre-lorente et al., 2020). These policies should focus on strengthening heat pump supply chains, enhancing the availability of skilled labour for installations, integrating renewable energy sources into district heating networks, scaling up biomethane production, streamlining permitting regulations for large-scale renewable heat projects, and supporting alternative business models for heating.

The UK Government has a legal commitment to achieve net-zero emissions (100% abatement) across the entire economy by 2050[8]. However, the use of negative emission technologies in specific sectors allows for some variations in reaching this target, considering different end-use energy demand sectors and industries. Industries with hard-to-abate emissions, like the steel industry, may take advantage of this opportunity to achieve net-zero emissions. In the shorter term (2020-2030), achieving net-zero emissions will heavily rely on the adoption of existing or currently available technologies (Wilson et al., 2023). In the long-term goal, disruptive technologies will be essential to meet the UK's legally bound net-zero target under the 2008 Climate Change Act, which was amended in 2019 to prioritize carbon neutrality. One promising option is hydrogen-based processing. Incentives, investments, and recovery funding will be directed towards final consumers, who will benefit from demand-pull incentives such as electric vehicle (EV) purchase subsidies, and firms or service providers, who will receive technology-push incentives like infrastructure investments in EV production lines or battery manufacturing facilities (Wilson et al., 2020).

Norway has committed to participate in EU climate legislation from 2012 to 2030, which encompasses three key components: the EU Emissions Trading System (EU ETS)[9], the Effort

[8]https://commonslibrary.parliament.uk/research-briefings/cdp-2023-0124/#:~:text=In%20June%202019%2C%20with%20the,as%20the%20net%20zero%20target.
[9] https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

Sharing Regulation for non-ETS emissions[10], and the regulation for land-use, land-use change, and forestry (LULUCF)[11]. As the EU ETS mainly addresses emissions from industrial production and the oil and gas industry, the Norwegian government, building upon the foundation laid by the 2030 Climate Action Plan (CAP) focuses on reducing emissions not covered by the EU Emissions Trading System (non-ETS emissions). This encompasses the development of Carbon Capture and Storage (CCS), hydrogen and offshore wind, reinforcing the power grid, and fostering a future-oriented oil and gas industry that maintains low emissions from upstream activities. The climate action plan employs various policy instruments to achieve its goals, including greenhouse gas (GHG) emissions taxation, regulatory measures, climate-related requirements in public procurement processes, information dissemination on climate-friendly alternatives, financial support for technology development, and initiatives to promote research and innovation.

Lastly, policymakers should engage in public awareness campaigns to promote renewable energy adoption and environmentally conscious behaviors. Educating citizens about the benefits of renewable energy and the importance of reducing their EF can drive behavioral change and increase support for sustainable policies of modern economic growth. Zafar et al. (2020) highlighted the importance of education on environmental awareness as a policy tool in OECD countries. A strong link between insufficient focus on R&D activities and poor educational attainment is present. Therefore, it is essential to revise educational curricula and improve education to raise the level of environmental awareness. In this direction, SDG 9, which focuses on industry, innovation, and infrastructure, can be aligned with policies focusing on other SDGs such as SDG 4 (quality education), SDG 13 (climate action), and SDG 12 (responsible consumption and production). By aligning these SDGs and focusing on environmental education and awareness, nations can work towards achieving a more sustainable and ecologically friendly future, fostering a greater penetration of renewable energy solutions and contributing to the overall well-being of both the environment and society.

Finally, the current study is not without limitations. First, this work is limited to the investigation of OEDC economies and only a relatively small number of variables describe the significance of energy transition and innovations on EF. This reduces the generalizability of

[10] https://climate.ec.europa.eu/eu-action/effort-sharing-member-states-emission-targets/effort-sharing-2021-2030-targets-and-flexibilities_en#:~:text=The%20Effort%20Sharing%20Regulation%20establishes,agriculture%2C%20small%20industry%20and%20waste.

[11] https://www.consilium.europa.eu/en/ infographics/fit-for-55-lulucf-land-use-land-use-change-and-forestry/

the findings. In addition, other studies shall accurately point towards the linkages between the main factors to reduce the gaps between supply and demand side of current energy transition and growth processes. Given the heterogeneity of the latter in OECD countries, this issue should be taken into consideration in future studies by providing comparisons within sub-groups of nations. Also, future works shall look at comparative analyses across new emerging blocks of economies with OECD countries. In terms of methodology, it would be beneficial for further researchers to apply several other advanced quantitative techniques. Particularly important will be the exploration of technological innovations in the energy sector and the relevance of public R&D expenditures to better address energy transitions processes across countries.

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Chapter 3

Investigating a new energy justice index on carbon emissions: A global study of 95 economies during 1996-2021

Abstract. The present study contributes to the international debate on energy justice (EJ) by developing a new energy justice index (EJI) through the use of the entropy-based method, aligned with the Sustainable Development Goals (SDGs) 7 (equitable clean energy access), 10 (inequality reduction), and 13 (climate action), and thus extending the 2015 work of Sovacool & Dworkin. The study applies the obtained index, as well as other socio-economic variables such as technological innovations (TI), natural resource rent (TNR), export (EXP), globalization (GLO), and financial development (FD), to infer on CO2 emissions in 95 different income groups economies such as high-income (HICs), upper-middle-income (UMICs), lower-middle-income (LMIC), and low-income countries (LMICs) from 1996 to 2021. Main findings from the Method of Moments Quantile Regression (MMQR) indicate that EJI and TI significantly reduce CO2 emissions in HICs and UMICs, but LMICs, throughout all quantiles. Whereas, TNR positively affects CO2 emissions in UMICs and LMICs, thus confirming the existence of a 'resource curse hypothesis' in these country groups. As a result, ad-hoc policy measures taking into account top-down regulations, market-based instruments, and bottom-up perspectives are advised according to the specific economic framework and trends at country and country-group level to achieve carbon neutrality goals.

Keywords: Energy justice index; Entropy method; Method of Moments Quantile Regression

1. Introduction

In the era of technological advancement, energy emergency and economic inequalities are at the heart of the international debate (Liu et al., 2023). The advancement of national economies is shaped by numerous factors, although the key element is the availability, safety and accessibility of energy.

World economies are relying on centralised energy systems, in which energy is generated at large scale through coal, oil, gas and distributed through specific energy infrastructural grids to final consumers and firms. Often, a centralised energy system works under a monopoly market, thus posing several negative effects in the aggregate society in terms of increased energy inequalities, reliance on carbon-intensive energy sources, and social disparities within and across countries. As a result, energy production and distribution must shift from centralized to decentralized systems according to a justice principle in the energy sector (Khan et al., 2022).

The concept of energy justice (EJ) describes the fair distribution of energy sources and addresses the inequalities of current energy systems (Droubi et al., 2022; Skare et al., 2024a). This is aligned with several justice frameworks associated with accessibility, affordability, and sustainability issues (Casta et al., 2022). It has emerged as pioneering research within Social Sciences, striving to apply justice-oriented principles across diverse dimensions of energy, from policy and production to consumption, activism, security, energy trilemma, and the political economy of climate change (Heffron & McCauley, 2017).

During the 1970s, the energy justice movement originated in North America as a response to the disproportionate distribution of environmental problems affecting Black and ethnic minority populations (Williams, 1999). Since then, the movement is linked to an equitable access and distribution of natural resources across individuals and generations and the risks associated with the pollution generated by the mis-use and production of energy inputs (Davies, 2006; Ul-Durar et al., 2024).

The existing literature qualitatively explains the concept of EJ and its core principles (Lappe-Osthege & Andreas, 2017; Tysiachniouk et al., 2018), as well as a significant number of studies primarily focus on the context of developed nations (Lacey-Barnacle et al., 2020).

As for the former, numerous approaches include the definition and ‘measures’ of EJ, but a standardized and widely accepted framework is not yet developed and implemented. To accommodate the lack of a harmonised measure of EJ, the present study aims to construct an energy justice index (EJI) through the use of the entropy method (Hwang &Yoon, 1981) by considering the three core components of EJ as defined by Sovacool & Dworkin (2015) such as distributive justice (which ensures the fair distribution of resources/energy accessibility), procedural justice (i.e. community involvement in the energy decision-making process/ voice

and accountability), and recognition justice (i.e. recognition of energy affordability and environmental sustainability). EJI values lie between -1 to 1. This index serves as a valuable tool for policymakers to identify key issues related to energy (in)justice that might be addressed via the decentralization of the energy system (Oliveira et al., 2024).

As for the latter issue, the present study also aims to investigate the effect of the constructed EJI on CO2 emissions using a balanced panel of 95 global economies during 1996-2021. Countries are split according to the per-capita income classification of the World Bank[12]. The sub-sample consists of 38 HICs, 25 UMICs, 20 LMIC, and 12 LMICs (Table S1 Supplementary material). Given the countries' heterogeneity, the investigation assumes that the effect of EJI on CO2 emissions may present major econometric problems like cross-sectional dependency, unit root, and endogeneity (Gao et al., 2024). Thus, a rigorous inferential analysis is addressed to provide robust results of the estimated coefficients from the Method of Moments Quantile Regression (MMQR). In addition, the inferential model includes main economic co-variates deriving from the international debate.

The remainder of the paper is organized as follows: Section 2 describes the main theoretical framework and literature background, including a bibliometric analysis of EJ in support of the employed co-variates; Section 3 illustrates the value added of the study; Section 4 describes the construction of the new EJI through the entropy method and explains the inferential approach; Section 5 explores the estimated outcomes. Finally, section 6 offers some policy recommendations and concludes the paper.

2. Literature background

2.1 Main theoretical framework

The classical school of thought emphasizes the significance of the free market economy, individual interest, and efficient allocation of resources through the market forces of demand and supply (Smith, 1977). Classical economists assume that energy is a capital good that enhances economic productivity, but this framework overlooks social justice and produces economic disparities. Fluctuations in oil prices result in market failures contributing to energy (in)justice (Murat et al., 2023). The literature debates whether energy can be considered a public good (Emre & Yavuz, 2023). In the context of renewable energy sources 'energy' is a public good (non-excludable and non-rival), and thus, regardless of financial status, all individuals have equal access to it or, in general, to all natural resources. In contrast, in the context of the current global energy system, energy is considered a private good (Estevão

[12] https://datatopics.worldbank.org/world-development-indicators/the-world-by-income-and-region.html.

et al, 2024). Additionally, the production of electricity from non-renewable energy sources produces negative externalities, that disproportionally affect vulnerable populations (Jiglau et al., 2024).

As a consequence, social, economic, and environmental disparities affect EJ. Sovacool & Dworkin (2015) argue that EJ depends on three core principles of justice: *distributive justice, procedural justice,* and *recognition justice*.

Distributional justice enhances the equitable distribution of energy sources between marginalized economies and promotes the fair distribution of energy costs and benefits (Ford et al., 2021). This type of justice directly alleviates energy poverty by providing energy production rights to local individuals and reducing their reliance on insufficient and/or polluted energy sources (Goforth et al., 2025). In addition, it contributes to the widespread adoption of clean energy sources, declining energy costs, and improving the overall collective well-being (Heffron & McCauley, 2017).

Procedural justice emphasizes the individual involvement in the decision-making process. Currently, a centralised energy system presents several drawbacks like unfair energy distribution, inefficiency and energy losses, and poor environmental impact. To overcome these problems, procedural justice enhances local people's voice and accountability in energy production and distribution systems by ensuring their participation in decision-making (Healy & Barry, 2017).

Recognition justice recognizes energy affordability needs of vulnerable populations by providing fair solutions tackling social, economic, and environmental issues (Schlosberg, 2007).

Given the above, EJ can be considered as a comprehensive indicator integrating social justice principles with energy supply chain processes (production, consumption, and distribution). Figure 1 explains the above energy justice concept.

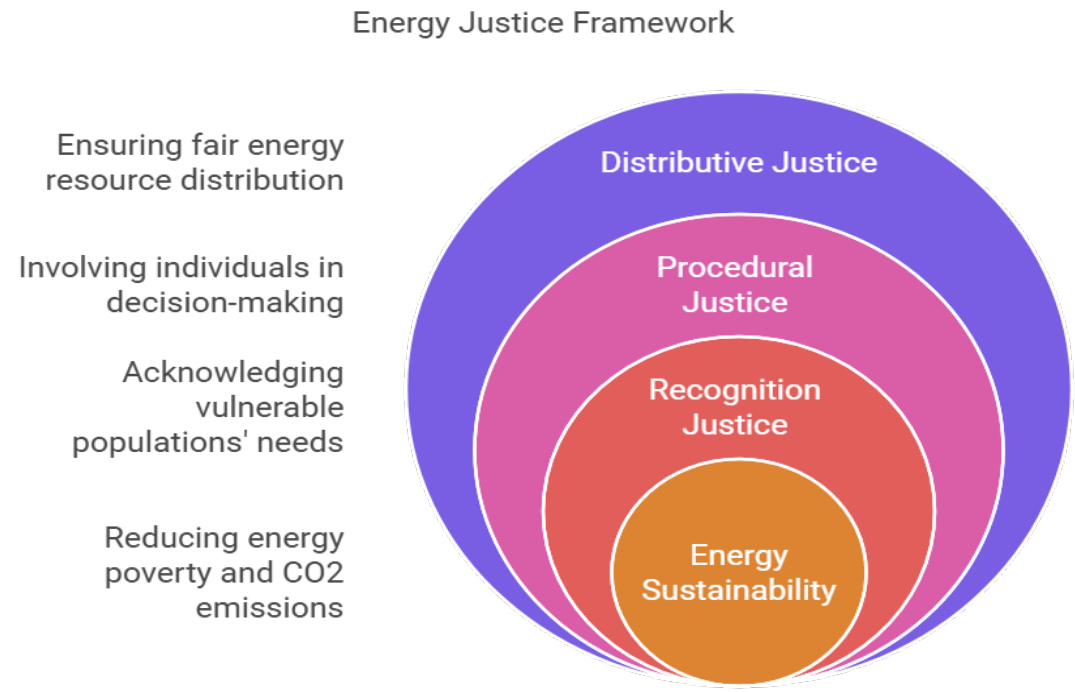


Figure 1. Theoretical framework of EJ. *Source*: Authors' own elaborations.

2.2 Bibliometric analysis of EJ

The present study performs a brief bibliometric analysis of the literature related to EJ. This type of approach is a visual method which helps researchers and policymakers to retrieve information on specific research topics, issues, and domains (Donthu et al. 2021; Parsons et al., 2024). To this purpose, the query '*energy justice*' was performed through internationally recognised search engines such as SCOPUS and Web of Science. The initial database comprised of 180 items. Based on the publications' DOI, title, and publisher details a 13% overlap (13/100 × 180) between the two search engines was found. Consequently, 23 items were initially excluded from the analysis. Additional filters for non-inclusion were applied such as conference abstracts and book reviews (n=26) and non-English language papers (n=3)[13]. The final sample comprised of 151 research articles. VOSviewer v. 1.6.19 (Van Eck & Waltman, 2007) was used to visualise a network map (van Eck & Waltman, 2010; 2014) among relevant keywords form the obtained sample[14].

The network analysis showcases four interconnected clusters (Figure 2). The *blue cluster* focuses on EJ through environmental policies, social justice, and investment in green infrastructures. The *red cluster* aligns its research on the issue of energy efficiency which is closely related to 'technological advancement'. The latter promotes energy use through

[13] A general overlap of about 50% is generally found between these two search engines (Chistov et al., 2021).
[14] A further inspection was performed to remove non-relevant keywords (Senellart & Blondel, 2002).

efficient energy appliances, smart grids and metering, thus reducing the burden of energy distribution loss and the overall economic cost of energy production. The *yellow* and *green clusters* focus respectively on 'energy transition' and 'energy sources'. While the former requires a significant amount of income and investment in the long run aiming at improving a collective wellbeing and EJ across societies, the latter highlights the use of abundant, non-rival and non-excludable energy and natural resources.

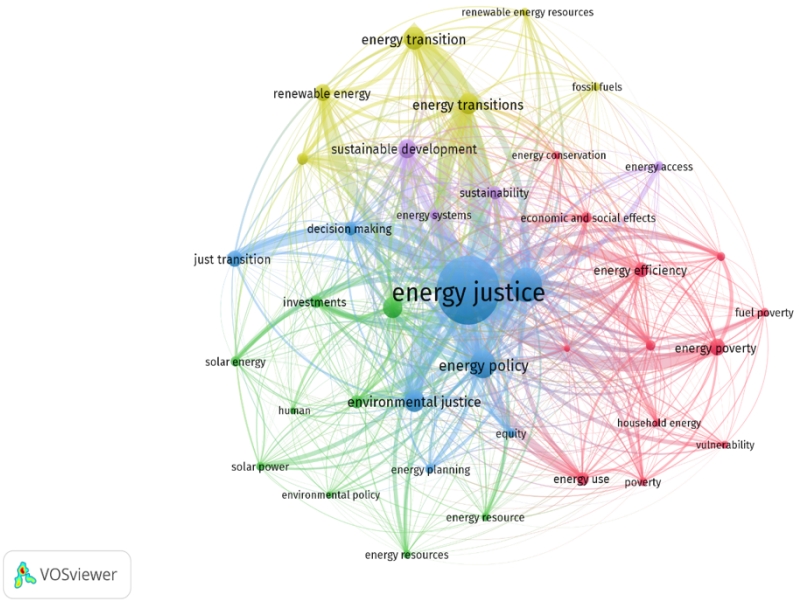


Figure 2. Bibliographic network of keywords. Layout: Attraction = co-occurrence; Repulsion = default; Clustering: Resolution = 0.1-0.5 ; Min. Cluster size = 150; Clusters=4 ; links=543; Total link strength=1050.

3. Value added of the study

In the existing literature, numerous studies have qualitatively explained the concept of EJ, whereas more quantitative oriented approaches have used 'distributional justice' or 'energy accessibility' as a proxy of EJ. Based on earlier works, the present study considers a novel approach of EJ based on the creation of a new EJI with the use of the entropy method (Hwang & Yoon, 1981), thus allowing a thorough view of EJ as defined by Sovacool & Dworkin (2015) for inclusion in the inferential analysis (see below). As for this latter issue, existing research predominantly use traditional mean estimators to assess the association among the studied variables. However, mean-based approaches ignore unit root and cross-sectional issues and often generate inconsistent and misleading conclusions. To address these issues, this study

employs a Method of Moments Quantile Regression (MMQR) which offers advantages in handling individual effects and conditional heterogeneous covariance effects.

4. Methodology

4.1 Variables definition and measurement unit

4.1.1 Dependent variable

This study uses CO2 emission as a proxy variable of environmental degradation and measured in kilo-watt tons(kt). Earlier studies used this proxy to measure environmental quality across various country groups as already mentioned above.

4.1.2 Independent variables

Energy justice index. The present work develops an EJI by considering the definition of EJ provided by Sovacool & Dworkin (2015) and recently accounted for in the work by Apergi et al. (2024). This concept is closely related to SDG 7 (energy for all), 13(climate actions), and 10 (reduce inequalities, fair distribution). According to the World Development Report (World Bank, 2024) approximately 940 million individuals worldwide do not have access to energy and 3 billion individuals do not have access to clean energy for cooking (Apergi et al., 2024). As such, this study considers 'energy accessibility' as a proxy of distributional justice, 'energy affordability' as an indicator of energy intensity, and 'renewable energy' as a sustainability indicator. The EJI is constructed by considering the entropy method (Hwang &Yoon, 1981) and values range between -1 and 1. In the existing literature, few studies used this approach, particularly for the construction of energy resilience and energy vulnerability indexes (Dong et al., 2021; Liu et al., 2023). The spatial distribution of EJI across the study sample is presented in Figure 3.

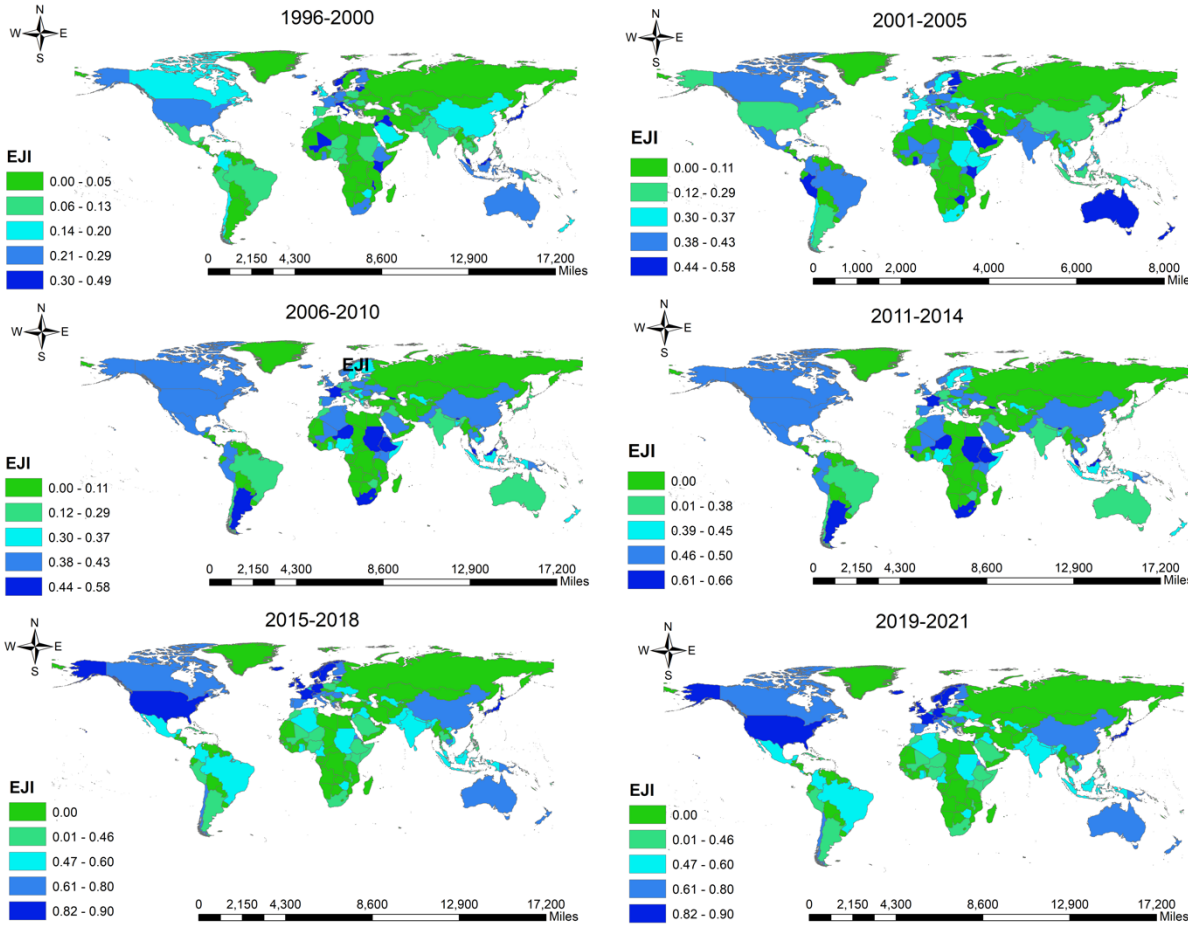


Figure 3. Global spatial-temporal distribution of EJI. *Source*: Authors' own elaborations.

Natural resources. This covariate represents natural resources rent (TNR) which is measured in % of GDP. Data was collected from the WDI database. TNR is the sum of oil, mineral, gas, and forest rents and can produce a negative or positive effect on the environment: $\frac{d(CO2)}{d(TNR)} < 0; \frac{d(CO2)}{d(TNR)} > 0.$

Technological innovation. TI is used as proxy for technological innovations and measured in terms of number of patent applications. It plays a significant role for the reduction of ecological footprint (Lin & Ullah, 2024). In contrast, as the degree of TI varies across regions according to the innovative ideas of stakeholders, government spending on research and development (R&D), and infrastructures (Uche et al., 2023), a negative or positive relationship on CO2 emissions is expected, as follows $\frac{d(CO2)}{d(TI)} < 0; \frac{d(CO2)}{d(TI)} > 0.$

Control variables. This study uses export of goods and services (EXP), financial development (FD) and globalization (GLO) as control variables. EXP is measured as % of GDP. The expected signs between these control variables and CO2 emissions can be both negative or

positive $\frac{d(CO2)}{d(EXP)} < 0; \frac{d(CO2)}{d(EXP)} > 0;\ \frac{d(CO2)}{d(FD)} < 0; \frac{d(CO2)}{d(FD)} > 0;\ \frac{d(CO2)}{d(GLO)} < 0; \frac{d(CO2)}{d(GLO)} > 0.$ FD is retrieved from the International Monetary Fund (IMF) and measures the efficiency of a financial institution, ranging from 0 to 1. Based on the available literature, FD positively affects carbon emissions if financial resources are distributed across clean energy sources. Nonetheless, this relationship can vary across countries. Similarly, GLO affects the open economy of a country and, as a result, it may directly affect CO2 emissions. Variable descriptions, measurement units, and data sources are presented in Table 1.

Table 1. Variables description, measurement and source

Variable	Acronym	Measurement	Database	Expected sign
Carbon emission	CO2	CO2 emissions (kt)	WDI	
Energy Accessibility	EAc	% of the total population	WDI	-/+
Energy Affordability	EAf	MJ/$2017 PPP GDP	WDI	-/+
Voice and accountability/ decision making	VA	Index 1-100	WDI	
Environmental sustainability	ES	% of renewable energy sources in total electricity production	WDI	-/+
Energy justice index	EJI	0-1 (continuous)	Estimated	-/+
Natural resources	TNR	% of GDP	WDI	-/+
Technological innovations	TI	Number of patents	WDI	-/+
Financial Development	FD	Index (0-1) (continuous)	IMF	+/-
Globalization	GLO	KOF globalization index (1-100)	ETH Zurich	-/+
Exports	EXP	% of exported goods and services	WDI	-/+

Notes: WDI - World development indicators (https://data.worldbank.org/indicator); IMF- International Monetary Fund (https://data.imf.org); ETH Zurich KOF Globalisation index (https://kof.ethz.ch/en/forecasts-and-indicators/indicators/kof-globalisation-index.html).

4.2 Inferential analysis

This study uses an advanced econometric approach based on five steps. First, cross-section dependency (CSD) between sample series is tested through the Pesaran (2021) and Pesaran scaled LM tests (Pesaran, 2004) and the Bias-corrected scaled LM (Baltagi et al., 2012). Second, a slope heterogeneity check is carried out (Pesaran & Yamagata, 2008). Third, the stationary properties of the considered variables are observed by using second-generation unit root tests (i.e. covariate augmented Dickey-Fuller – CADF – test and the cross-sectionally augmented IM-Pesaran-Shin – CIPS – test) (Pesaran, 2007). Additionally, the Westerlund panel cointegration test is used to assess the long-run association among variables (Westerlund,

2007a,b). Lastly, the MMQR model is applied to obtain the magnitude of the heterogeneous coefficients across different quantiles and a robustness check is carried out through the Fully Modified Ordinary Least Squares (FMOL) and Dynamic Ordinary Least Squares Estimator (DOLS) models.

4.2.1 *MMQR regression model*

The MMQR regression model considers fixed effects and examines the distributional and heterogeneous effect of the covariates on the quantiles of the dependent variable (Machado & Santos Silva, 2019). Therefore, it determines the conditional heterogeneous covariance effects of CO2 emissions, providing space for individual effects to alter the overall distribution, rather than solely adjusting mean values concerning other variables. Furthermore, unlike the classical OLS estimator, MMQR estimators are not restricted by normal distribution assumptions. It resolves endogeneity issues and produces efficient and robust outcomes. The general model for conditional quantiles $\mathcal{Q}_y\left(\delta \mid \vec{X}_{it}\right)$, is as follows:

$$Y_{it} = \acute{\phi}_i + X_{it}\dot{\beta} + \left(\tilde{\partial}_i + \acute{z}_{it}\xi\right)\acute{U}_{it} \tag{1}$$

where, Y_{it} is the dependent variable (i.e. CO2 emissions), X_{it} represents the co-variates[15], and $(\acute{\phi}_i, \tilde{\partial}_i, \beta)$ are parameters to be estimated. $\left(\tilde{\partial}_i + \acute{\epsilon}_{it}\ \xi\right) > 0\} = 1$ shows the probability of being in a given quantile. In a similar vein, $\acute{z}$ is a K-vector of known components of (X), while i =1….n, highlights the individual fixed effects. $\acute{U}_{it}$ follows an identical and independent distribution across individual country i over time t and is orthogonal to X_{it}. Machado and Silva (2019) describe that standardized momentum conditions $\acute{U}_{it}$ are extraneous to X_{it}. By following Eq.(1), the quantile-distribution of the dependent variable is obtained:

$$\mathcal{Q}_y(\delta \mid X_{it}) = \left(\acute{\phi}_i + \tilde{\partial}_i q(\tau)\right) + X_{it}\dot{\beta} + \acute{z}_{it}\xi q(\tau) \tag{2}$$

where $\left(\acute{\phi}_i + \tilde{\partial}_i q(\tau)\right)$ is the quantile-fixed effect for country i. This can also be interpreted as a scalar coefficient $\acute{\phi}_i \tau$. Re-arranging, the following model is obtained:

[15] All co-variates are considered in their log transformation (except for EJI and FD), to overcome data sharpness and fluctuation issues.

$$QCO_{2it}\left({}^{\tau_{it}}/_{\emptyset_{it}}, X_{it}\right) = \emptyset_{it} + \psi_{1t}EJI_{it} + \psi_{2t}TNR_{it} + \psi_{3t}TI_{it} + \psi_{4t}FD_{it} + \psi_{5t}EXP_{it} + \\ +\psi_{1t}GLO_{it} + \mu_{1t} \quad (3)$$

5. Results and discussion

5.1 Descriptive statistics

Table 2 displays the descriptive statistics of the studied variables for both the global panel and four country groups. The mean values of CO2, EJI, TNR, TI, FD, EXP, and GLO vary in different income group economies; furthermore, they are greater than their respective standard deviations, pointing to an uneven data distribution. Additionally, skewness outcomes reveal that EJI, TNR, TI, and FD show a positively skewed distribution, while the opposite is observed for CO2, EXP, and GLO. Furthermore, the Jarque-Bera (JB) test results reject the assumption of normality, suggesting that data does not conform to a normal distribution (Dam et al., 2024).

Table 2. Descriptive statistics

Global Panel							
	CO2	EJI	TNR	TI	FD	EXP	GLO
Mean	10.45	0.50	4.17	6.90	0.38	3.35	62.90
Median	10.69	0.45	1.43	7.06	0.38	3.39	62.41
Maximum	16.21	0.94	31.20	14.28	1.00	5.53	93.57
Minimum	4.22	0.02	36.58	1.01	0.50	4.69	22.65
Std. Dev.	2.24	0.26	6.00	2.54	0.28	0.72	16.49
Skewness	-0.31	0.11	1.73	0.08	0.28	-0.98	-0.02
Kurtosis	2.86	1.72	6.77	3.06	2.15	9.41	2.05
Jarque-Bera	41.64	172.39	2,69.30	2.71	106.40	4620.2	93.33
Probability	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Observations	2,470	2,470	2,470	2,470	2,470	2,470	2,470
HICs							
Mean	11.28	0.51	0.70	7.72	0.57	3.73	77.06
Median	11.06	0.48	0.40	7.65	0.58	3.73	79.90
Maximum	15.57	0.95	3.90	13.34	1.26	5.53	93.57
Minimum	7.14	0.18	36.58	1.39	0.07	0.69	43.87
Std. Dev.	1.68	0.11	1.43	2.31	0.16	0.55	11.29
Skewness	0.03	1.54	-17.70	0.34	0.34	-0.46	-0.80
Kurtosis	3.01	8.28	468.27	2.92	5.02	4.04	2.78
Jarque-Bera	0.17	1,535.71	895.00	19.45	185.83	79.03	106.45
Probability	0.00	0.00	0.00	0.00	0.00	0.00	0.00
UMICs							
Mean	10.94	0.41	5.86	7.54	0.27	3.33	62.00
Median	11.34	0.41	3.09	7.54	0.10	3.30	62.90
Maximum	16.21	0.75	17.47	14.28	1.00	4.80	81.40
Minimum	4.22	0.19	0.02	2.48	-	-4.69	89.00
Std. Dev.	2.29	0.14	5.86	1.97	0.33	0.61	9.65
Skewness	-0.67	0.32	0.85	0.45	1.26	-3.35	-0.52
Kurtosis	3.68	2.12	2.14	3.64	3.12	48.83	4.98
Jarque-Bera	61.58	32.31	99.37	33.36	171.71	581.10	136.00
Probability	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LMICs							

Mean	10.09	0.34	5.23	7.17	0.30	2.96	49.00
Median	9.95	0.38	2.77	7.07	0.22	3.09	49.36
Maximum	14.71	7.53	31.20	11.03	1.00	4.03	68.46
Minimum	4.82	-9.13	0.04	3.97	0.13	0.97	22.65
Std. Dev.	1.82	0.58	6.22	1.35	0.26	0.70	9.66
Skewness	-0.03	-4.58	1.71	0.55	1.17	-0.74	-0.28
Kurtosis	3.22	183.21	5.63	3.41	3.60	2.85	2.56
Jarque-Bera	1.09	7054.10	402.77	29.81	127.26	48.03	10.78
Probability	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LICs							
Mean	7.37	0.38	9.92	2.52	0.36	2.82	42.86
Median	7.11	0.38	7.74	2.52	0.35	2.73	43.16
Maximum	10.23	1.02	26.20	4.03	1.00	5.23	56.38
Minimum	4.53	0.02	0.00	1.01	-0.50	-0.48	25.22
Std. Dev.	1.37	0.12	7.98	0.87	0.24	0.80	7.22
Skewness	0.33	0.69	0.81	0.00	0.34	0.43	-0.32
Kurtosis	2.35	6.12	2.65	1.80	3.20	4.42	2.37
Jarque-Bera	11.03	151.01	35.57	18.60	6.65	35.85	10.28
Probability	0.00	0.00	0.00	0.00	0.00	0.00	0.00

5.2 CSD and slope of heterogeneity tests

Given the above, the current study moved to second-generation methodologies as described in section 4.2. Table 2 displays the statistical outcomes of CSD among the sampled economies. Based on the p-values(=0.00) of Breusch Pagan LM, Pesaran Scaled CSD, and Pesaran CSD tests, we reject the null hypothesis of cross-sectional independence at 1% significance level within the confidence interval (C.I) and conclude that HICs, UMICs, LMICs, and LICs economies are interdependent to each other. Additionally, the estimated values of Delta (=15.98 p-value=0.00) and Adj. Delta (=19.19 p-value=0.00) coefficients, rejects the null hypothesis within 1% C.I. levels, thus arguing the existence of heterogeneous slopes across the panel (Table 3).

Table 2. Cross-sectional dependency (CSD) outcomes

	Statistics	P-value
Global Panel		
Breusch Pagan LM	10395.65	0.00
Pesaran Scaled LM	62.75	0.00
Pesaran CD	3.78	0.01
HICs		

Breusch Pagan LM	4718.77	0.00
Pesaran Scaled LM	107.07	0.00
Pesaran CD	2.34	0.00
UMICs		
Breusch Pagan LM	2930.01	0.00
Pesaran Scaled LM	103.00	0.00
Pesaran CD	210.92	0.00
LIMCs		
Breusch Pagan LM	1972.30	0.00
Pesaran Scaled LM	83.46	0.00
Pesaran CD	20.59	0.00
LICs		
Breusch Pagan LM	723.62	0.00
Pesaran Scaled LM	57.23	0.00
Pesaran CD	15.18	0.00

*, ** and *** indicate 10 %, 5 %, and 1 % level of significance, respectively.

Table 3. Heterogeneity outcomes

Test	Statistics	P-value
Delta	15.98	0.00
Adj. Delta	19.19	0.00

*, ** and *** indicate 10 %, 5 %, and 1 % level of significance, respectively.

5.3 Panel unit root tests

The estimated results of CADF and CIPS tests presented in Table 4 show that CO2, EJI, TI, FD, EXP, and GLO are not stationary at integrated order zero I[0]. This means their mean, variance, and co-variance are not constant over time. However, after taking the first difference I[1] all variables became stationary. Thus, the null can be rejected at 1% level of significance.

Table 4. Estimated results of CIPS and CADF tests

	CIPS		CADF	
Variable	Level	Difference	Level	Difference
Global panel				
CO2	-3.32	-4.52*	-4.02*	-6.75*
EJI	-2.38	-5.31*	0.14	-11.66*
TNR	-3.52	-5.63*	-5.78*	-16.60*

TI	-2.82	-5.22*	-3.59	-10.12*
FD	-2.98	-5.56*	-1.82	-14.90*
EXP	-2.80*	-5.78*	-0.19	-14.07*
GLO	-2.39	-4.70*	0.49	-8.36*
HICs				
CO2	-0.96	-2.52*	-0.94	-3.23*
EJI	-1.46	-4.64*	0.146	-2.74*
TNR	-2.75	-4.90*	-1.12	-3.32*
TI	-2.40	-4.34*	-1.23	-2.62*
FD	-2.27	-5.34*	-1.82	-2.56*
EXP	-1.47*	-3.70*	-2.00	-2.76*
GLO	-1.39	-4.23*	0.190	-2.37*
UMICs				
CO2	-1.57	-2.95*	-1.28	-6.755*
EJI	-1.59	-4.62*	-2.99	-3.93*
TNR	-2.64	-4.57*	-1.51	-2.72*
TI	-1.86	-3.45*	-1.06	-3.43*
FD	-4.38	-5.13*	-1.83	-4.76*
EXP	-3.91*	-4.20*	-0.13	-3.07*
GLO	-4.17*	-6.70*	-1.09	-4.23*
LMICs				
CO2	-2.94	-4.52*	-1.23	-4.34*
EJI	-2.22	-4.12*	0.146	-2.43*
TNR	-1.34	-4.60*	-1.67	-3.43*
TI	-2.45	-4.83*	-2.34	-4.12*
FD	-2.98	-5.12*	-1.82	-4.90*
EXP	-1.80	-4.39*	-0.19	-2.04*
GLO	-1.39	-4.54*	0.49	-3.36*
LICs				
CO2	1.46	-3.29*	-2.34	-4.34*
EJI	-2.38	-5.31*	-1.20	-3.45*
TNR	-2.24	-4.34*	-2.46	-3.53*
TI	-1.35	-3.56*	-2.59	-4.12*
FD	-1.13	-3.54*	-1.24	-3.90*
EXP	-2.54*	-4.85*	-0.86	-3.07*
GLO	-2.34	-4.44*	0.34	-2.361*

Note: * indicate significance at 1%; Critical values are: 1% = -2.10, 5% = -2.07 and 10% = -2.01.

5.4 Cointegration test

Table 5 outlines the estimated results for the Westerlund (2007) test. It reveals that the mean groups (Ga = -5.14 and Gt = -1.88) alongside the panel groups (Pa = -11.8 and Pt = -32.73) are significant at 1% significance level within the confidence interval C.I. Nevertheless, the present study argues in favour of the alternative hypothesis and ascertain that cointegration exists within the series.

Table 5. Cointegration test estimated results

Statistic	Value	Z-value	P-value	Robust P-value
Gt	-1.88	9.60	1	0.08
Ga	-5.14	13.06	1	0.10
Pt	-32.73	-7.08	0.09	0.03
Pa	-11.8	1.60	0.06	0.00

Notes: Pt, Pa, panel cointegration; and Gt, Ga, cointegration for each country.

5.5 MMQR estimated results

Table 6 shows the estimated results of the MMQR model. For ease of reading and interpretation, the quantiles distribution is split into three groups such as lower (τ= from 0.10 to 0.30) middle (τ= from 0.40 to 0.60), and upper (τ= from 0.70 to 0.90) quantiles. The estimated coefficients indicate that EJI is significantly negatively correlated with CO2 emissions across all quantiles in the global panel and the HICs group, which suggests that increases in EJI improves environmental quality in most developed economies. In particular, a 1% increase in EJI in the global panel estimates decrease CO2 emissions between (-)6 and (-)7% in lower quantiles and 9% in medium quantiles, respectively. This inverse relationship highlights the continuing efforts of HICs for encouraging the use of renewable energy sources within each country contexts. In contrast, the same result is not yet fully evident in UMICs and LMICs (Burke & Stephens, 2018; Byaro et al., 2024; Fuchs et al., 2024). It can be argued that the motive of 'energy for all' deriving from the definition of EJI and based on the 'energy equity' principle, may prioritize the continued consumption of fossil fuels which are budget-friendly and easily accessible in the short run (Skare et al., 2024b).

As for TNR estimates, these show a positive effect on CO2 emissions, although these appear relatively significant in middle and upper quantiles by 1%, 7% , and 8%, respectively. The positive effect of TNR on CO2 emissions can be justifiable. To meet their energy and material

demands, UMICs and LMICs economies are overexploiting their natural resource reserves, thus intensifying their environmental stress (Fraser et al., 2023). Similar arguments are raised by the findings by Caglar et al., (2022) for BRICS economies and Khan et al., (2022) for South Asian countries. In contrast, in the HICs group, TNR presents a relatively little impact (i.e. 2-6%) on CO2 emissions from lower to middle quantiles, although this effect is not significant for the remaining quantiles. One possible explanation is the stringent environmental regulation in this country group, which does not allow for an excessive extraction of TNR (Alvarado et al., 2024).

Thirdly, the estimated coefficient of TI in global panel estimates is positively correlated to CO2 emissions across all quantiles. In particular, a 1% increase in TI leads respectively to an increase in carbon emissions between 44-46% in the lower quantile and 49-51% in the upper quantile. As a result, notwithstanding the technological advancement undergoing in HICs and the respective negative estimated coefficients of (-)13-61% and (-)54-58% as well as in UMICs of (-)13-19% and (-)25-32%, across medium and upper quantiles respectively, LMICs and LICs still rely on old and outdated infrastructures for energy distribution (Obolensky et al., 2019; Che et al., 2024). Similar results also appear in the study by Jamil et al., (2021) and Chen et al. (2022) for BRICS economies; and Chen et al. (2022) for 30 Chinese provinces.

As for the estimated outcomes of the control variables such as EXP, GLO, and FD these are significantly increasing CO2 emissions in the global panel, as well as in upper quantiles of LMICs, and LICs. Particularly for EXP, export-oriented industries like textile and electronics, typically produce energy-intensive goods, which tend to emit a significant amount of CO2 emissions into the atmosphere (Iqbal et al., 2023). Additionally, the existence of a pollution haven hypothesis is also evident from the estimated positive coefficients of EXP in LMICs and LICs. Similar outcomes are found in the works by Shahzad et al. (2020) and Waris et al. (2023) for 66 developed economies and ASEAN countries. The studies by Aminu et al. (2023) for Sub-Saharan countries; Esmaeili et al. (2023) for N-11 countries; and Das & Sethi (2023) for LMICs, also confirm the presence of the pollution haven hypothesis. As for GLO, the estimated positive impact between 2-7% on CO2 emissions, obtained in the global panel across all quantiles, derives from the net effect in HICs and LMICs. Similarly, for FD, the estimated positive impact between 15-47% on CO2 emissions in medium and lower quantiles, derives from a net effect in UMICs between (-)11 and 14% in medium and upper quantiles, between in 11-16% in medium quantiles and 23-32% in upper quantiles and between (-)39-44% in upper quantiles in LICs.

Table 6. MMQR model estimated results

			Lower quantile			Middle quantile			Upper quantile		
Variable	location	scale	0.10th	0.20th	0.30th	0.40th	0.50th	0.60th	0.70th	0.80th	0.90th
Global panel											
EJI	-0.08***	0.02	-0.07*	-0.01**	-0.06**	-0.08**	-0.08***	-0.08***	-0.09**	-0.09**	-0.09*
	(0.03)	(0.02)	(0.04)	(0.01)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.04)
TNR	0.01	0.06	0.05	0.04	0.03	0.05	0.01	0.01*	0.08**	0.08**	0.07**
	(0.01)	(0.03)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
TI	0.47***	0.02**	0.44***	0.45***	0.46***	0.47***	0.47***	0.48***	0.49***	0.49***	0.51***
	(0.01)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)
EXP	0.09***	-0.08**	0.07***	0.07***	0.05***	0.04***	0.03**	0.08**	0.02	0.01	0.01
	(0.05)	(0.05)	(0.03)	(0.08)	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
GLO	0.01***	-0.01***	0.03***	0.02***	0.02***	0.03***	0.01***	0.04***	0.04***	0.07**	0.01
	(0.001)	(0.01)	(0.02)	(0.01)	(0.02)	(0.02)	(0.01)	(0.02)	(0.02)	(0.04)	(0.01)
FD	0.15**	-0.20***	0.47***	0.35***	0.27***	0.21***	0.15**	0.07	0.01	-0.04	-0.15
	(0.07)	(0.04)	(0.10)	(0.08)	(0.08)	(0.07)	(0.07)	(0.06)	(0.07)	(0.08)	(0.09)
Constant	5.75***	2.02***	2.70***	3.83***	4.59***	5.16***	5.83***	6.51***	7.10***	7.67***	8.77***
	(0.19)	(0.12)	(0.29)	(0.23)	(0.21)	(0.19)	(0.19)	(0.19)	(0.19)	(0.21)	(0.26)
HICs											
EJI	-0.04*	-0.06***	-0.15***	-0.12***	0.09***	-0.07**	-0.14*	0.02	0.01	-0.02	-0.06
	(0.02)	(0.01)	(0.04)	(0.03)	(0.03)	(0.031)	(0.03)	(0.03	(0.03)	(0.03)	(0.03)
TNR	-0.03***	0.01***	-0.06***	-0.05***	-0.05***	-0.04***	-0.03***	-0.03***	-0.02**	-0.01	-0.01
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
TI	0.60***	-0.03***	0.66***	0.64***	0.63***	-0.61***	-0.60***	-0.59***	-0.58***	-0.56***	-0.54***

	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
EXP	-0.09	0.07	-0.03	-0.02	-0.02	-0.02	-0.08	-0.05	-0.03	-0.04	0.03
	(0.01)	(0.00)	(0.01)	(0.01)	(0.02)	(0.02)	(0.01)	(0.001)	(0.02)	(0.01)	(0.01)
GLO	-0.01***	0.03*	-0.012***	-0.01***	-0.01***	-0.04***	-0.04***	-0.09***	-0.09***	-0.08***	-0.09**
	(0.02)	(0.02)	(0.03)	(0.03)	(0.03)	(0.002)	(0.03)	(0.03)	(0.03)	(0.03)	(0.04)
FD	-0.09	0.05	-0.17*	-0.15*	-0.13*	-0.11**	-0.09*	-0.07	-0.05**	-0.03*	-0.09
	(0.18)	(0.11)	(0.264)	(0.23)	(0.21)	(0.19)	(0.18)	(0.18)	(0.19)	(0.21)	(0.24)
Constant	7.50***	0.79***	6.31***	6.60***	6.94***	7.24***	7.53***	7.81***	8.05***	8.37***	8.79***
	(0.25)	(0.14)	(0.32)	(0.31)	(0.28)	(0.26)	(0.25)	(0.25)	(0.26)	(0.28)	(0.32)
Observations	988	988	988	988	988	988	988	988	988	988	988
UMICs											
EJI	0.05*	-0.08*	0.07*	0.06*	0.05	0.01	0.05	0.05*	0.04*	0.04*	0.04*
	(0.11)	(0.08)	(0.26)	(0.19)	(0.15)	(0.12)	(0.11)	(0.09)	(0.09)	(0.09)	(0.09)
TNR	0.10***	-0.08***	0.28***	0.20***	0.16***	0.12***	0.10***	0.07***	0.03***	0.02*	-0.08
	(0.01)	(0.01)	(0.03)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01	(0.01)
TI	-0.13**	-0.14***	0.17	0.03	-0.03	-0.10	-0.13**	-0.19***	-0.25***	-0.28***	-0.32***
	(0.05)	(0.04)	(0.19)	(0.09)	(0.07)	(0.06)	(0.05)	(0.04)	(0.04)	(0.04)	(0.04)
EXP	-0.01**	-0.07	-0.08	-0.01	-0.01	-0.014*	-0.01**	-0.01**	-0.01***	-0.01***	-0.01**
	(0.01)	(0.04)	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)	(0.01)
GLO	0.03	-0.01	0.02	0.01	0.01	0.04	0.09	-0.03	-0.08	-0.01	-0.01
	(0.01)	(0.09)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.08)	(0.06)	(0.01)
FD	-0.11	-0.02	-0.06	-0.08	-0.09	-0.10	-0.11*	-0.12*	-0.13*	-0.13*	-0.14**
	(0.27)	(0.20)	(0.62)	(0.45)	(0.37)	(0.29)	(0.26)	(0.22)	(0.213)	(0.21)	(0.23)
Constant	11.53***	4.13***	3.07***	6.860***	8.81***	10.72***	11.68***	13.31***	15.04***	15.75***	16.80***
	(0.98)	(0.75)	(2.21)	(1.62)	(1.32)	(1.06)	(0.95)	(0.86)	(0.76)	(0.77)	(0.80)

Observations	650	650	650	650	650	650	650	650	650	650	650
LMICs											
EJI	0.43***	0.10***	0.289***	0.32***	0.35***	0.37***	0.41***	0.46***	0.51***	0.57***	0.60***
	(0.05)	(0.03)	(0.06)	(0.03)	(0.05)	(0.05)	(0.05)	(0.07)	(0.06)	(0.09)	(0.07)
TNR	0.01	0.01***	-0.02*	-0.01	-0.01	-0.02	-0.02	0.03	0.01	0.04*	0.05*
	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)	(0.0)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
TI	0.50***	-0.07*	0.60***	0.58***	0.55***	0.54***	0.51***	0.48***	0.44***	0.40***	0.38***
	(0.08)	(0.04)	(0.09)	(0.09)	(0.08)	(0.08)	(0.08)	(0.08)	(0.09)	(0.11)	(0.11)
EXP	0.07	-0.03	0.02	0.03	0.03	0.02	0.01	0.06**	0.09**	0.09**	0.10***
	(0.02)	(0.02)	(0.00)	(0.02)	(0.02)	(0.01)	(0.01)	(0.03)	(0.03)	(0.03)	(0.06)
GLO	0.01	0.01**	-0.05	-0.05	0.02	0.03	0.01	0.01*	0.02**	0.03***	0.03***
	(0.08)	(0.01)	(0.01)	(0.01)	(0.00)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
FD	0.13***	0.11**	-0.02	0.02	0.05	0.07	0.11**	0.16**	0.23**	0.295**	0.322***
	(0.18)	(0.09)	(0.21)	(0.19)	(0.18)	(0.18)	(0.18)	(0.18)	(0.20)	(0.23)	(0.25)
Constant	5.50***	0.38*	4.97***	5.19***	5.23***	5.30***	5.44***	5.61***	5.83***	6.03***	6.12***
	(0.42)	(0.23)	(0.49)	(0.46)	(0.43)	(0.45)	(0.42)	(0.43)	(0.47)	(0.59)	(0.59)
Observations	520	520	520	520	520	520	520	520	520	520	520
LICs											
EJI	-0.01	0.06	0.07	0.06	-0.01	0.07	-0.02	0.03	0.01	0.02	0.01
	(0.07)	(0.04)	(0.09)	(0.07)	(0.01)	(0.07)	(0.07)	(0.07)	(0.08)	(0.01)	(0.01)
TNR	-0.03	0.01	-0.01	-0.01	-0.06	-0.05	-0.03	-0.01	0.02**	0.04***	0.06**
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
TI	0.11*	-0.02	0.15**	0.138**	0.12**	0.12**	0.11*	0.10*	0.08	0.08*	0.07*
	(0.05)	(0.03)	(0.07)	(0.05)	(0.06)	(0.05)	(0.05)	(0.06)	(0.06)	(0.07)	(0.08)
EXP	0.08	0.04	0.08	0.09	0.09	0.09	0.09	0.04	0.10*	0.08*	0.08*

	(0.08)	(0.03)	(0.03)	(0.04)	(0.04)	(0.04)	(0.04)	(0.03)	(0.06)	(0.06)	(0.06)
GLO	-0.01	0.08	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
FD	-0.23	-0.15	0.08	-0.09	-0.13	-0.17	-0.22	-0.27	-0.35	-0.39*	-0.44*
	(0.19)	(0.11)	(0.25)	(0.22)	(0.19)	(0.19)	(0.19)	(0.20)	(0.22)	(0.23)	(0.25)
Constant	9.89***	1.53***	7.41***	8.45***	8.93***	9.30***	9.75***	10.35***	11.10***	11.49***	12.04***
	(0.60)	(0.36)	(0.80)	(0.67)	(0.63)	(0.67)	(0.60)	(0.63)	(0.69)	(0.71)	(0.84)
Observations	312	312	312	312	312	312	312	312	312	312	312

*, ** and *** indicate 10 %, 5 %, and 1 % level of significance, respectively

6. Conclusion and policy implications

The key element from the obtained findings is that EJ has an heterogeneous effect on CO2 emissions in the studied country groups over time. In light of this heterogeneity, countries should set up and implement ad-hoc policy strategies tailored to their unique 'country' contexts. Particularly, governmental agencies in UMICs and LICs should improve energy access and affordability and contribute to advance energy poverty issues by focussing on decentralizing the structure of the current energy system, thus allowing individuals to participate in the energy market, other than providing market-based instruments to increase competitiveness. Decentralized energy system models have been successful in several developed economies. For instance, in Europe, the Green Deal strategy[16] is progressively moving its steps towards greener cities and regions. Spain has achieved a revolutionary milestone by becoming the first country to use wind power as its main energy source for energy production (International Energy Agency, 2021). Similarly, the French legislature enacted an extensive energy and climate law mandating that 45% of the country's electricity production will be based upon renewable sources by 2030 (Bétaille, 2022). Also in Italy, in the last two decades, the renewable energy sector has grown rapidly, allowing the country to contribute to lower its reliance on imported fuels (International Renewable Energy Agency – IRENA, 2024a).

The USA, China, and Japan need to revise their eco-environmental policies to achieve their decarbonization goals. The USA is the second biggest liquid biofuel consumer worldwide, after Sweden (International Energy Agency, 2021). Additionally, the economic policy stability is critical for the USA to enhance market confidence, along with the political will and acceptance of regulations supporting the energy transition (Trimmel et al. (2024). Trough public spending on local green energy projects governments can provide electricity production rights to vulnerable population. The US Congress implemented the Renewable Fuel Standard (RFS) program as part of the Energy Policy Act of 2005, mandating the substitution of a specific volume of gasoline with renewable sources in 2019 (US Environmental Protection Agency, 2019).

The Japanese government follows the 3E + S energy framework to achieve its green energy targets by 2050. This framework focuses on Energy security, Economic efficiency, Environment, and Safety, serving as a vital component in energy planning and decision-making. According to IRENA (2024b), Japan ranks third globally in terms of geothermal and

[16] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.

wind energy potential, with an estimated capacity of 87 GW after China and US. To support innovation and drive investment in an array of decarbonization technologies, several plans, including the Basic Hydrogen Strategy[17] and the CCS Long Term Roadmap, have been recently introduced by the Japanese government (Japan Green Transformation Policy, 2024)[18]

China, the largest CO2 emitter worldwide, can reduce its dependence on fossil fuels in energy generation and industrial activities by revisiting its Nationally Determined Contribution (NDC) climate pledges and pursuing several initiatives, including high carbon taxes, the adoption of carbon capture and storage technology, and the implementation of emission trading scheme (ETS) (Jochheim, 2022). In an effort to combat climate change, China is enhancing its ETS and imposing stricter fines on energy-intensive industries that do not adhere to regulations (The Oxford Institute for Energy Studies, 2024).

Based on the above examples, developing economies have high potential to produce energy from renewable energy sources due to their high investment in green technology (Kim, 2018). Governing bodies should establish a supportive and inclusive legal framework that promotes and facilitates the integration of renewable energy sources into their energy systems.

In LICs, where EJ does not have a significant impact on CO2 emissions, several populations are living without access to energy and suffering from poverty, unemployment, and income inequalities. Biomass (i.e. wood and animal dunk) is mainly used for cooking and heating (Padhan et al., 2023). Thus, energy use is relatively low as compared to their counterparts. In addition, low access to financial resources prevents these countries to invest in R&D to effectively implement green energy projects. More synergies across developed and low income countries are suggested to help the latter to efficiently move toward the green transition as well as low interest rates and/or green energy funds should be promoted to ease credit access.

In addition, the study findings indicate that countries rich in natural resources struggle with carbon emissions pollution. Resource-protective policies as well as ad-hoc community-based natural resource management (CBNRM) strategies are advised to secure natural reserves to help reducing EJ unbalances.

6.1 Limitations and further research

The present study is not without limitations. The macro-level view of the inferential analysis prevents to consider the specific attributes within individual countries. In addition, data

[17] https://www.meti.go.jp/shingikai/enecho/shoene_shinene/suiso_seisaku/pdf/20230606_5.pdf.
[18] https://www.cas.go.jp/jp/seisaku/gx_jikkou_kaigi/pdf/kihon_en.pdf.

availability is an issue across countries and time. Further research should address an understanding of how structural constraints, economic barriers, and geopolitical risks hinder EJ. Furthermore, there is the need to explore how small-scale green energy projects affect the economic and environmental well-being of the local population and also highlight the regularity and financial challenges to provide a broader view on EJ across countries and time.

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Supplementary material

Table S1. Country groups list

Code	Country name	Code	Country name
HICs			
1	Australia	21	Latvia
2	Austria	22	Lithuania
3	Belgium	23	Luxembourg
4	Canada	24	Malta
5	Chile	25	Netherlands
6	Croatia	26	New Zealand
7	Czechia	27	Norway
8	Denmark	28	Poland
9	Estonia	29	Portugal
10	Finland	30	Romania
11	France	31	Saudi Arabia
12	Germany	32	Slovak Republic
13	Greece	33	Slovenia
14	Hungary	34	Spain
15	Iceland	35	Sweden
16	Ireland	36	Switzerland
17	Israel	37	United Kingdom
18	Italy	38	United States
19	Japan		
20	Korea, Rep		
UMICs			
39	Albania	51	Georgia
40	Algeria	52	Indonesia
41	Argentina	53	Iran, Islamic Rep.
42	Azerbaijan	54	Iraq
43	Brazil	55	Malaysia
44	China	56	Mexico
45	Colombia	57	Peru
46	Costa Rica	58	Serbia
47	Cuba	59	South Africa
48	Dominican Republic	60	Thailand
49	El Salvador	61	Tonga
50	Fiji	62	Turkiye
		63	Ukraine
LIMCs			
64	Bangladesh	75	Nepal
65	Cambodia	76	Nigeria
66	Cameroon	77	Pakistan
67	Egypt, Arab Rep.	78	Sri Lanka
68	Ghana	79	Tanzania
69	Haiti	80	Tunisia
70	India	81	Uzbekistan
71	Jordan	82	Viet Nam
72	Kenya	83	Zimbabwe
73	Morocco	84	
74	Myanmar		

LICs			
85	Eritrea	91	Somalia
86	Ethiopia	92	Sudan
87	Guinea-Bissau	93	Togo
88	Malawi	94	Uganda
89	Mali	95	Yemen, Rep.
90	Niger		

Chapter 4

The effect of macroeconomic PESTLE indicators on green growth: A spatial-temporal analysis in 30 European economies

Abstract. The novelty of this study is the use of the PESTLE (Political, Economic, Social, Technological, Legal, and Environmental) approach at macro level to investigate green growth in 30 EU economies during 1996-2021. The study also tests spatial dependencies and spillover effects through a Spatial Durbin Model. Main findings suggest that improvements in the home country's institutional quality, financial development, human development, technological innovation, and environmental policy favors green growth in adjacent countries. The need of national regulations for energy infrastructures and cross-border collaborations for a renowned European industrial and energy policy are highly encouraged to favour green growth.

Keywords: Green growth; PESTLE; Spatial Durbin Model; Spillover effects; Spatial marginal effects.

1. Introduction

Green growth (GG) has emerged as a key strategy for sustainable development. The Organisation for Economic Co-operation and Development (OECD) defines GG as an alternative measure of economic growth that goes beyond GDP, emphasizing the importance of environmental quality (OECD, 2024a).

The pioneering micro-level (firm) strategic management PESTLE – Political, Economic, Social, Technological, Legal, and Environmental – approach suggests that each of these factors exogenously impact the green performance of a firm (Francis Aguilar, 1967). The trajectory of GG largely depends on the effectiveness of institutional settings and strategic government policies (Sandberg et al., 2019). Strong institutional quality (IQ) fosters political stability, by enhancing investors' confidence in green energy markets (Muganyi et al., 2021; Jianguo et al., 2022). Political stability also favours the adoption of environmental policies (EPs) to limit carbon emissions (Behera et al., 2023; Qamruzzaman & Karim, 2024; OECD, 2024b). In addition, financial development (FD) supplies the essential physical and monetary capital needed to promote green firms (Evans et al., 2023), although contrasting views appear (Li et al., 2022; Afshan & Yaqoob, 2022, Ahmed et al., 2022).

The impact of technological innovations (TIs) on GG has been ongoing since the 1960s. Some experts argue that such innovations enhance green energy markets (Khan et al., 2020; Shahbaz et al., 2023), other than lowering firm's long-run average costs, equipment loss, and improving product efficiency (Maiti, 2022). However, increased industrial activities driven by TIs and population growth may lead to excessive energy consumption (Yao et al., 2020; Saud et al., 2023).

The aim of the current study is to contribute to the existing body of literature according to a dual perspective. On one hand, it moves the (micro-economic) comprehensive PESTLE approach to investigate a (macroeconomic) PESTLE study on GG for 30 EU economies (Table S1 in the supplementary material) during 1996-2021. On the other hand, it tests spatial dependence and spillover effects of the investigated framework through a Spatial Durbin Model (SDM).

No previous study has simultaneously explored the spatial effect of a macroeconomic PESTLE approach in European economies. There are two rational reasons behind the selection of this group of economies: (i) European economies appear as the second largest investors on renewables, power grids and energy efficiency and use (Vezzoni, 2023; International Energy Agency, 2024), making them an ideal macro-spatial unit to study; and (ii) the close proximity

across spatial units (Tobler, 1970; Lesage & Pace, 2014), sharing common regulations and policies. Finally, the use of a spatial econometric model is justified over previous inferential methods as it explores the effects of proximity across regions and overcomes major inferential problems as evidenced by previous studies (Ramzan et al., 2023; Jiang et al., 2023; Wei et al., 2024).

The remainder of the paper is structured as follows: Section 2 presents a brief theoretical background and existing literature; section 3 outlines the methodology and data sources; section 4 illustrates the estimated findings; and, section 5 concludes and offers some policy recommendations.

2. Theoretical framework and literature background

The extension of the PESTLE framework to a macro-level (country) perspective enquires a 'temporo-spatially' approach, where the theoretical foundations can be rooted in: Endogenous growth theories; Schumpeterian theory of creative destruction; Environmental Kuznets Curve (EKC) framework; and Ecological modernization theory (EMT).

Endogenous growth models explore how technological innovations, knowledge and human capital drive economic growth (Romer, 1990). One key concept is creative destruction introduced by Joseph Schumpeter (Schumpeter, 1939), which refers to the process by which new innovations replace outdated technologies and foster economic growth processes. This 'replacement' process is explained by Aghion & Howitt (1992) into modern endogenous growth theories (Romer, 1986; Romer, 1990; Barro, 1990; Gradus & Smulders, 1993). The long-lasting debate on the EKC (Grossman et al., 1991) claims that initial stages of economic growth worsen environmental quality, whereas up to a certain income threshold the latter reaches a turning point where TIs and EPs induce a technology substitution effect at increasing levels of income. Ligthart & van der Ploeg (1994) extend the work of Romer (1986) to examine the influence of government policies on environmental growth and suggest that an optimal EP is required to achieve current economic targets. The EMT framework suggests that through robust legal frameworks economies can internalize their ecosystem stress (Hajer, 1995; Karim, 2024). Thus, ecological benefits lie in the reduction of ecological footprints (EFs), whereas economic advantages in the enhancement of a green economic output (Lee et al., 2024).

In line with the above theories and this study's scope and data availability (Table 1 below), the current debate on relevant relationships of each segment of the (macroeconomic) PESTLE framework with GG, is described:

(P) Institutional quality and green growth. IQ reflects the credibility of public institutions, which plays an important role in the economic decision-making process. Various scholars show how IQ enhances GG in E-7 economies (Jiang et al. (2023), Arab regions (Abdelbary & Benhin, 2019), South Asian countries (Ahmed et al., 2022), and BRICS economies (Gao & Fan, 2023), while an opposite effect is realised with uncertainties and political instabilities (Sohail et al., 2022), weak institutional quality (Safi et al., 2022), high degrees of corruption (Tawiah et al., 2024), and inefficient bureaucratic systems (Li et al., 2023).

(E) Financial development and green growth[19]. Recent findings on the nexus between FD and GG, show that FD positively impact GG (Liu & Liu, 2021; Cao et al. (2022). In line with this, Shobande & Ogbeifun (2022) and Ngo et al. (2022) claim that FD significantly mitigates environmental degradation, particularly through investments in the renewable energy market. Similarly, Capasso et al. (2019) and Zhao et al. (2021), argue against a weak financial system as being one of the biggest challenges of GG.

(S) Human development and green growth. Human development (HD) is an integral part of economic growth, playing an important role for GG. Zhao et al. (2021) argue that investments in HD through education and training enhance individual capabilities for the understanding of green energy use. In contrast, Diebolt & Hippe (2019), in a study dealing with European economies, argue that heterogeneity in HD in certain areas may be a reason for disparities of sustainable economic progress in other areas. Additionally, Ngo et al. (2022) highlight that through different channels such as education and innovative ideas, HD contributes to GG as evidenced in China (Li et al., 2022), OECD (Yao et al., 2020), or BRICS economies (Ganda, 2022).

(T) Technological innovations and green growth. According to neo-classical economic models, TI is the most important factor of production and growth of a country. More recently, Zhou et al. (2022), Cao et al. (2022) and Li et al. (2023) argue how TI favours the implementation of green energy sources in the total energy mix of a country and mitigates greenhouse gas (GHG) emissions. Likewise, the application of a Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) framework finds a positive relationship between TI and GG (Talebzadehhosseini & Garibay, 2022; Herman, 2023). In addition, the studies by Saqib & Usman (2023) for China and US, and Saqib et al. (2023) for EU economies conclude that TIs shift the dynamics of economic growth by streamlining industrial structures and increasing

[19] Other economic variables are used in this study as control co-variates.

production efficiency. These results contrast the works of Danish & Ulucak (2020) and Rahman et al. (2022).

(L) Environmental policy and green growth. A number of studies addressing this topic finds contradictory results. Doğan et al. (2022) highlight an inverse relationship between carbon emissions and environmental regulations in G-7 economies. For OECD countries, Ma et al. (2023) argue that EP significantly promotes environmental protection through the use of green research and development (R&D) investments, whereas the work by Tanchangya (2022), Maiti (2022) Wang et al. (2023), and Khan et al. (2023) argue that EP enhances GG allowing the efficacy of production strategies.

(E) Ecosystem stress and green growth. The literature on the relationship between ecosystem stress and green growth appears somehow limited. Lopes (2015) recognises the importance of engineering biological systems to foster GG such to provide an adequate knowledge to the complexity of a sustainable value chain management. On a similar vein, recent studies consider the positive effect of ecological footprint (EF) on GG (Usman et al., 2023; Dam et al., 2024), whereas other research highlights contrasting results (Xiuqing et al., 2022). Empirical literature summary is presented in Table 1.

Table 1. Summary of empirical studies

Studies	Years	Regions	Variables	Methods	Outcomes
Jiang et al., (2023)	1996-2019	E-7	QI, EPU, REC,GG	Panel Quantile regression	IQ increases GG
Gao & Fan, (2023)	2002-2019	BRI	QI, TI,NRES, GG	GMM	Found a positive association b/w IQ and GG
Dam et al, (2024)	1996-2020	OECD	IQ, GG, ES,POP	PMG-ARDL	IQ improves GG
Safi et al., (2022)	1995-2019	E-7	QI, EC,EIN,NREC, EXP,IMP,GG	CS-ARDL	Inverse association
Tawiah et al., (2024)	2000-2017	123 countries	CRO,GDP, POP,FA,FDI,GG	MMQR	Corruption declines GG
Sohail et al.,(2022)	1990-2019	Pakistan	EG,FD,PS,GG	N-ARDL	Political instability declines GG
Ahmed et al.,(2022)	2000-2019	South Asian countries	GG,IQ,FD	FMOLS,DOLS	IQ improves GG
FD and GG					
Cao et al., (2022)	2011-2018	China	GG,FD,TI,STO	SDM	FD accelerates GG
Liu & Liu, (2021)	2012-2019	China	GG, FD, HD	SAR	FD reduces CO2 emissions

Shobande & Ogbeifun, (2022)	1980-2019	OECD	GG,FD, EC,FDI,CO_2	Blundell–Bond dynamic model	Confirms bi-directional association b/w FD and GG
Ngo, et al., (2022)	1996-2014	36 developed and Emerging economies	GG, CO_2,, EDU, FD, HDI	GGM	FD improves GG
Abdelbary & Benhin, (2019)	1995-2018	Africa	ES, FD, IQ, UB	Pooled OLS	FD enhances Environmental sustainability
Zhao et al., (2021)	2003-2018	63 Countries	Co2, FD, TI	SYS-GMM	FD raises the ecological deficit and reduces GG
Huang, (2024)	1990-2021	BRICS	GG, FD, NNR, GLO	GLS	weak financial system declines the GG
HD and GG					
Zhao et al., (2021)	2003-2018	63 Countries	Co2, HD, FD, TI,GG	SYS-GMM	HD reduces the ecological deficit and enhances GG
Ngo et al., (2022)	1996-2014	36 developed	GG, CO2, EDU, FD, HDI	GGM	HD accelerates GG
Yao et al., (2020)	1870-2014	20 OECD	CO_2, HD, INV, EDU	Structural break model	HD protects the environment and increases the GG
Li et al., (2022)	1990-2018	China	CO_2, HD, RE, ET	ARDL	HD reduces CO2 emissions and improves GG
Diebolt & Hippe (2019),	1960-2010	15 EU economies	HD, GDP, EF, ES,POP	OLS model	HD accelerates the EG
Ganda, 2022	1990-2017	BRICS	GG,CO_2,HD,REC, FDI, GDP	CS-ARDL	HD increases EQ and enriches GG. While GDP increases the ecological deficit.
TI and GG					
Zhou et al., (2022)	1990-2019	China	GG,TI,FTI	GMM	TI boosts GG
Li et al., (2023)	2000-2020	China	GG,TI,TNR,NRE	GMM	TI accelerates GG
Cao et al., (2022)	2011-2020	China	GG,TI,FD,STO	SDM	Positive spillover effects
Talebzadehhosseini & Garibay, (2022)	2003-2015	OECD	GG,TI,TNR, EC	Partial Least Square - Structural Equation Modelling.	TI and RE increase GG
Saqib & Usman, (2023)	1990-2020	16 EU	GG, TI,RE,NRE	AMG	TI boosts GG

Saqib et al., (2023)	2012Q1-2020Q4	USA and Chian	GG,TI,RE,NRE	QARDL	TI increases GG
Danish & Ulucak, (2020)	1992-2014	BRICS	GG, TI,TNR,NRE	FMOLS DOLS	TI reduces CO_2,emissions
Rahman et al., (2022)	1990-2018	22 developed economies	CO_2, TI, EXP, RE GDP	NARDL	TI increases the ecological deficit
Herman, (2021)	2002-2019	Global south	TI, EP, GG	Bibliometric analysis	TI enhances the GG
Khan et al., (2023)	2000-2020	26 EU economies	TI,GG,RE,EI,CO_2	Quantile regression	TI, and RE boost the GG and decline the CO_2
EP and GG					
Doğan et al., (2022)	1992-2016	G-7	GG,EPS,RE,EC	FMOLS	EP reduces CO2 emissions
Ma et al., (2023)	1990-2020	OECD	EF,EP,RE, NR,POP	CS-ARDL	EP accelerates GG
Wang et al., (2023)	1990-2019	BRICS	GG,ESP, ETI,NR	MMQR	EP increases GG
Chen & Tanchangya, (2022)	2000-2020	28 EU	GG,ESP,BR	2SLS	A higher degree of EP reduces. EF
Maiti, (2022)	2000-2015	32 countries	ESP,GG,TI,RE	Dynamic panel threshold regression	EP and RE boost GG
Yirong, (2022)	1997-2019	TOP 5 CO2 emitters	CO_2,, EPS, TECh, POP	N-ARDL	EP improves EQ and enhances the GG
ES and GG					
Usman et al.,(2023)	1991-2017	13 top pollutant economies	GG, EF, GDP, NRE, RE, EP	CS-ARDL	EF declines the GG
Xiuqing et al.,2022	2006-2018	108 prefecture-level cities China	ES, EF,IS	Fixed effect and panel threshold regression	EF declines the environmental sustianablity
Lopes, (2015)	2009-2015	Brazil, the USA, and France	BRI, EF, ES	OLS	Biorefinery innovations enhancing sustainability, while EF declines the ES

3. Methodology

3.1 Model specification

3.1.1 Spatial weight matrix

To capture spillover effects, this study uses a k-nearest neighbor (KNN) distance weight matrix (Anselin, 2002) as it addresses consistency issues (Weng et al., 2023), particularly in the presence of islands or spatial units which do not share a land border but have strong political, economic, and trade links (Naveed et al., 2023). The geographical distance is computed as $w_{ij} = \frac{1/d_{ij}}{\sum_{j=1}^{N} 1/d_{ij}}$, where N shows the number of spatial units, whereas $1/d_{ij}$ shows the distance between spatial units i and j. A low distance means that high spatial spillover effects take place, and vice versa.

3.1.2 Spatial autocorrelation

Spatial autocorrelation displays the association between variables at different spatial units in space. Moran's I (Moran, 1950) and Geary's C tests are used for the detection of spatial autocorrelation. The statistical interval of Moran's I index ranges between (-1 to 1)[20] (Moran, 1950). The latter primarily considers spatial properties of geographical units as a whole (i.e. across the entire study area), while the former looks at the spatial attributes of a single geographical unit (i.e. can gauge the heterogeneity of spatial associations across countries included in the study)(Feng & Wang, 2019).

3.1.3 Spatial model specification

To capture the spatial-macro-dynamics of the (macroeconomic) PESTLE framework, this study considers spatial lag effects of dependent and independent variables (Lesage & Pace, 2014; Yesilyurt & Elhorst, 2017). SDM is a generalized form of the spatial autoregressive model (SAR) and spatial error model (SEM) (Kelejian & Prucha, 1998; Paroussos et al., 2020), which takes the following form:

$$Y_{it} = \dot{\rho} \sum_{j=1}^{N} w_{ij} y_{it} + X_{it}\beta + \sum_{j=2}^{N} w_{ij} X_{jt}\theta + \gamma_i + \varphi_t + \varepsilon_{it} \quad (1)$$

[20] I > 0 (positive spatial autocorrelation); I < 0 (negative spatial autocorrelation) and I = 0 (no spatial autocorrelation).

where Y_{it} is the dependent variable across countries i and time t; $\dot{\rho}$ is the spatial autoregressive coefficient; $\sum_{j=1}^{N} w_{ij} y_{it}$ captures the endogenous effect; $X_{it}\beta$ is the matrix of independent variables, whereas β is the elasticity coefficient of both explanatory and control co-variates; $\sum_{j=2}^{N} w_{ij} X_{jt}\theta$ represents the exogenous interaction; $\gamma_i \; and \; \varphi_t$ show the spatial and time-fixed effect. In addition, to fully capture spillover effects, LeSage & Pace, (2009) suggest, through a partial differential method, the decomposition of the spillover effect into direct, indirect and total effect. The former explains the unit change in independent variables on the outcome variable in country *i*; the indirect effect can be interpreted as a unit change in explanatory variables of neighbouring countries on the dependent variable of country *i*, and the total effect is the sum of both.

3.2 Variables and data sources

Table 2 summarises data sources and description from five databases worldwide.

Green growth (explained variable). This study uses 'CO2 productivity' as a measure of GG (Wang & Li, 2019). It is a comprehensive measure of GG as it simultaneously considers an economic and environmental aspects of a country's growth.

Institutional quality: A principal component analysis (PCA) is used to construct an IQ index by considering six key political indicators such as government effectiveness, rule of law, control of corruption, absence of violence, and voice and accountability. The constructed index offers a broader overview of the political landscape of countries (Achuo et al., 2024) and overcomes high collinearity among the above six indicators, thus providing more efficient estimates. The study tests the hypothesis (H1) of a spatial positive relationship between IQ and GG, such that an increase of IQ in the home country not only has positive effects on its GG, but generates spillover effects on the GG in adjacent countries.

Financial development: This study employs an FD index by Taddese & Abebaw (2023). Hypothesis (H2) tests a positive spatial relationship between FD and GG, such that at increasing levels of FD in the home country, it affects its GG and also that of adjacent countries'.

Human development: According to the international literature, the HD index has been widely used under a variety of contexts. As such, hypothesis (H3) tests a positive spatial relationship such that increasing levels of HD, not only affects GG of the home country but provides spillover effects on GG in adjacent countries.

Technological innovations: TI is measured by the number of patent applications per thousand population. Hypothesis 4 (H4) is a positive spatial relationship between TI and GG, such that

increasing levels of TI in the home country, affects its GG and presents spillover effects also in adjacent countries.

Environmental policy: EP is a combination of restrictive (carbon tax, R&D expenditures, feed-in tariff) and supportive indicators (subsidies) of environmental policies. Hypothesis 5 (H5) tests a positive spatial relationship between EP and GG in home and adjacent countries.

Ecological footprint: EF is used as a proxy variable of ecosystem stress. Hypothesis 6 (H6) tests a spatial negative (positive) relationship, arguing that increasing levels of EF in the home country may positively (negatively) affect its GG and that of adjacent countries.

Control variables: Population growth rates (POP), globalization (GLO), natural resources (TNR), and government expenditures (GE) are used as control variables. The higher population growth rates, the higher the demand for energy, heating and primary needs (Tawiah et al., 2021). As such, hypothesis 7 (H7) between POP and GG maybe either a spatial positive or negative relationship such that at increasing levels in POP in the home country, its GG may be positively or negatively be affected as well as that in adjacent countries. As for GLO, this study uses the globalisation index from the KOF Swiss Economic Institute[21]. According to Shahbaz et al. (2023), the KOF index holds greater significance than traditional quantitative measures of economic globalization, such as trade openness, and foreign direct investment. As a result, hypothesis 8 (H8) tests a spatial positive relationship such that at increasing levels of GLO in the home country, it affects its own GG and also has spillover effects on GG in adjacent countries. In terms of GE, the controversial results from the international literature provide that the expected sign between GE and GG may be either a spatial positive or negative relationship (hypothesis 9 - H9) such that increasing levels of GE in the home country, negatively or positively affect GG in adjacent countries. Similarly, the literature between TNR and GG appears contrasting (Khan et al., 2023; Wang et al., 2023) such that hypothesis 10 (H10) is similar to the above.

Table 2. Variable description and data sources

Variables	Description	Unit of measurement	Data sources	Types of Variables
GG	Green growth	GDP per unit of energy-related CO2 emissions/ US dollars per kilogram, 2015	OECD	Endogenous
IQ	Institutional quality	Index	PCA self-estimated	Ind. var

[21] https://kof.ethz.ch/en/forecasts-and-indicators/indicators/kof-globalisation-index.html

FD	Financial Development Index	Index (0-1)	IMF	Ind. var
HD	Human development	Government expenditures on education and health % of GDP	WDI	Ind. var
TI	Technological innovations	Number of patent applications per thousand population	WDI	Ind. var
EP	Environmental policy	Policy Stringency index (0-6)	OEDC	Ind. var
EF	Ecological stress	Ecological footprints gha per person	GFN	Ind. var
TNR	Total Natural resources rent	% of GDP	WDI	CV
GLO	Globalization	Index (0-10)	KOF	CV
POP	Population growth rate	Population growth rate (%)	WDI	CV
GE	Government expenditures	% of GDP	WDI	CV

Notes: OECD - Organization of Economic Cooperation and Development (https://search.oecd.org/greengrowth);
IMF - International Monetary Fund (https://data.imf.org);
WDI -World development indicators (https://databank.worldbank.org);
GFN - Global Footprint Network (https://www.footprintnetwork.org/);
KOF - KOF Swiss Economic Institute (https://kof.ethz.ch/en/forecasts-and-indicators/indicators/kof-globalisation-index.html);
CV - Control variable;
Ind. var - Independent variable.

4. Results

4.1 Descriptive statistics

Descriptive statistics of the study variables is presented in Table 3. Overall, the selected variables present low values of standard deviation, indicating low variability in the data. Based on the skewness values GG, EP, TNR, and GE are positively skewed, in contrast to IQ, FD, HD, POP, and GLO. In addition, GG, FD, IQ, TI, and EP present a leptokurtic distribution, in contrast to the platykurtic one of HD and EP. Lastly, Jarque-Bera test statistics highlights that data is not normally distributed. As a visual analysis of the descriptive statistics.

Table 3. Descriptive statistics

	GG	IQ	FD	HD	TI	EP	EF	POP	GLO	TNR	GE
Mean	5.89	2.85	0.61	0.83	7.54	2.60	2.32	15.57	4.04	0.83	20.01
Median	5.41	3.07	0.65	0.86	7.50	2.50	2.56	15.99	4.44	0.38	19.66
Maximum	17.09	4.32	1.00	0.96	13.33	5.36	4.89	18.22	4.54	12.89	28.15
Minimum	1.05	-0.72	0.10	0.42	3.13	1.13	0.17	11.25	3.80	0.04	11.67
Std. Dev.	2.59	1.16	0.17	0.09	2.03	0.70	1.10	1.57	0.129	1.56	3.01
Skewness	1.23	-0.89	-0.54	-2.47	0.50	1.01	-0.26	-0.38	-2.185	4.58	0.122
Kurtosis	5.38	3.16	3.07	4.53	3.40	4.50	2.02	2.47	8.08	2.157	2.77
Jarque-Bera	33.73	91.55	33.97	153.76	32.87	181.45	34.88	26.98	146.89	200.98	3.62
Probability	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Observations	780	780	780	780	780	780	780	780	780	780	780

Source: Authors' own computations.

4.2 Spatial autocorrelation

4.2.1 Global Moran's I

Table 4 reports the statistical outcomes of the global Moran's index (GMI) and Geary's C tests. Based on p-values, the null hypothesis of 'no spatial dependence' is rejected and the existence of positive spatial autocorrelation among the sampled countries is found.

Table 4. Moran's I and Geary's C

	I	p-values	C	p-values
GG	0.37	0.00	0.29	0.00
IQ	0.57	0.06	0.31	0.00
FD	0.59	0.05	0.50	0.00
HDI	0.65	0.07	0.40	0.00
TI	0.76	0.00	0.59	0.00
EP	0.71	0.01	0.51	0.00
GLO	0.46	0.00	0.53	0.00
POP	0.53	0.00	0.25	0.00
TNR	0.33	0.00	0.20	0.00

GE	0.24	0.00	0.60	0.00

Source: Authors' own computations.

4.2.1 Local Moran's I scatter plots

Figure 1 shows the scatter plots of local Moran's I index. Each scatterplot is divided into four quadrants. The 1st and 3rd quadrants represent High-High [H(H)] and Low-Low [(L(L)] agglomerations. H(H) represents the group of countries that have the same high-level development in terms of the variables of interest; and vice versa for L(L). On the other hand, the 2nd and 4th quadrants reveal distance clustering values, High–low [H(L)] and Low-High [L(H)], respectively. H(L) refers to an agglomeration of countries in which some present a high value of the variables of interest, while neighbouring countries rely on low values of it; and vice versa for the L(H) agglomeration.

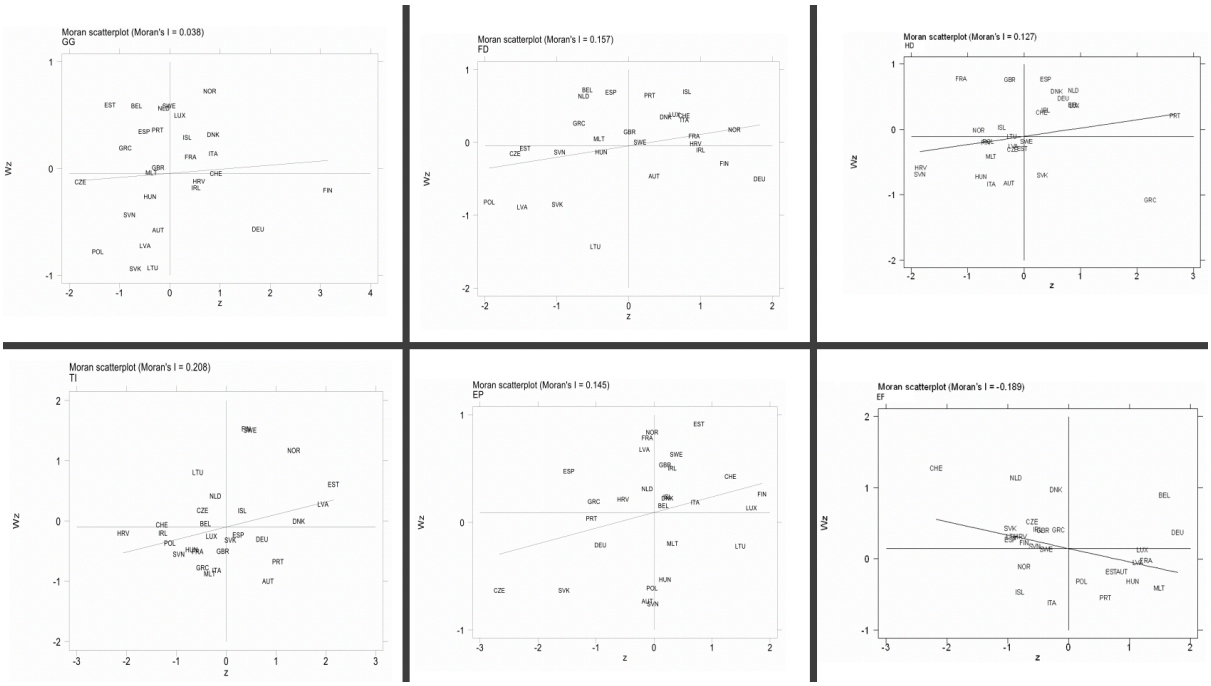


Figure 1. Local Moran's I scatter plots. *Source*: Authors' own computations.

4.1.3 Local indicators of spatial association (LISA) clusters

Figure 2 shows LISA clusters (Mahmood, 2022) for GG, while Figures S1-S6 (in the Supplementary material) shows LISA clusters for the co-variates. . LISA is a mapping

technique that is used to pinpoint the regions on a map, where data values closely match or differ from each other (Mahmood, 2022). Orange and red coloured countries highlight positive spillover effects, and vice-versa for blue and/or green coloured countries.

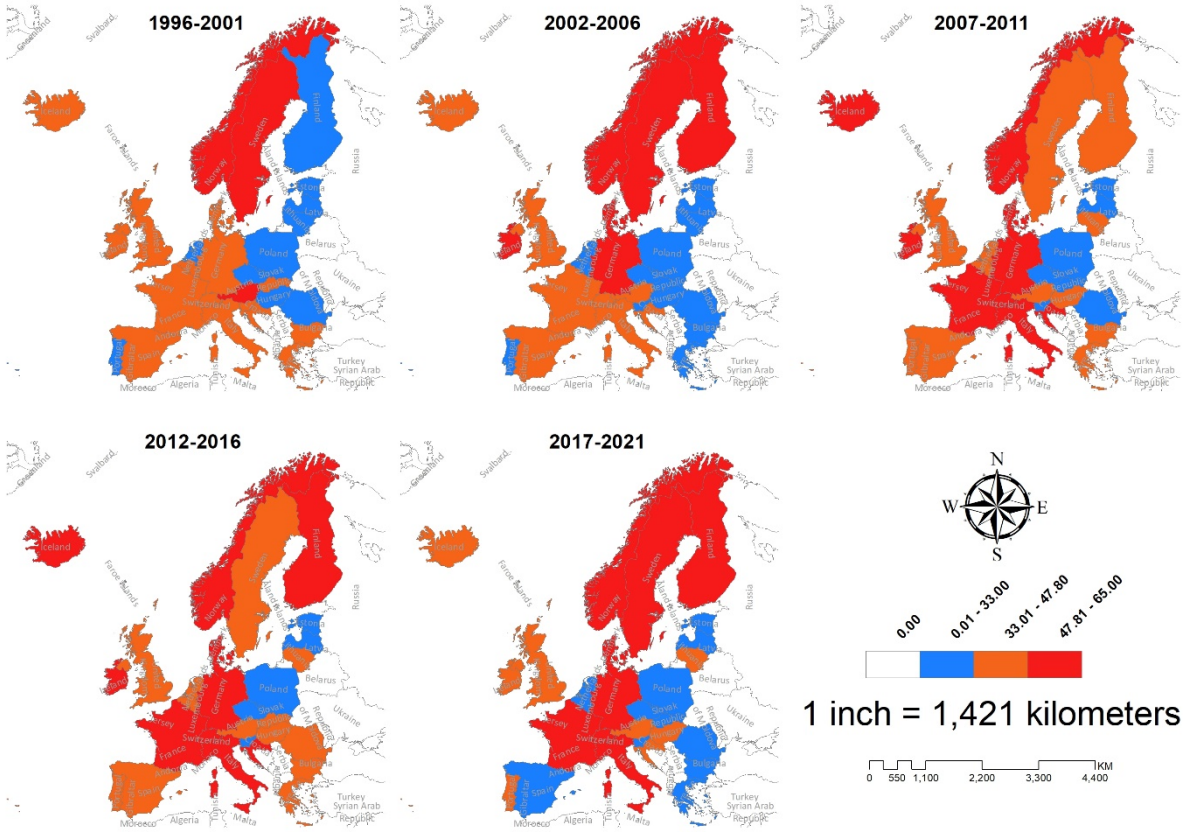


Figure 2. LISA clustering for GG. *Source*: Authors' own computations.

4.3 Model results

Table 5 shows estimated results of the SDM with spatial fixed and time effects. In this study, the SDM is not nested with SAR and SEM models (Likelihood ratio test Chi2=138.82 p-value=0.00) (Baltagi et al., 2019). Also, the Hausman test (Chi2=94.92 p-value=0.00) favours a fixed *vs* random effect model (Hausman, 1978), while the Wald test (Chi2=47.00 p-value=0.00) addresses the presence of spatial dependence (Hidalgo & Hausmann, 2009).

Finally, the Akaike information criteria (AIC=2349.06 p-value=0.00), and Schwarz's Bayesian information criteria (SBIC=2404.97 p-value=0.00) reinforce the validity of the SDM. Due to the presence of feedback effects, the coefficients of SDM do not accurately depict the marginal effects of variables. For this reason, the partial differential model is applied to quantify the direct, indirect (spillover) and total effects of variables (Anselin, 2002).

Table 5. Estimated results of the Spatial Durbin fixed effect model

	Spatial fixed and time effect	
Variable name	Coeff.	W
ρ		0.29***
		(2.86)
IQ	0.21***	0.73***
	(3.51)	(4.10)
FD	0.34***	0.70***
	(4.02)	(2.89)
HD	0.08**	0.28***
	(2.50)	(2.76)
TI	0.05*	0.03*
	(1.69)	(1.91)
EP	0.27***	0.10
	(4.88)	(0.58)
EF	-0.13***	-0.40***
	(-2.69)	(-3.73)
POP	0.02	-0.39***
	(0.60)	(-3.01)
TNR	-0.12***	-0.39***
	(-2.71)	(-2.91)
GLO	-0.04	-0.05
	(-1.11)	(-0.58)
GE	0.05***	0.15***
	(2.68)	(2.84)
L.W_GG	-0.537***	
	(-4.77)	
Obs.	780	
Spatial model selection tests		
	Statistics	p-value
Likelihood ratio test	Chi2=138.82	0.00

Wald test	Chi2=47.00	0.00
Hausman Tests	Chi2=94.92	0.00
AIC	2349.06	2230.24
SBIC	2404.97	2332.75

Notes: ∗∗∗, ∗∗ and ∗ illustrate 1%, 5% and 10% significance level, respectively. t-statistics in parentheses.

Source: Authors' own computations.

4.2.1 Estimated marginal effects

Table 6 shows the estimated results of the short and long-run marginal effects. The majority of estimates are statistically significant within conventional confidence intervals (CIs). The estimated coefficient of IQ has a significant positive direct (short run=0.17 t-stat.=2.66; long run=0.19 t.stat.=3.18), and indirect (short run=0.35 t-stat.=3.01; long run=0.54 t.stat.=3.64) effect on GG. This suggests that strong institutional frameworks with stable economic indicators encourage economies (local and neighbouring) to adopt sustainable practices such to ameliorate the CO2 productivity. These outcomes are in line with the findings of Barra & Falcone (2024) for European economies, and Zakaria and Bibi (2019) and Ahmed et al. (2022) for South Asian countries.

Similar results are found for FD, although the spillover effect in the short run is not statistically significant. The estimated coefficients present a substantial positive direct (short run=0.32 t-stat.=3.65; long run=0.33 t-stat.=4.01), and indirect (long run=0.47 t.stat.=2.41) effect. It can be argued that adequate monetary and financial frameworks within European economies, particularly effective in the long run, enhance stakeholders' accessibility to credit, thus, to increase potential (green) investments to favour GG. Numerous studies, including Yin (2023) for EU economies, Zhong and Li (2020) and Tian et al. (2021) for China, and Ramzan et al. (2023) for the 10 greenest worldwide economies, argue that financial progress improves credit distribution, and investment rates, thereby fostering GG.

The estimated marginal spatial lag coefficients of HD present direct (short run=0.06 t-stat.=2.03; long run=0.07 t-stat.=2.35), and spillover (short run=0.13 t-stat.=2.11; long run=0.21 t-stat.=2.48) effects on GG. It is evident that the advancement of HD, particularly effective in the long run in the home country favours the implementation of green practices, motivating the new generation of stakeholders in adjacent countries (spillover effect), to adopt sustainable solutions (Saqib et al., 2024). The above findings are in agreement with earlier studies of Asumadu et al. (2020) and Zhou et al. (2024).

In terms of the estimated coefficients of TI, these have a relatively small marginal positive spillover effects (short run=0.02 t-stat.=1.70; long run=0.02 t-stat.=1.89) on GG, most probably due to the latest push on eco-innovation and digital transition from the Green Deal strategy (European Innovation Agency, 2024; Faggian et al., 2024). Similar results are also supported for European economies by Diebolt & Hippe (2019), Nosheen et al. (2021) and Ngo et al., (2022), and in other contexts such as China (Cao et al., 2022), G-7 and G-10 economies (Hao et al., 2021; Razzaq et al., 2023), or 'Belt and Road'[22] countries (Yang & Ni, 2022).

As for EP, significant positive direct effects (short run=0.29 t-stat.=5.09; long run=0.28 t-stat.=5.07) on GG are found. These indicate that ad-hoc policy strategies (taxes and subsidies), reduce the negative effects of economic activities on the environment in the home country, thus providing positive outcomes in terms of GG. These findings are in line with Dogan et al. (2023), as well as other contexts such as BRICS (Li et al., 2023), or OECD economies (Hassan et al., 2022; Appiah et al., 2023). In contrast, the direct (short run=-0.12 t-stat.=-2.01; long run=-0.12 t-stat.=-2.31) and spillover effects (short run=-0.17 t-stat.=-2.32; long run=-0.28 t-stat.=-2.98) of EF are negative and significant. It can be argued that although much has been done by European economies to put into practice sustainable growth mechanisms, more should still be faced to overcome the worsening of EFs across countries and time. Although energy transition is among the most relevant transformations of the economy (Shokoohi et al., 2022), European economies should also focus on other challenging economic activities such as sustainable agricultural practices (Pelucha & Kveton, 2017), sustainable consumption habits (Saari et al., 2021), green initiatives for large industrial sites (InnoEnergy, 2024), or transportation (Chen & Vickerman, 2016).

Other control variables' outcomes reveal that POP has a statistically significant negative spillover (short run=-0.26 t-stat.=-3.10; long run=-0.32 t-stat.=-3.04) on GG. (Byaro et al., 2024). It can be argued that, particularly for EU economies, large proportions of population growth are due to migratory fluxes in search for jobs from north African or west Asian countries, which requires additional energy consumption levels (Borghesi & Ticci, 2019). As such, excessive demand and exploitation of resources lead to a negative spatial impact on GG over time. In terms of TNR estimates, a negative direct (short run=-0.10 t-stat.=-2.13; long run=-0.11 t-stat.=-2.45) and spillover (short run=-0.17 t-stat.=-2.05; long run=-0.28 t-stat.=-2.48) effect is found. This may address the resource curse hypothesis, where the over-extraction of natural resources in the home country raises production costs, reduces competitiveness and

[22] https://greenfdc.org/countries-of-the-belt-and-road-initiative-bri/

undermines sustainability (Liu & Hong, 2024) not only in the same country but also in neighboring economies. Lastly, the marginal estimates of GE also show the presence of a relatively small direct (short run=-0.07 t-stat.=-3.18; long run=-0.06 t-stat.=-2.95) and spillover (short run=-0.12 t-stat.=-3.42; long run=-0.14 t-stat.=-3.00) effect. This outcome may be due to the structure of GE in several EU countries. Over the years, the majority of GE for all EU countries is directed towards social protection and health expenditures, other than other functions, including environmental protection (Ortiz-Ospina and Roser, 2016).

Table 6. Estimates of SDM marginal effects

	Short run			Long run		
	Direct effect	Spillover effect	Total effect	Direct effect	Spillover effect	Total effect
IQ	0.17***	0.35***	0.52***	0.19***	0.54***	0.74***
	(2.66)	(3.01)	(4.81)	(3.18)	(3.64)	(4.73)
FD	0.32***	0.24	0.57***	0.33***	0.47**	0.81***
	(3.65)	(1.62)	(4.08)	(4.01)	(2.41)	(3.98)
HD	0.06**	0.13**	0.20***	0.07**	0.21**	0.28***
	(2.03)	(2.11)	(3.12)	(2.35)	(2.48)	(3.07)
TI	0.00275	0.02*	0.02**	0.04	0.02*	0.03**
	(0.36)	(1.70)	(2.01)	(0.56)	(1.89)	(2.01)
EP	0.29***	-0.07	0.21*	0.28***	0.021	0.30*
	(5.09)	(-0.71)	(1.87)	(5.07)	(0.15)	(1.85)
EF	-0.12**	-0.17**	-0.28***	-0.12**	-0.28***	-0.40***
	(-2.01)	(-2.32)	(-4.10)	(-2.31)	(-2.98)	(-3.97)
POP	0.054	-0.26***	-0.20***	0.03	-0.32***	-0.29***
	(1.27)	(-3.10)	(-2.64)	(0.89)	(-3.04)	(-2.62)
TNR	-0.10**	-0.17**	-0.28***	-0.11**	-0.28**	-0.40***
	(-2.13)	(-2.05)	(-3.24)	(-2.45)	(-2.48)	(-3.18)
GLO	-0.01	-0.012	-0.05	-0.04	-0.03	-0.06
	(-1.00)	(-0.20)	(-0.87)	(-1.05)	(-0.44)	(-0.87)
GE	-0.07***	-0.12***	0.05	-0.06***	-0.14***	-0.07
	(-3.18)	(-3.42)	(1.60)	(-2.95)	(-3.00)	(-1.59)

Note: ***, ** and * illustrate 1%, 5% and 10% significance level, respectively. t-statistics in parentheses.
Source: Authors' own computations.

4.3 Robustness check

Table 7 shows two different robustness tests: (i) A spatial autoregressive model (SAR); and (ii) an SDM with 6-KNN matrix to check the validity and stability of the estimates of the SDM model. Here, the majority of the estimated coefficients and signs are consistent with the obtained outcomes. A similar result is also provided by the robustness check of marginal effects in Table 8.

Table 7. Robustness check: Estimated results of SAR and SDM 6-KNN

		SDM 6-KNN	SAR
Variable name	Coeff.	W	W
ρ		0.24***	0.56***
		(2.91)	(17.19)
IQ	0.16***	0.59***	0.15**
	(2.75)	(3.93)	(2.03)
FD	0.27***	0.30	0.30***
	(3.26)	(1.49)	(2.83)
HD	0.08**	0.14*	0.22***
	(2.36)	(1.79)	(6.49)
TI	0.01	0.02*	0.07
	(0.26)	(1.72)	(0.84)
EP	0.58***	0.17	0.45***
	(4.63)	(1.18)	(8.22)
EF/CC	-0.13***	-0.25***	-0.09*
	(-2.83)	(-2.78)	(-1.78)
POP	-0.01	-0.48***	0.13**
	(-0.45)	(-4.51)	(2.56)
TNR	-0.12***	-0.02	-0.13**
	(-2.72)	(-0.21)	(-2.24)
GLO	-0.04	0.01	-0.03
	(-0.35)	(1.42)	(-0.69)
GE	-0.06***	0.07	0.11***
	(-2.89)	(1.50)	(-4.47)
L.W_GG	-0.59***		
	(-5.90)		

Note: ∗∗∗, ∗∗ and ∗ illustrate 1%, 5% and 10% significance level, respectively. t-statistics in parentheses.

Source: Authors' own computations

Table 8. Robustness check: Estimated results of marginal effects

Variable name	Direct effects	Indirect (spillover) effects	Total effect
IQ	0.16**	0.19*	0.36**
	(2.01)	(1.91)	(1.97)
FD	0.32***	0.37***	0.70***
	(2.89)	(2.69)	(2.82)
HD	0.24***	0.28***	0.53***
	(7.06)	(6.80)	(7.54)
TI	0.08*	0.09*	0.01*
	(1.86)	(1.85)	(1.80)
EP	0.48***	0.05	1.03***
	(8.84)	(7.69)	(9.25)
EF/CC	-0.09*	-0.11*	-0.20*
	(-1.77)	(-1.75)	(-1.77)
POP	0.14**	0.16**	0.30**
	(2.50)	(2.35)	(2.45)
TNR	-0.14**	-0.16**	-0.30**
	(-2.33)	(-2.25)	(-2.31)
GLO	-0.03	-0.04	-0.07
	(-0.62)	(-0.62)	(-0.62)
GE	0.11***	0.13***	0.25***
	(4.40)	(3.94)	(4.27)

Note: ∗∗∗, ∗∗ and ∗ illustrate 1%, 5% and 10% significance level, respectively. t-statistics in parentheses.

Source: Authors' own computations.

5. Conclusion and policy implications

Based on the study findings and the latest events on energy security in Europe (Gökgöz et al., 2018; Mišík et al., 2022; Gritz et al., 2024; LaBelle et al.,2024), critical decisions and ad-hoc strategies, should be taken at country as well as cross-border level to actively implement current European Commission's main green policies (e.g. European Green Deal, REPowerEU plan) (European Commission, 2019a; 2022a).

On one hand, although the integration on modern renewable energy sources into current energy systems has been widely adopted (Hoicka et al., 2021; Busch et al., 2023), much remains to do in terms on each country's internal regulations to improve the efficiency of energy infrastructures, distribution grids and buildings to help reducing the current dependence on

(imported) fossil fuels (Braungardt et al., 2023; IEA, 2022). Second-best (market-based) instruments may not be enough to achieve the above aims (European Environment Agency, 1996; European Commission, 2022b; Primc et al.,2024). As a result, the promotion of public-private partnerships (PPPs) (European Commission, 2019b) should be further implemented and enhanced to accelerate collaborations on technological advancements and information transfer between small-medium enterprises (SMEs), academics, research centres, universities, industry and public companies, other than addressing financial investments in energy storage technologies and smart grid upgrades.

On the other hand, a higher degree of coordination, in terms of industrial and fiscal policies is advisable to guarantee a further harmonization of green products, and increases of productivity aiming at reducing energy prices and favour energy competitiveness. To address the issue of a relatively small TI effect on GG, the whole industrial policy, actually based on the middle technology trap (Fuest et al, 2024), should be revisited by focussing, among other things, on financing the whole value chain, from R&D to scale-up and full production as well as reducing the digital gap within and across European economies. Also, to further benefitting from spillover effects of FD, a higher degree of harmonization within financial markets should be favoured against insolvency issues as a result of the third stage (i.e. European deposit insurance scheme) of the completion of the Banking Union[23]. Lastly, public awareness initiatives for the increasing use of renewable energy and environmentally responsible behaviours should also be further promoted to increase the positive impacts of HD on GG, and support positive long-term spillover effects across countries.

5.1 Limitations and future research

This study is not without limitations. Due to data limitations across time, some European economies and other countries having their boundaries with or within Europe[24], were not included in the panel. This may cause potential inconsistencies in terms of reliability of the estimated outcomes. Whereas data availability is present, future studies can use more comprehensive data, such as for instance eco-innovation patents, government expenditures on environmental protection, green R&D investments, or GINI index as a measure of income inequality, and extend the present PESTLE (macroeconomic) framework by exploring other spatial units to test regional or sub-regional spillover effects.

[23] https://finance.ec.europa.eu/banking/banking-union/what-banking-union_en?prefLang=it
[24] Ukraine, Belarus, Serbia, Albania, San Marino.

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Supplementary material

List of investigated countries

Table S1. List of investigated countries

Country name
Austria
Belgium
Bulgaria
Croatia
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Iceland
Ireland
Italy
Latvia
Lithuania
Luxembourg
Malta
Netherlands
Norway
Poland
Portugal
Romania
Slovak Republic
Slovenia
Spain
Sweden

Switzerland

United Kingdom

LISA maps of co-variates

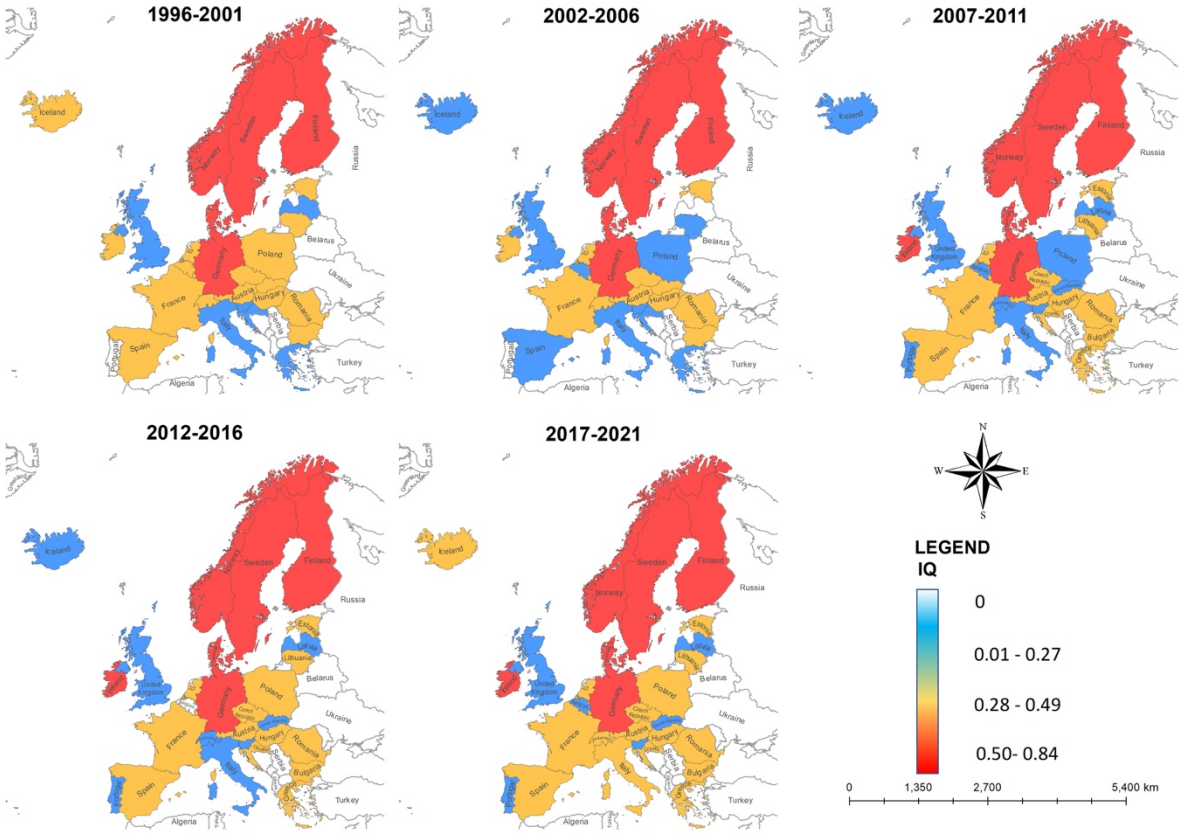


Figure S1. LISA clustering for IQ. *Source*: Authors' own computations.

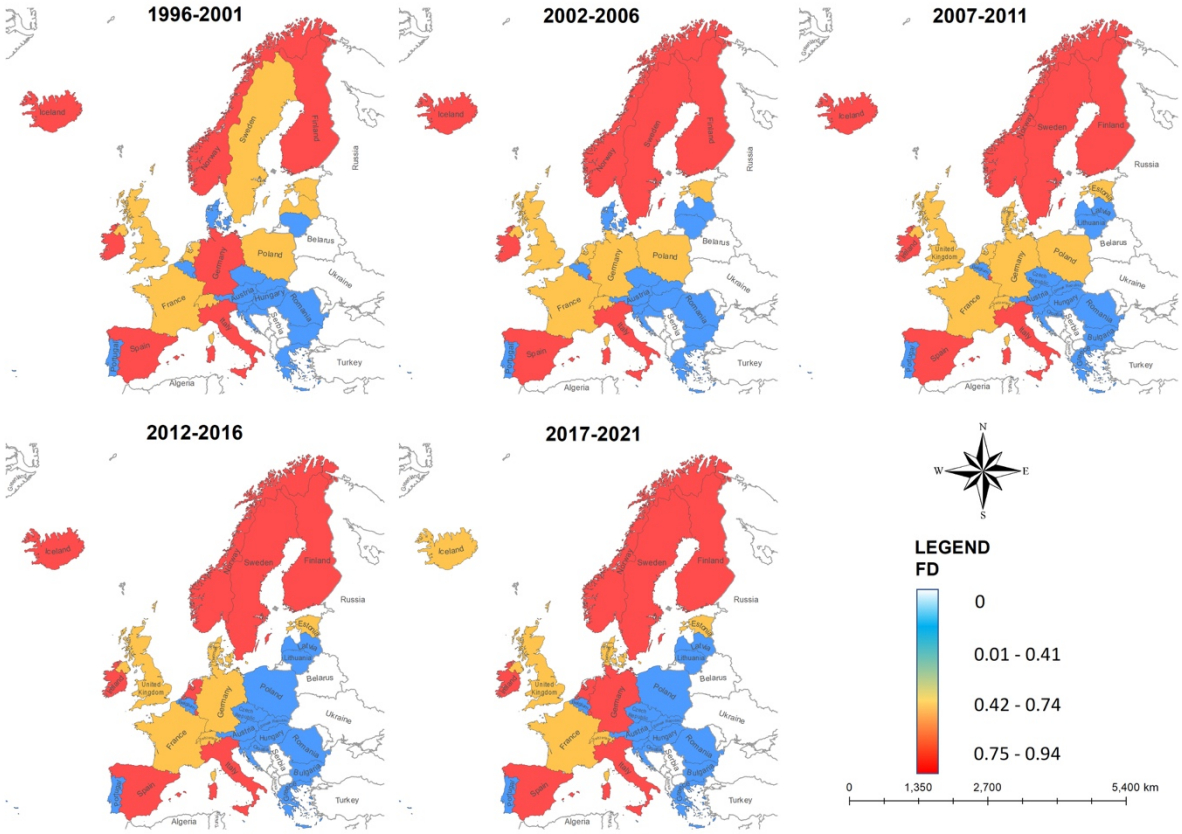


Figure S2. LISA clustering for FD. *Source*: Authors' own computations.

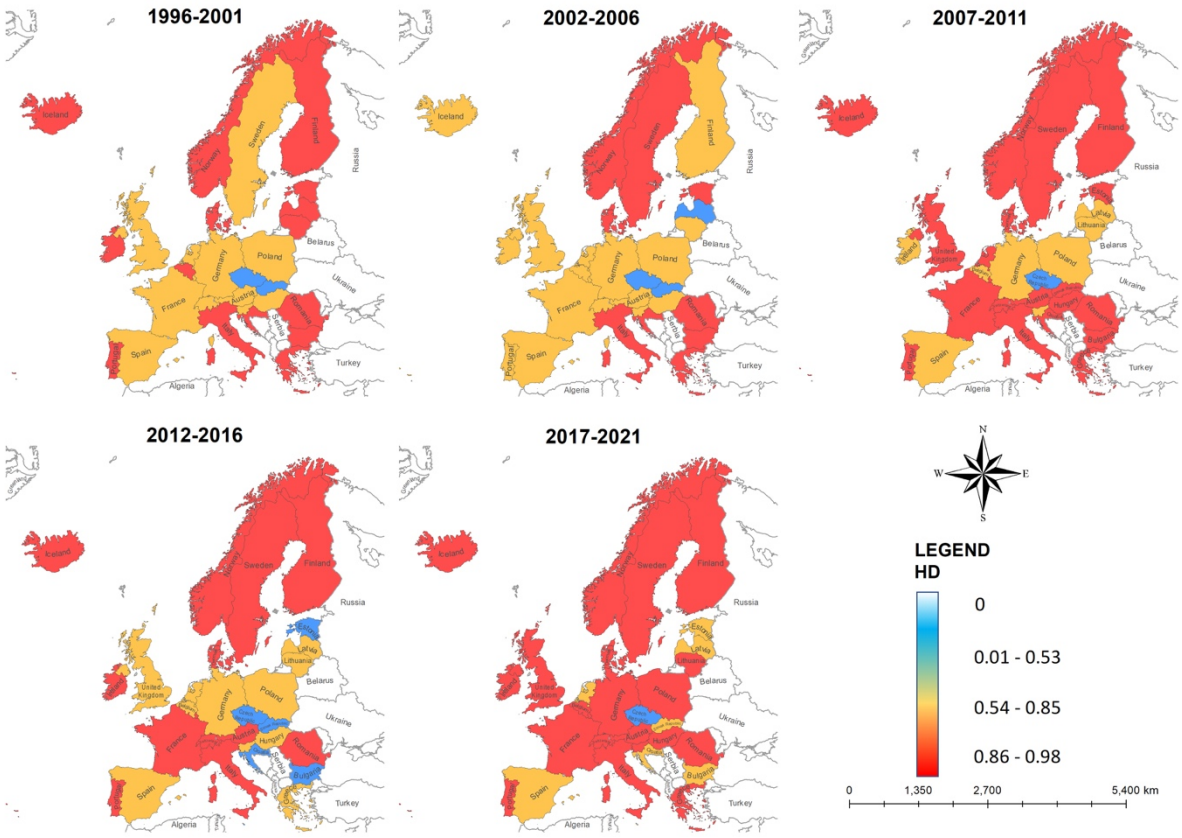


Figure S3. LISA clustering for HD. *Source*: Authors' own computations.

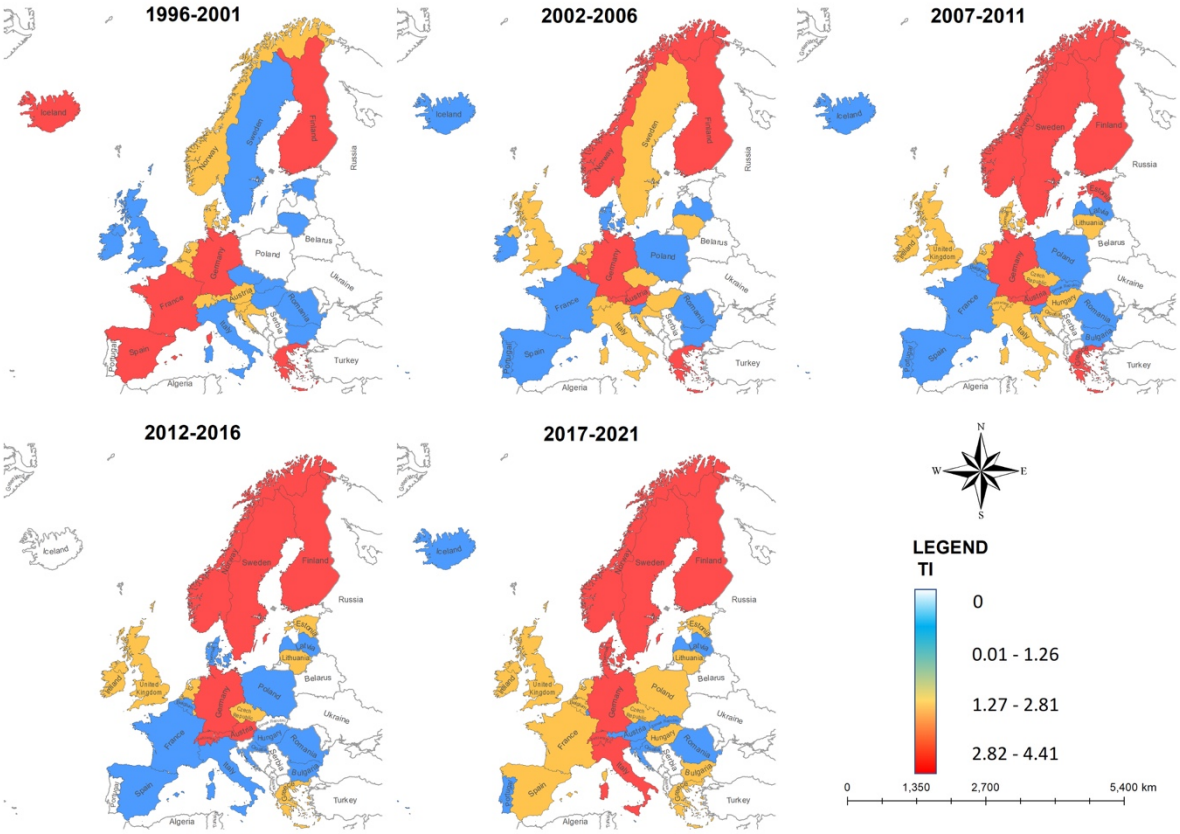


Figure S4. LISA clustering for TI. *Source*: Authors' own computations.

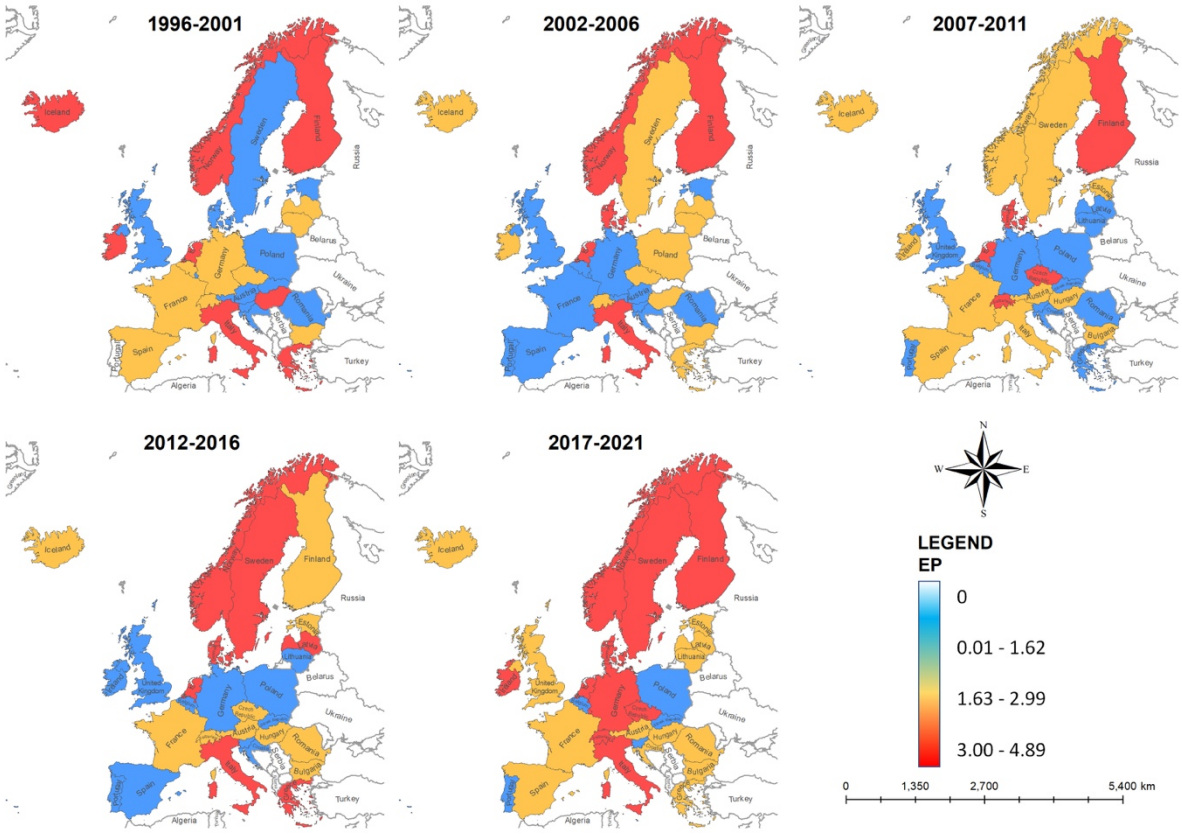


Figure S5. LISA clustering for EP. *Source*: Authors' own computations.

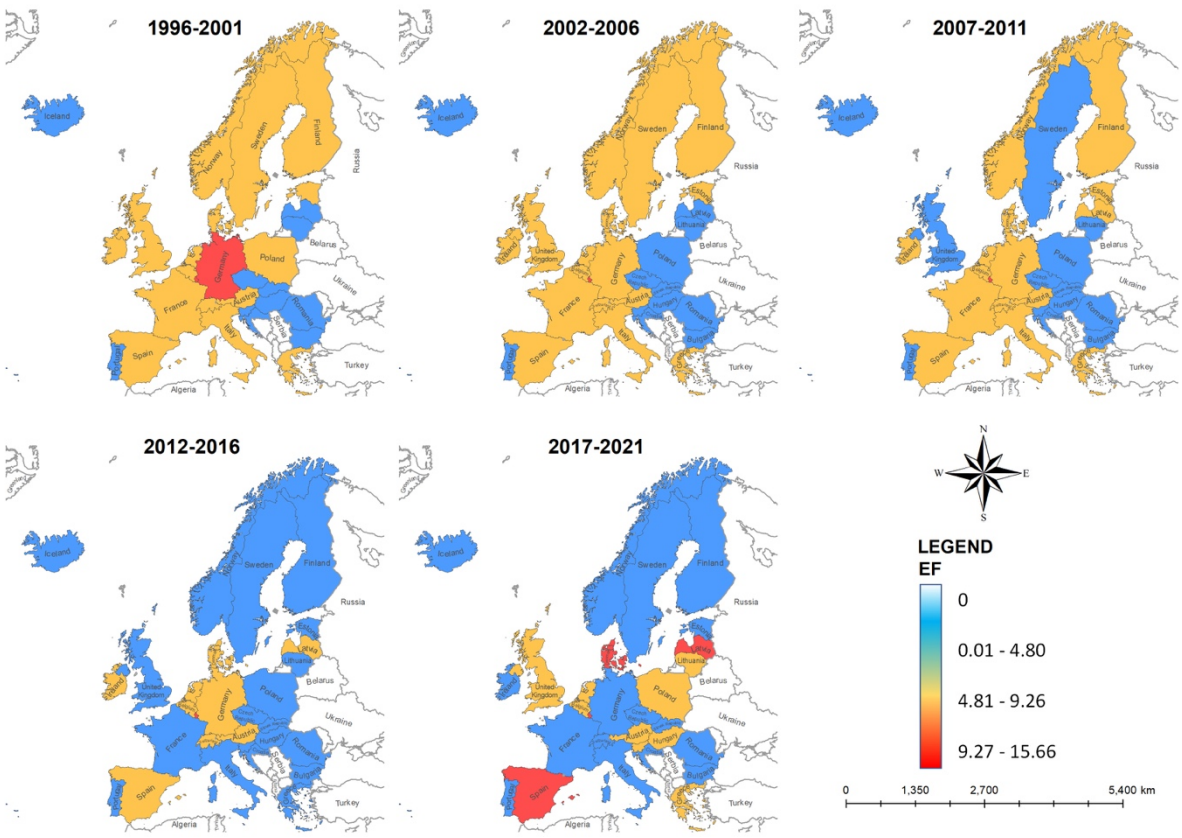


Figure S6. LISA clustering for EF. *Source*: Authors' own computations.

Chapter 5

General Conclusion

My PhD dissertation is the combination of three research articles. The first objective of this study was to explore the influence of energy innovations, renewable energy utilization, research and developmental expenditures and non-renewable energy on environmental quality in 21 OECD economies from "1998-2018". Earlier studies did not explore the role energy innovations in the improvement of environmental sustainability. To examine this association this study had applied advanced econometric models. The empirical outcomes of PMG model show that energy innovations, and renewable energy sources decline the ecological footprints. Further we explored the effect of income growth on environmental quality and confirmed the existence of the EKC hypothesis in OECD economies. This article has been published in Technological Forecasting and Social Change journal. The first paper prioritizes advancements of energy innovations and renewable sources for curtailing environmental footprints. The first paper did not explore social disparities. The second article focused on how energy justice enhances the energy equity, reduce the energy poverty and environmental issues in different income levels (low, middle, upper-middle, and high-income) economies. By considering the definition of energy justice, which aligns with three Sustainable Development Goals; SDG 7 (energy accessibility, affordability, and sustainability), SDG 10 (reducing income inequalities), and SDG 13 (climate action), I constructed a new energy justice index by using the entropy method. After the construction of index, we examined the presence and absence of cross-sectional dependence (CSD) and slop homogeneity (SH) in data series. After the detection of CSD, and SH issues in the dataset we moved towards advanced panel data techniques. For the identification of long run relationship between energy justice, technological advancement, natural resources ,exports and CO2 emission we employed the Method of Moments Quantile Regression (MMQR) model which was formalized by Machado and Silva (2019). It does not compute the average effect as traditional ordinary least square model. Instead, it measures relationships at varying quantile points (lower, middle and upper quantiles). The outcomes of the MMQR model reveal that energy justice declines environmental disparities.

The drive towards sustainability is very challenging. Energy justice can only be achieved by investing in the renewable energy market. To overcome the economic and environmental challenges green growth plays a key role. Thus, the third paper explored the drivers of green energy growth in 30 European economies. We applied a PESTLE (Political, Economic, Social, Technological, Legal, and Environmental) framework and highlighted the challenges on the

way of green economic growth. In this paper instead of relying on traditional and second-generation models, which ignore the geographical effect, we applied spatial econometric models. Moran's I, and Geary'c, confirmed the existence of spatial autocorrelation among sampled series. Subsequently, LISA clustering reveals significant variation in green growth across European countries over the time. Nations such as Finland, Sweden, Norway, Germany, Italy, and Ireland demonstrate high levels of green growth, reflecting lower emissions. In contrast, countries like Estonia, Slovakia, Slovenia, Malta, Poland, and Portugal face economic disparities. Secondly, the empirical outcomes of SDM showed that improvement in the neighbouring countries' institutional quality, financial development, human development, technological innovation, and environmental policy accelerate the green growth in European economies under study. While ecological footprints directly and indirectly enhance ecological crisis and decline green growth.

5.1 *Policy implications*

There is no single solution or approach that works for all economies because each single nation has a unique status in terms of income, resources, political situation, and geographical location. However, the overall objective of global economies is to reduce climate vulnerabilities and economic crises, and the solution only lies in the transition of energy sources. To do this, governments should allocate major part of their. budgets on research and development in view of the implementation of renewable energy markets. Government should categorize public spending priorities into developmental and non-developmental expenditures, invest in green energy infrastructure projects, and improve the overall economic and environmental well-being of societies.By providing financial incentives including feed-in tariffs, tax credits, grants, and subsidies government can influence the individual behaviour and promote the implementation of local renewable energy projects. Additionally, financial institutions should offer interest rate breaks to individuals or firms who are investing in clean energy market (e.g, solar, wind and turbine). Moreover, they should increase the payback period on green energy loans.

Carbon pricing system is another important policy tool which helps the government bodies in achieving carbon neutrality goals. A well-designed carbon pricing system offers the potential to reduce greenhouse gases while raising significant revenues that can be reinvested in clean energy technologies and other sustainability initiatives. Setting a price on carbon emissions allows policymakers to incorporate the external costs of fossil fuel usage, leading to increased economic viability for renewable energy sources. The International Energy Agency (IEA,

2022a; 2022b) indicates that the inclusion of renewable resources in the national energy framework could alleviate budget pressures, which would enable governments to allocate additional funds to research and development in the energy field. Besides the development of renewable energy sources, policy makers should also focus on energy efficiency measures in all the sectors of the economy. A good example could be setting stringent energy efficiency standards for buildings and appliances, which can reduce energy demand and lower the carbon footprint for households and businesses. Furthermore, policymakers need to tackle the inconsistencies of certain renewable energy sources by investing in energy storage solutions and enhancing smart grid systems. The implementation of extensive energy storage alternatives, such as battery storage, pumped hydro, and advanced grid management systems, can ensure a reliable balance between energy supply and demand.

Moreover, it is vital for governments to enhance funding for research and development alongside awareness campaigns focused on education. These efforts will encourage the embrace of climate technologies and decrease reliance on fossil fuels, ultimately supporting environmental sustainability. By investing in research and development countries can find the comparative advantage of locally available renewable energy sources (which renewable energy source is more abundant). For instance, global south economies can produce energy form solar, and government should give a tax exemptions to the solar producing industries and financially support the households.The countries nearby coastal areas should produce the energy form wind, because it will be cheaper. The countries near the volcanic area should generate energy for geothermal energy. power (Ezekiel et al., 2020). To promote geothermal energy, policymakers could lower taxes on local installation and maintenance companies and provide incentives for next-generation energy technologies such as heating pumps and displacement devices (Sun et al., 2018).

Setting ambitious renewable energy targets is another important policy strategy, which helps the states in reducing carbon emissions (Güney et al.,2022). Ambitious targets reveal the intention of governments toward sustainability. To do this government can quantify the share of renewable energy within their total energy framework by an assigned year. In addition, international collaboration might help to overcome the financing obstacles that characterize many renewable energy projects, especially in developing countries. This can be facilitated by global financial institutions and development agencies, which can provide the required finance for building, clean energy infrastructures in regions that do not have enough resources to invest in such renewable technologies themselves.

5.2 *Limitations and future studies*

This PhD dissertation has numerous limitations. In this study we have empirically examined the environmental effects of energy innovations, energy justice, and green economic growth in various income group economies. Due to the shortage of time and resources we used the secondary databases and constructed the energy justice index. This study examined the influence of energy justice on environmental degradation. However, future studies can examine the influence of income growth, energy prices, and R&D on energy justice at regional level. Furthermore, they should explore how small-scale green energy projects affect the economic and environmental well-being of the local population.

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