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Renewable Energy Consumption and Economic Growth

Edited by

José Alberto Fuinhas, Matheus Koengkan and Renato Filipe de Barros Santiago

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Preface to ”Renewable Energy Consumption and Economic Growth”

The world is currently facing a critical environmental crisis, and the shift towards renewable energy sources has become increasingly urgent. However, the impact of this transition on macroeconomic stability and economic output must be carefully considered. This *Sustainability* Special Issue aims to explore the complex relationship between renewable energy consumption and economic growth.

While previous studies have focused on the nexus between renewable energy and economic growth, many unanswered questions and implications still require a further assessment. This Special Issue aimed to increase the theoretical and empirical evidence on the effects of renewable energy development and deployment on economic growth. It is crucial to consider factors such as a country’s stage of development, capacity to absorb new technologies, and dependence on fossil fuel exports or imports to predict the economic results of the energy transition accurately.

This Special Issue contains 14 papers that cover a wide range of topics related to energy use efficiency in various countries and economic sectors. The articles include studies on adopting renewable energy sources, the impact of battery electric vehicles on greenhouse gas emissions in the European Union, the influence of philanthropy on eco-efficiency, and the impact of energy efficiency regulations on energy poverty. Other articles examine the role of economic complexity and export quality on the ecological footprint, the impact of institutional quality and financial development on reducing the ecological footprint without hindering economic growth, and the effect of the control of corruption and the income level on African environmental quality. The collection also includes studies on the race to zero emissions in MINT economies, the competitiveness of the cultural industry and its impact on Chinese economic growth, and the impact of educational levels on the energy–growth–environment nexus. The collection concludes with an extensive analysis of how renewable energy and CO_2 emissions contribute to economic growth and sustainability. The collection provides important insights into energy use efficiency theories, methods, and diverse applications.

In conclusion, this Special Issue served as a call to action for all stakeholders to contribute to the global energy transition by identifying and analyzing the effects of renewable energy consumption on economic growth. It inspires policymakers, researchers, and practitioners to embrace sustainable energy practices and support the development of measures that foster green growth. We hope that this Special Issue will serve as a valuable resource for anyone interested in the future of energy and its impact on the global economy.

José Alberto Fuinhas, Matheus Koengkan, and Renato Filipe de Barros Santiago
Editors

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Editorial

Renewable Energy Consumption and Economic Growth—Special Issue

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Short Biography of Authors

José Alberto Fuinhas is a renowned expert in the field of economics, holding a PhD in economics and serving as a professor of Monetary Economics and Intermediate Econometrics at the Faculty of Economics of the University of Coimbra in Portugal. With years of experience in his field, Professor Fuinhas is also an accomplished Macroeconomics, Energy Economics, and Environmental Economics researcher. He is affiliated with the prestigious CeBER-Centre for Business and Economics Research, where he conducts groundbreaking research and contributes to developing new theories and practices in his field.

Matheus Koengkan holds a PhD in Economics from the University of Évora and currently works as an Associate Researcher in Energy and Environmental Economics at the University of Coimbra Institute for Legal Research (UCILeR) in Coimbra, Portugal. He has a strong publication record, having authored three books on topics such as "Globalisation and Energy Transition in Latin America and the Caribbean: Economic Growth and Policy Implications", "Obesity Epidemic and the Environment: Latin America and the Caribbean Region", and "Physical Capital Development and Energy Transition in Latin America and the Caribbean". His research has also been published in prestigious WoS/Scopus-indexed journals.

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Article

The Impact of Energy Efficiency Regulations on Energy Poverty in Residential Dwellings in the Lisbon Metropolitan Area: An Empirical Investigation

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Abstract: This research examines the effect of energy efficiency regulations on reducing energy poverty in residential dwellings in 18 municipalities of the Lisbon metropolitan area from 2014 to 2020. In its empirical investigation, this study uses Ordinary Least Squares (OLS) with fixed effects and Moments Quantile Regression (MM-QR) methodologies. The results of the OLS and MM-QR models suggest that energy efficiency regulations for the residential sector positively impact energy poverty (101.9252). However, this result may suggest that the current regulations are not effectively mitigating energy poverty in Lisbon's metropolitan area and Portugal. This ineffectiveness could be due to economic, institutional, and behavioural barriers that impede the achievement of regulation policy goals. In maximising economic and social benefits, policymakers should consider implementing policies that link energy efficiency with clean energy generation in dwellings, promote economies of scale by recycling residuals from dwelling renovations, and provide clear guidance for materialising the energy strategy.

Keywords: econometrics; empirical; energy economics; energy efficiency; energy policy; energy poverty; energy regulation; European Union; Lisbon; policies; Portugal

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1. Introduction

Increasing energy demand and economic growth have led to significant environmental, fiscal, and social challenges. Globally, energy demand is rising steadily. The International Energy Agency (IEA) predicted that energy demand will reach 18,300 million tons of oil (Mtoe) by 2040 [1]. However, it can be said that the increase in energy demand is relatively small in developed countries, whereas it is growing rapidly in developing countries. Specifically, the future growth of energy demand will be driven by developing countries, particularly China and India, rather than by developed countries [2,3].

The building sector is one of the largest energy consumers, along with industry and transportation. From 2010 to 2021, building energy consumption rose from 115 exajoules to about 135 exajoules. The building sector accounted for 30% of total global final energy consumption and 27% of total energy sector emissions in 2021 [4]. In the European Union (EU), buildings are responsible for 40% of energy consumption and 36% of greenhouse gas emissions, mainly due to construction, use, renovation, and demolition [5]. The residential sector comprises a significant portion of the total energy consumption in the building sector. In 2020, residential energy consumption accounted for 27% of total energy consumption in the EU [6]. This energy consumption included all household energy, excluding energy for transportation, such as lighting, water heating, heating, cooling, and consumer products. It is expected that residential energy consumption will account for approximately 13% of the total energy consumption and grow by about 1.4% per year by 2040 [7]. Hence, improving energy efficiency in buildings is essential for reducing energy costs, decreasing environmental degradation, and advancing environmental development goals.

Several factors, such as geography, income level, building characteristics, energy policies, accessibility to energy resources, and energy infrastructure, influence the share of residential energy consumption. As a result, electricity consumption in the residential sector varies considerably across regions and countries [7–9]. In particular, the residential sector's energy consumption is lower in Southern European countries in the European Union (EU) region. Among these countries, Portugal merits closer examination due to its unique characteristics [10,11]. Firstly, Portugal's residential building stock is old, with roughly 15% of buildings constructed before 1945 and 70% before 1990. This has resulted in buildings that are not energy efficient, leading to high energy consumption to provide minimal comfort [10–12]. Secondly, the final electricity consumption for heating and cooling in the residential sector differs substantially among European countries, with buildings in Southern Europe, including Portugal, less able to withstand severe climate change than those in Northern Europe [11–13]. Thirdly, about 34% of buildings in Portugal require some intervention, and around 50% require extensive renovations to meet modern comfort and safety standards [14]. The building sector also accounts for 17% of Portugal's final electricity consumption, making it the third most energy-intensive sector [15]. Lastly, Portugal has some of Europe's most expensive power and gas prices [16]. Therefore, focusing on Portugal as a Southern European country may provide significant results in implementing efficient and effective energy efficiency policies.

The growing energy demand and poor thermal performance of residential structures can result in energy poverty, which is the inability of households to fulfil their energy needs. In the EU, many people face difficulty with heating or cooling their homes or paying their energy bills, leading to a prevalence of energy poverty [17]. In 2021, the average share of the population unable to keep their homes warm in 27 EU countries was around 7%, but in Portugal, the share was 16%, which was higher than the average [18]. Energy poverty and housing conditions are closely linked to various health outcomes, such as increased mortality risk, mental and physical health problems, and developmental issues in infants [19–23].

Residential buildings have the most significant potential for energy savings in Europe [24], with household energy savings accounting for the highest share (44%) compared to those of other sectors [25]. Moreover, with a significant proportion of buildings requiring intervention and extensive renovations to meet modern standards and an ageing residential building stock in Portugal, implementing energy efficiency policies in residential buildings can help increase efficiency and reduce energy consumption. This situation is why many EU energy efficiency policies focus on the residential sector to reduce energy consumption. Initially, the primary objective of building energy performance policies in the EU was to establish minimum standards, but over time, governments have introduced various additional tools, such as financial incentives, standards and codes, regulatory standards, and energy efficiency labels [9,10].

Previous studies have investigated various energy efficiency policies in EU countries. Some have reported the positive impact of financial incentives on energy efficiency [9,26,27]. Others have focused on the effects of tax incentives, subsidies, and energy efficiency [28,29]. However, some have found a weak or negative relationship between energy policy instruments and energy efficiency [30,31]. The results of studies on energy efficiency in residential properties have been mixed, with different energy policy tools producing different results in different EU countries. Despite this, well-designed and appropriate energy efficiency measures can increase energy efficiency and reduce energy consumption in the residential sector.

European countries should therefore implement effective energy policies to increase energy efficiency, considering their unique characteristics (e.g., building structure and climate) and requirements. However, although there have been several studies on energy efficiency measures in the residential sector across various European countries, few have focused on Portugal. This study aims to bridge this gap by examining the impact of energy efficiency regulation policies on energy poverty in residential dwellings in Portugal. This study focuses on 18 municipalities in the Lisbon metropolitan area from 2014 to 2020 and uses Ordinary Least Squares with fixed effects and Method of Moments Quantile Regression (MM-QR). In addition, other factors that may affect energy poverty, such as GDP, credit agreements, and the number of new family housing constructions and reconstructions, are also considered in the analysis.

Research on energy efficiency policies for residential dwellings is relatively new and innovative. This study contributes to the literature by conducting a new analysis of the impact of energy efficiency regulation policies on energy poverty in Portugal. This study also uses a macroeconomic approach and econometric methods to examine the relationship between energy poverty and energy policies for a group of municipalities in Portugal. To the best of the authors' knowledge, this study is the first to evaluate the efficiency of energy regulation policies on energy poverty in the Lisbon metropolitan area.

The findings of this study offer valuable information for governments and policymakers in their efforts to reduce energy consumption and increase energy efficiency in residential buildings. The investigation results provide evidence of the impact of energy regulation policies on energy poverty in residential properties in Portugal and may serve as a guide for other European countries with similar characteristics. Additionally, this study highlights the importance of evaluating the barriers to energy efficiency in the residential sector to ensure sustainable mechanisms for achieving energy and environmental sustainability.

The structure of this paper is as follows: Section 2 provides a review of the relevant literature, Section 3 outlines the data and methodology used in this study, Section 4 presents the empirical results, Section 5 discusses the main findings, and Section 6 draws conclusions and offers policy implications. Finally, Section 7 acknowledges this study's limitations and outlines potential avenues for future research.

2. Literature Review

In the European Union, no specific conditions are required to be considered energy-poor, but low household incomes, high energy prices, and an energy policy orientation can contribute to energy poverty [32]. The most common causes of energy poverty are low energy efficiency in buildings, low household income, and high energy prices [17]. On the other hand, factors such as low income, the age of buildings (as a proxy for energy efficiency), and climatology play a role in the phenomenon of "hidden energy poverty" or involuntary underconsumption [33].

Energy poverty can be tackled through numerous measures, including energy savings, renewable energy integration, consumer protection, financial assistance, and information provision [11]. Preventive measures are just as critical as financial aid based on income [32]. Regulatory policies addressing different objectives and requirements in various countries or policy contexts are being implemented at different levels, including sub-national and supra-national levels [34]. At the supra-national level, energy poverty is a priority issue, as seen in the "Clean Energy for all Europeans Package", leading to the implementation of national regulatory policies and the discussion of sub-national policies [35].

European countries with the lowest (below 5%) and highest (above 20%) rates of energy poverty have the fewest measures in place per country. Among these measures, regulatory actions and payment arrangements are the most common [35]. In the EU, countries either focus on energy efficiency measures or social policy to address energy poverty, depending on whether the primary cause is a low income and poverty or energy policy [36]. In EU Member States with lower incomes, shifting from an energy policy to a social policy approach can decrease the probability of energy poverty, although this effect is less pronounced when energy prices are high [32]. Higher energy efficiency in a country can help reduce energy poverty [37]. However, financial and policy awareness barriers in the private rental sector, which houses about 30% of European citizens, may impede the effectiveness of energy efficiency policies in addressing energy poverty [38]. Institutional measures to remove non-market barriers are necessary to facilitate more in-depth and quicker investment in building renovations, although they are not enough on their own [39].

Energy poverty is particularly prevalent in the Southern and Eastern European regions, and it has mainly been tackled through consumer protection and energy savings policies [11]. Most research on energy efficiency policies and poverty in Southern European countries focuses on Spain, where social policy is the predominant approach, followed by Greece and Italy, which have an energy-policy focus [36,40]. In Spain, the effects of municipality-level direct interventions aimed at increasing knowledge about energy efficiency or providing low-cost energy efficiency materials for reducing energy poverty in vulnerable groups vary depending on the type of social vulnerability and housing conditions [41]. Policy effectiveness is not well-documented in countries with an energy-policy focus (Greece and Italy). Policies aimed at reducing fuel poverty should consider building energy efficiency and be tailored to the specific needs of different municipalities within the same region [42].

Portugal's setting of lower-income, high prices, and energy policy orientation lead to energy poverty [32]. Previous studies have viewed Portugal's policy focus as mixed, with energy poverty being defined by energy law but based on socioeconomic criteria [36], resulting in a focus on consumer protection and energy savings [11]. Despite this, Portugal has relatively low scores in terms of access to energy justice and, more importantly, access to resources for energy efficiency investment in the face of energy poverty [35]. The recently implemented policies in Portugal primarily target households and are mandatory standard/information and financial policies. The social tariff for electricity and natural gas has a limited impact [15]. Although financial policies have the potential to support energy-efficient housing investment, income limitations prevent such investments [9]. However, the social tariff can also be counter-productive and trap households in energy poverty [11].

One of the most well-studied areas in the field of energy efficiency and energy poverty is the measurement of energy poverty, with ongoing efforts to develop new composite indicators to capture the multiple dimensions of the problem better and to ensure that policies are effective and just for all income groups [33,43].

Past studies have commonly examined the effectiveness of energy efficiency policies at the national or local level [44] or compared effects between countries [45]. However, there is limited research on the multi-level interconnectedness of policies and their differential effects on different regions and social groups within a country. Additionally, although there is a growing body of literature on the differential effects of energy efficiency policies on social groups [41], there is a lack of research on pathways to reduce inequalities resulting from these policies [39]. Finally, behaviour-informed interventions may be helpful, but there is a need for a better understanding of how changes in household behaviour can lead to increased energy efficiency in energy-poor households [46].

These research gaps may hinder the ability of policymakers to make informed decisions, especially given calls for local action [44] and the fact that different municipalities may have different energy poverty policies and that multi-level funding programs are increasing [35].

3. Data and Method

This section presents the variables and methodology utilised in this experimental study. Specifically, the variables are provided in Section 3.1, and an overview of the method approach is provided in Section 3.2.

3.1. Data

This experimental study selects eighteen municipalities from the Lisbon metropolitan area, including Alcochete, Almada, Amadora, Barreiro, Cascais, Lisbon, Loures, Mafra, Moita, Montijo, Odivelas, Oeiras, Palmela, Seixal, Sesimbra, Setúbal, Sintra, and Vila Franca de Xira (refer to Figure 1 below). This group of municipalities has not been previously explored in the literature, making this investigation novel and innovative compared to other studies.

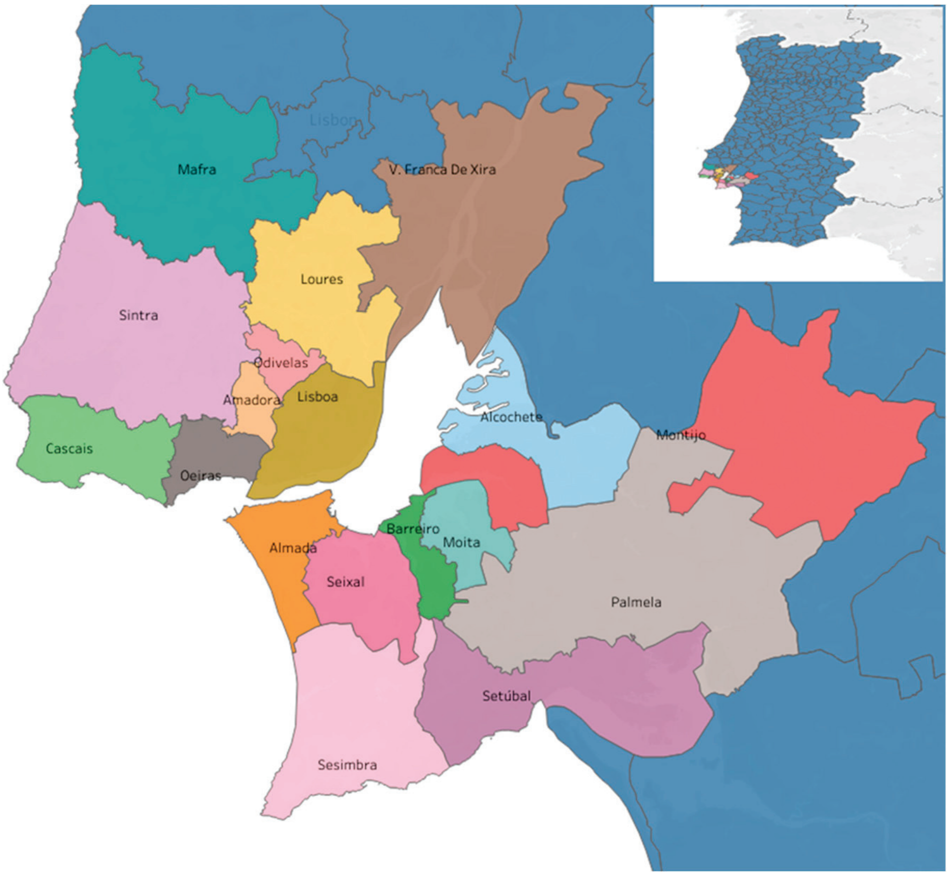

Figure 1. Municipalities of the Lisbon metropolitan area. The authors created this figure.

The Lisbon metropolitan area is a sub-region and NUT II region located in the centre-south of Portugal, with the capital city of Lisbon as its centre. It has a population of 2,871,133 inhabitants [47], making it the most populous region in the country with a population density of 957 inhabitants per km^2 and the largest urban area in Portugal with a total area of 3001 km^2, making it the fifth most extensive region in the country [47]. In addition, the Lisbon metropolitan area is the wealthiest region in Portugal, with a per capita GDP of EUR 29,291 in 2020 [48].

A concentration of shacks, slums, and buildings with high levels of deterioration characterises this region. This situation is due to a lack of investment by landlords. The freezing of rents was mainly caused during the Estado Novo dictatorship in Portugal (1933–1974) and by the low quality of construction in many dwellings [49]. These issues have contributed to energy poverty in this region. In addition, according to the Lisbon energy and environment agency (Lisboa-E.Nova), approximately 40% of Lisbon residents have admitted to feeling discomfort regarding the temperature inside their homes during winter, and 32% have admitted to feeling discomfort during summer [50].

In the Lisbon metropolitan area, the number of residences with low energy efficiency ratings, including D, E, and F efficiency certificate ratings, was 26,434 in 2014, reaching 20,460 in 2020 (see Figure 2 below).

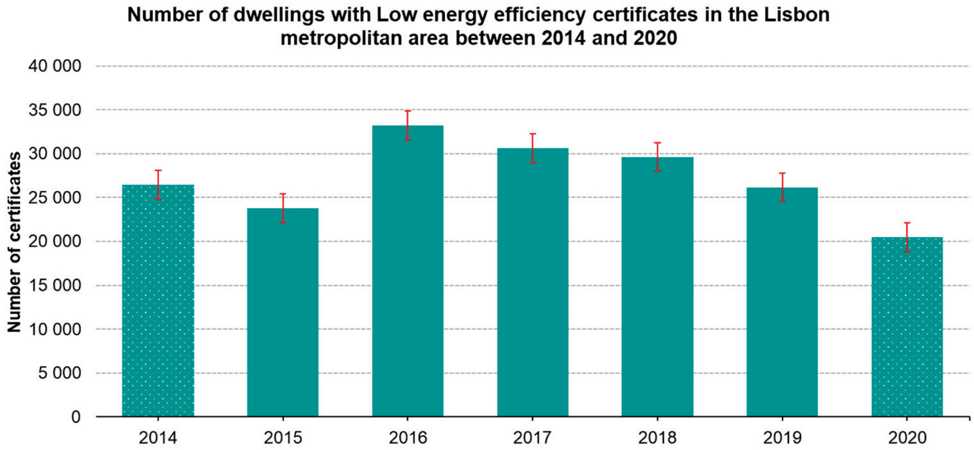

Figure 2. Number of dwellings with low energy efficiency certificates in the Lisbon metropolitan area between 2014 and 2020. This figure was based on a database from SCE [51].

In the Lisbon metropolitan area, the municipalities with a high concentration of residences with low energy efficiency ratings (e.g., D, E, and F) include Lisbon, Sintra, Oeiras, Amadora, Loures, Almada, and Seixal. For instance, in 2014, the municipality of Lisbon had 8118 homes with low energy efficiency ratings, which decreased to 5702 in 2020. On the other hand, the municipalities with low residences are Alcochete, Barreiro, Moita, Montijo, Mafra, Palmela, Odivelas, Vila Franca de Xira, Cascais, and Sesimbra. For example, the municipality of Alcochete had 228 homes with low energy efficiency ratings in 2014, which reduced to 98 in 2020 (as depicted in Figure 3 below).

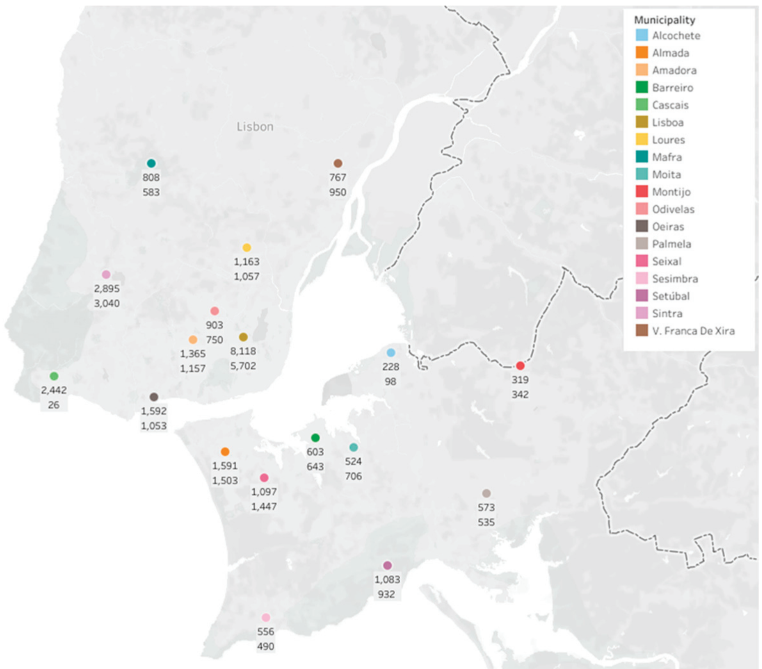

Figure 3. Number of dwellings with low energy efficiency certificates by municipality in the Lisbon metropolitan for the years 2014 and 2020. This figure was based on a database from SCE [51].

Therefore, the number of homes with low energy efficiency ratings decreased in 2017 due to the property boom in the Lisbon metropolitan area and Portugal as a whole, where the property market grew by 50% in the same year [52]. The property boom in the Lisbon metropolitan area allowed for the construction of new homes with high energy efficiency and the reconstruction and upgrading of older homes with low energy efficiency. As a result, the number of completed homes in the Lisbon metropolitan area for family housing rose from 1132 in 2014 to 3471 in 2020 (see Figure 4 below).

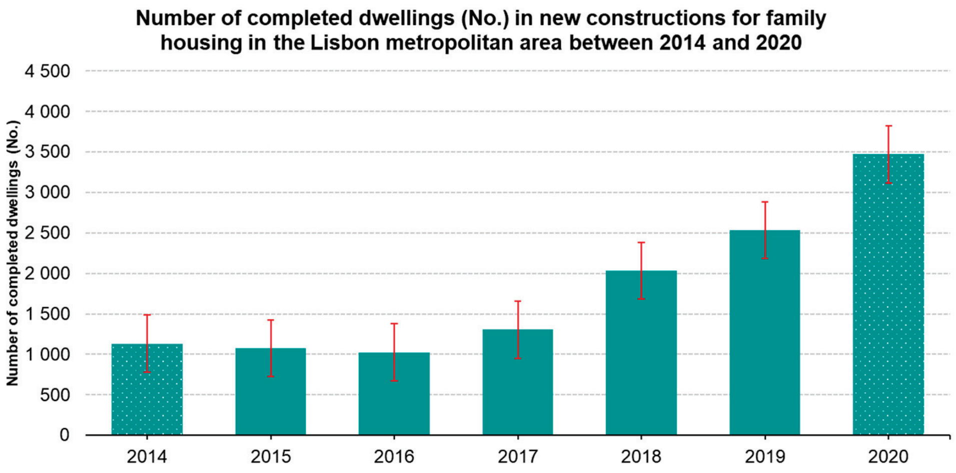

Figure 4. Number of completed dwellings (No.) in new constructions for family housing in the Lisbon metropolitan area between 2014 and 2020. This figure was based on a database from INE [53].

However, the ratio of restorations completed per 100 completed new constructions was 1.5 in 2014 and decreased to 0.5 in 2020 (see Figure 5 below).

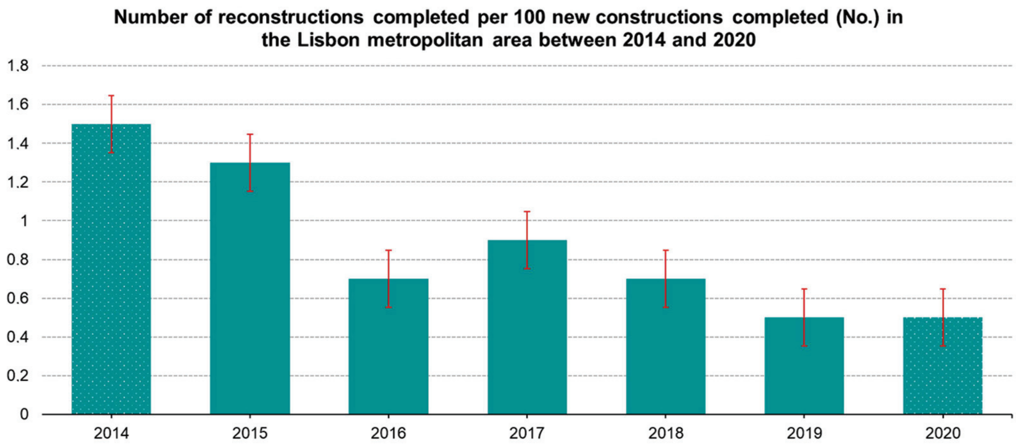

Figure 5. Number of reconstructions per 100 new constructions completed (No.) in the Lisbon metropolitan area between 2014 and 2020. This figure was based on a database from INE [54].

The Lisbon metropolitan area experienced growth from 2014 to 2019 due to tax benefits, tourism, attractive property prices, favourable interest rates, political stability, social peace, and a mild climate [55]. Portugal's rapid economic recovery also fuelled this growth after the Troika period between 2011 and 2014. The real Gross Domestic Product (GDP) growth rate was 0.795% in 2014, 1.79% in 2015, 2.02% in 2016, 3.51% in 2017, 2.85% in 2018, and 2.68% in 2019. However, the real GDP growth rate declined to −8.30% in 2020 due to the COVID-19 pandemic [56].

This growth positively impacted the Lisbon metropolitan area's GDP per capita (base = 2016). In 2014, it was EUR 27,831 (Euros) and increased to EUR 28,373 in 2015, EUR 28,876 in 2016, EUR 29,682 in 2017, EUR 30,770 in 2018, and EUR 32,029 in 2019. However, due to the COVID-19 pandemic, the Lisbon metropolitan area's GDP per capita (base = 2016) decreased to EUR 29,291 in 2020 (see Figure 6 below).

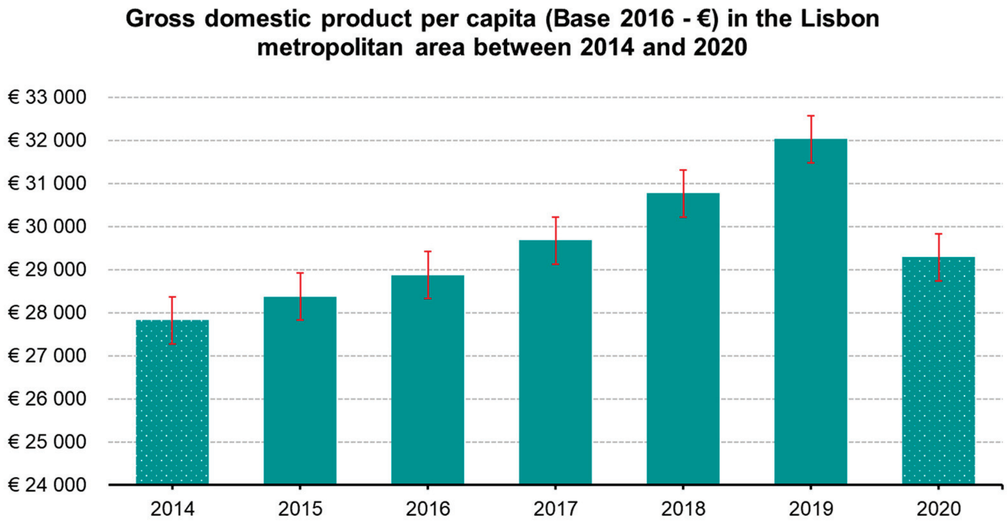

Figure 6. Gross domestic product per capita (base 2016—EUR) in the Lisbon metropolitan area between 2014 and 2020. This figure was based on a database from INE [48].

Therefore, the growth in GDP per capita between 2014 and 2019 enabled households in the Lisbon metropolitan area to purchase new, high-energy-efficient homes and renovate or upgrade existing low-energy-efficient homes [55]. Additionally, the increase in credit agreements for purchasing, constructing, and renovating primary or secondary residences during the economic growth of 2014–2019 also contributed to the property boom in Lisbon and throughout Portugal. For example, in the Lisbon metropolitan area, the value of credit agreements for the purchase, construction, and renovation of primary or secondary homes was EUR 35,105,803 (thousands) in 2014 and reached EUR 31,213,729 (thousands) by 2020 (as shown in Figure 7 below).

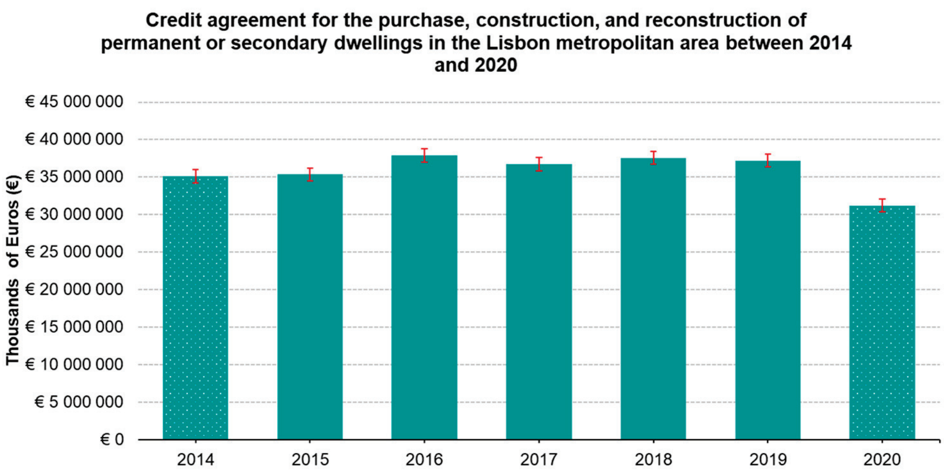

Figure 7. Credit agreements for purchasing, constructing and reconstructing permanent or secondary dwellings in the Lisbon metropolitan area between 2014 and 2020. This figure was based on a database from PORDATA [57].

Indeed, this increase was related to the reduction in housing credit interest rates. In 2014, this rate was 3.19%; in 2015, it was 2.38%; in 2016, it was 1.95%; in 2017, it was 1.65%; in 2018, it was 1.41%; in 2019, it was 1.22%; and in 2020, it reached 1.00% [58]. Another factor that might have contributed to the decrease in the number of dwellings with low energy efficiency ratings is the presence of energy efficiency policies for the residential sector. Energy efficiency regulation policies aimed at increasing energy efficiency and mitigating energy poverty were implemented in Portugal in 2006 [4].

There are five energy efficiency policies currently in force in Portugal. The first policy was implemented in 2006 with the regulation of Heating, Ventilation, and Air Conditioning (HVAC) systems in buildings. This regulation revised the national Regulation of Energy Systems for the Climatization of Buildings (RSECE) building code of 1998, which complemented the Portuguese implementation of the EU Directive 2002/91/CE on the Energy Performance of Buildings. This regulation set strict standards for HVAC energy use, including energy consumption limits for utilities of large buildings, indoor air quality, a legally fixed reference indoor air renovation rate, and limits on pollutant concentrations inside buildings. The second policy was implemented in 2007 with the Certificate of Energy Performance and Indoor Air Quality regulation. This regulation set strict standards for space cooling, heating, water heating, ventilation, and interior lighting. Finally, the third policy was implemented in 2008 with the National Energy Efficiency Action Plan. This regulation encompassed a set of measures aimed at increasing energy efficiency by about 10% of the final energy consumption, implementing the Energy Performance of Buildings Directive (EPBD) (Directive 2002/91/EU) [4].

The GDP per capita growth between 2014 and 2019 allowed households in the Lisbon metropolitan area to acquire new, high-energy-efficiency dwellings and to reconstruct and improve the energy efficiency of deteriorated dwellings [55]. The rapid economic growth during this period also increased credit agreements for the acquisition, construction, and reconstruction of permanent or secondary residences, contributing to the property boom in both the Lisbon metropolitan area and Portugal. In 2014, the value of credit agreements for the purchase, construction, and reconstruction of permanent or secondary dwellings in the Lisbon metropolitan area was EUR 35,105,803 (thousands), and this figure reached EUR 31,213,729 (thousands) in 2019 (as seen in Figure 7 above).

The reduction in housing credit interest rates was a factor in this increase. The interest rate dropped from 3.19% in 2014 to 1.00% in 2020 [58]. In addition, implementing energy efficiency policies for the residential sector in Portugal may have also contributed to the decrease in the number of dwellings with low energy efficiency ratings. Five energy efficiency policies are currently in force in Portugal. The first policy, implemented in 2006, revised the national Regulation of Energy Systems to the Climatization of Buildings and established strict standards for the energy use of HVAC systems in buildings. The second policy, implemented in 2007, established standards for space cooling, heating, water heating, ventilation, and interior lighting. The third policy, implemented in 2008, was the National Energy Efficiency Action Plan, which aimed to increase energy efficiency by 10% of the final energy consumption.

The fourth policy, the Energy Certification System of Buildings regulation, was implemented in 2013 and established strict standards for energy efficiency and using renewable energy systems in buildings. This regulation required minimum energy efficiency standards for HVAC systems, hot water preparation, lighting, and renewable energy and was implemented through Decree-Law No. 118/2013 of 20 August 2013. Finally, the fifth policy, the Environmental Fund program—Sustainable Buildings, was implemented in 2020 and provided funds to support more sustainable buildings through incentives for energy efficiency and decarbonisation [4]. This regulation followed Directive 2012/27/EU and later Directive 2018/844/EU, which set specific targets for reducing electricity consumption by 20% and 30% in 2020 and 2030, respectively, and aimed to accelerate the cost-effective renovation of existing buildings towards a decarbonised building stock by 2050 [59].

The period of this empirical investigation is from 2014 to 2020, as data for the energy efficiency certificate ratings (D, E, and F) and some other variables, such as the GDP per capita for all municipalities in the Lisbon metropolitan area and the number of completed homes in new constructions for family housing, are only available for this time frame. Table 1 provides evidence of the variables used in this empirical investigation.

Table 1. Data/variables and sources.

Acronym	Variables	Source	QR Codes
	Dependent variable		
ENERGY_POVERTY	Number of Houses with Low Energy Efficiency Ratings. This variable represents the count of dwellings with low energy efficiency certificates, such as ratings D, E, and F. This variable represents energy poverty.	SCE [51]	
	Independent variables		
GDP	GDP per municipality. It is calculated by multiplying the GDP (base 2016) of each region (25 NUTS III) by the ratio of the population of the municipality to the population of the region (25 NUTS III).	Constructed variable	
REGU_POLI	National Energy Efficiency Regulation Policies for the Residential Sector. This variable encompasses the policies of the (i) Heating, Ventilation, and Air Conditioning (HVAC) Systems in Buildings Regulation, (ii) Certificate of Energy Performance and Indoor Air Quality Regulation, (iii) National Energy Efficiency Action Plan, (iv) Energy Certification System of Buildings Regulation, and (v) Environmental Fund Program—Sustainable Buildings. These policies adopted different approaches, such as feed-in tariffs/premiums, grants and subsidies, loans, tax relief, taxes, funds to sub-national governments, infrastructure investments, advice and aid in implementation, information provision, comparison labels, endorsement labels, professional training and certification, auditing, codes and standards, monitoring, obligation schemes, and other mandatory requirements. The variable is constructed in an accumulated form, where each policy type implemented is represented by a cumulative value (e.g., 1, 1, 2, 2, 2, 3, 3) throughout its useful life or until it reaches its end.	IEA [60]	
HC	Credit Agreement for the Purchase, Construction, and Reconstruction of Primary or Secondary Residences or Rented Residences and Land Purchase for the Construction of Owner-Occupied Residences, in Euros.	PORDATA [57]	
CD	Number of Completed Family Homes in New Construction.	INE [53]	
CR	Number of completed renovations per 100 completed new constructions.	INE [54]	

This investigation aims to use low-energy-efficiency dwellings with certificates (e.g., D, E, and F) as a proxy for energy poverty (ENERGY_POVERTY) and a dependent variable. According to the European Commission, Directorate-General for Energy [61] and CEB [62], the concept of "energy poverty" lacks a universal definition but is generally understood to refer to households that expend an excessive portion of their income on energy or struggle to afford basic energy necessities. The causes of energy poverty can be multidimensional, stemming from low incomes, poor-quality homes, and energy-inefficient appliances.

Energy poverty is a term used to describe the inability of households to access affordable and reliable energy services. This can result from multidimensional factors, including low-quality housing and inefficient energy use. In particular, households may be considered to be energy inefficient if they live in a property with an energy efficiency rating of band D or below, and if their residual income after paying for heating falls below the official poverty line. One key factor contributing to energy poverty is the quality of a household's housing. In many cases, low-income households may be living in poorly insulated or otherwise inadequate properties that are expensive to heat and maintain. Additionally, the use of energy-inefficient appliances and equipment can further drive up energy costs, making it difficult for households to meet their basic energy needs [63]. This definition is also shared by ComAct [64], which defines energy poverty as dwellings with an Energy Performance Certificate (EPC) rating below D.

According to Energy Action Scotland [65], a house with an energy efficiency rating of D or below can be an indicator of potential energy poverty, and it should be used in conjunction with other measures, such as household income and energy bills, to assess the likelihood of energy poverty. Sánchez-Torija et al. [66] noted that the information contained in an energy efficiency certificate can be utilised to estimate the economic expenditure required to maintain a property in a comfortable state. This value is considered to be more reliable for calculating the energy poverty indicator as compared to the available data on actual expenditures.

Energy Performance Certificates (EPCs) show the energy efficiency of a house or dwelling. The certificates take into account various factors: (a) estimated energy costs; (b) the constructive characteristics of the property (e.g., whether the dwelling has a loft and/or wall insulation); (c) how sufficiently ventilated the building is; (d) the degree to which solar gains affect energy requirements; (e) the efficiency of and degree of control over the dwelling's heating system; (f) the extent to which energy may be required to cool the home; (g) the type of fuel(s) used to heat, cool, light, and (where applicable) ventilate the home; and (h) the presence of any renewable energy technologies. Moreover, this document or certificate also includes improvement measures to reduce consumption, such as installing double glazing, strengthening insulation or installing more efficient equipment [9].

Therefore, if households experience difficulties heating and cooling their home or accessing essential energy services, they rely on low-energy-efficiency products that consume non-renewable energy sources, such as fossil fuels. This situation is due to low income, high fuel prices, or a lack of investment in energy efficiency and is reflected in their Energy Performance Certificate (EPC) rating.

According to the UK Department of Energy and Climate Change [63], energy poverty in the UK can be measured through energy efficiency rate bands, where dwellings with rates between D and G are considered energy poverty, and those between A and C are not. In Portugal, 75% of buildings have poor energy performance, with EPC ratings below or equal to C (ranging from A+ to F) [67]. This study is the first in the literature to use this variable as a proxy for energy poverty, one of its innovative aspects. The decision was made to use Energy Performance Certificates (EPCs) as a proxy for energy poverty at the municipal level in Portugal, as no other indicators are available for this purpose. EPCs provide valuable information on the energy efficiency of buildings and can be used to identify potential areas for improvement. It is important to note, however, that EPCs do have limitations as a proxy for energy poverty. They only provide information on the energy efficiency of buildings and do not take into account other factors that can contribute to energy poverty, such as household income, energy prices, and the quality of heating systems. Therefore, although EPCs can be a valuable tool in assessing energy poverty, they should be used in conjunction with other indicators to provide a more comprehensive understanding of the issue.

The independent variable GDP is used in this study because the increase in income between 2014 and 2019 has allowed households to purchase high-energy-efficiency dwellings, reconstruct and retrofit low-energy-efficiency dwellings, and purchase appliances and equipment that consume green energy. This result is in line with the views of CEB [62], which posits that a rising income can help mitigate energy poverty in the long run.

The independent variable REGU_POLI is used because national energy efficiency regulations for the residential sector are expected to encourage increased energy efficiency, improved indoor air quality, and reduced energy poverty through increased space cooling, space heating, water heating, ventilation, and lighting efficiency. The literature provides evidence that these policies can increase energy efficiency in Portugal [9,10]. However, this study chooses to use national-level policies because Portuguese municipalities do not have the autonomy to create their energy efficiency regulations [10].

The independent variable HC is used because housing credit agreements allow households to purchase high-energy-efficiency dwellings and appliances, reconstruct low-energy-efficiency dwellings, and adopt renewable energy technologies. This case increases energy efficiency and reduces energy consumption and bills. In addition, the literature provides evidence that this variable helps increase the number of high-energy-efficiency dwellings in Portugal [10].

The independent variables CD and CR are used because the increase in income and the availability of housing credit allow households to purchase high-energy-efficiency dwellings, reconstruct low-energy-efficiency dwellings, and improve space cooling, space heating, water heating, ventilation, and lighting efficiency. New buildings in Portugal have been required to have high energy efficiency standards and certificates since July 2008, and existing buildings have been required to have valid certificates and high energy efficiency standards since 2009 [9]. In addition, Decree-Law No. 118/2013 of 20 August 2013 made it mandatory for energy efficiency certificates to be included in sales, rental, or lease contracts. This decree was updated to follow Directive (2012/27/EU), which set specific energy consumption targets for 2020 and 2030 (20% and 30% reduction, respectively), and was further updated by Directive (2018/844/EU), which aims for a decarbonised building stock by 2050 [59]. However, the literature has not used these variables to explain energy poverty.

3.2. Method

A subsequent methodological framework is adopted to assess the potential impact of energy efficiency policies on energy poverty in eighteen municipalities within the Lisbon metropolitan region, as illustrated in Figure 8 below.

After presenting the methodological framework for this research, it is crucial to present the preliminary tests, the model estimates, and the post-evaluation test.

3.2.1. Preliminary Tests

Before applying OLS regression with fixed effects and MM-QR estimators, it is crucial to conduct preliminary tests to determine the properties of the variables used in the econometric model. These tests aid in choosing the most suitable estimator for the model under consideration. Table 2 below shows the preliminary tests used and their purpose and commands in Stata 17.0 to facilitate their reapplication by other authors.

Table 2. Preliminary tests.

Test	Purpose	Stata Command
Descriptive statistics	Assess the statistical properties of the variables to be used in the econometric model.	*sum*
Shapiro–Francia test [68]	Determine if the variables in the econometric model follow a normal distribution. This evaluation is performed through a normality test, where the null hypothesis is that the data are normally distributed.	*sfrancia*
Shapiro–Wilk test [69]	Assess the normality of the variables in the econometric model. The null hypothesis for this test is that the data follow a normal distribution.	*swilk*

Table 2. *Cont.*

Test	Purpose	Stata Command
Variance inflation factor (VIF) test [70]	Determine the existence of multicollinearity among the variables.	*vif*
Cross-sectional dependence (CSD) test [71]	Assess the existence of cross-sectional dependence among the variables. This test assumes no interdependence between the units, and the null hypothesis is that the units are uncorrelated.	*xtcd, resid*
Fisher-type unit-root test [72]	Assess the presence of unit roots in the variables using the appropriate statistical tests. The null hypothesis, in this case, is that all panels in the data contain at least one unit root, indicating that the series is non-stationary.	*xtunitroot fisher with option pperron lags (1)* *xtunitroot fisher with option pperron lags(1) trend*
Kao cointegration test [73]	Examine the presence of cointegration among the non-stationary variables. The null hypothesis in this test is the absence of cointegration between the non-stationary variables.	*xtcointtest kao*
Hausman test [74]	Assess the presence of heterogeneity in the panel, explicitly examining if the panel has random effects (RE) or fixed effects (FE). The null hypothesis in this test is that the random effects estimator is both consistent and more efficient than the fixed effects estimator.	*hausman*

Notes: This table was created by the authors.

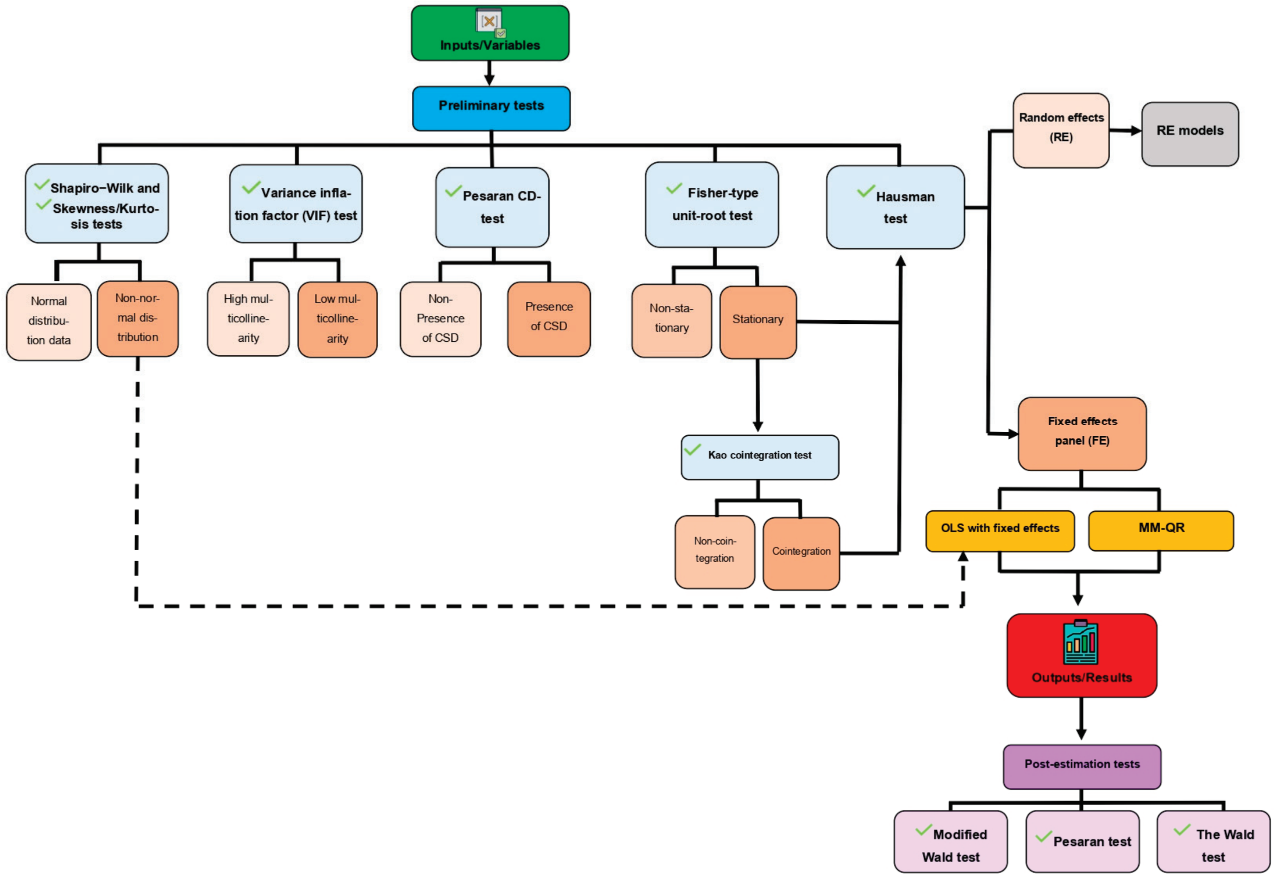

Figure 8. Methodology framework. The authors created this figure.

3.2.2. Ordinary Least Squares (OLS) with Fixed Effects

In this study, Ordinary Least Squares (OLS) regression is performed with fixed effects. This method is selected because it enables the determination of the slope and intercept for a set of observations. Additionally, OLS with a fixed effects estimator uses the conditional mean function to estimate the mean response for the fixed predictors [75]. The general equation for OLS with a fixed effects estimator is as follows:

$$ENERGY\_PORVERTY_{it} = k_{0i} + k_1 GDP_{it} + k_2 REGU\_POLI_{it} + k_3 HC_{it} + k_4 CD_{it} + k_5 CR_{it} + \varepsilon_{it} \quad (1)$$

where k_{0i} is the intercept, k is the value of fixed covariates being fitted to predict the dependent variable $ENERGY\_POVERTY_{it}$, ε_i is the error term, and each variable enters regression for each municipality i at year t. According to Fuinhas et al. [76], OLS with a fixed effects estimator evidences the relationship between the covariates, but it cannot be extended to non-central locations in the case of shapeshifts.

This empirical investigation chooses to calculate OLS with fixed effects with robust standard errors (FE Robust), and OLS with fixed effects with Driscoll–Kraay standard errors (FE D.-K). In the case of this research, FE D.-K is used due to the presence of heteroskedasticity and cross-sectional dependence (spatial dependence or spatial regimes) [77]. Table 3 below shows the commands to compute the OLS FE, OLS FE Robust, and OLS FE D.-K. estimators in Stata 17.0.

Table 3. Stata commands for OLS estimators.

Estimator	Stata Command
OLS with fixed effects (FE)	*xtreg a, b, c . . . , fe*
OLS with fixed effects with robust standard errors (FE Robust)	*xtreg a, b, c . . . , fe robust*
OLS with fixed effects with Driscoll–Kraay standard errors (FE D.-K)	*xtscc a, b, c . . . , fe lag (1)*

Notes: This table was created by the authors.

3.2.3. Method of Moments Quantile Regression (MM-QR)

The estimator of the MM-QR model was calculated to recognise the robustness of the OLS estimation results. Therefore, Machado and Silva [78] advised using MM-QR with a fixed effects estimator. MM-QR with a fixed effects estimator differs from the traditional method introduced by Koenker and Bassett [79] in that it relies on conditional means. This estimator model was discussed in the papers by Machado and Silva [78], Canay [80], and Koenker [81], where the authors concluded that this estimator model could capture unobserved distribution heterogeneity across countries within a panel.

The model estimation proposed by Machado and Silva [78] uses the conditional scaling function to estimate the regression quantiles. In addition, differences can be observed through the estimated parameters for each quantile. According to studies by Machado and Silva [78] and Koengkan et al. [82], this method presents several advantages compared to other techniques. For instance, it offers insights into how the explanatory variables impact the whole conditional distribution, enabling the use of methods that are only suitable for estimating conditional means. Moreover, this method can distinguish individual effects in panel data and offer information on how regressors affect the conditional distribution. It also allows for uncrossed estimation of regression quantiles. Koengkan et al. [82] also highlighted that this method is versatile, capable of providing estimates in the presence of cross-sectional models with endogenous variables, can accurately identify conditional means under exogeneity, and can determine the structural function of quantiles. MM-QR estimation is based on the following general equation.

$$x_{it} = a_i + e'_{it} k + \left(\delta_i + b'_{it} \gamma\right) U_{it}, \quad (2)$$

where $\{(x_{it}, e'_{it})'\}$ from a panel of n individuals $i = 1, \ldots$, n over T time periods with $P\{\delta_i + b'_{it}\gamma > 0\} = 1$. Furthermore, the parameters (α_1, δ_i), $i = 1, \ldots, n$, capture the individual i fixed effects, and b is a k-vector of known differentiable (with probability 1) transformations of the components of e with element l given by $b_l = b(e)$, $l = 1, \ldots, k$. The sequence $\{e_{it}\}$ is *i.i.d.* for any fixed i and independent across t. U_{it} is *i.i.d.* (across i and t), statistically independent of e_{it}, and normalised to satisfy the moment condition $E(U) = 0 \wedge E(|U|) = 1$. The MM-QR model is estimated using the 25th, 50th, 75th, and 90th quantiles in this study. Moreover, the results of the 50th quantile are similar to those using OLS with fixed effects [75]. The commands used to compute the MM-QR estimator in Stata 17.0 are presented in Table 4.

Table 4. Stata commands quantiles estimator.

Estimator	Stata Command
MM-QR estimator	*xtqreg a, b, c..., i (municipality) quantile (0.25 0.50 0.75 0.90) ls*

Notes: This table was created by the authors.

3.2.4. Post-Estimation Tests

This study conducts post-estimation tests after conducting OLS regressions with fixed effects and MM-QR model estimators. These tests aim to evaluate the characteristics of the estimated models. For ease of reapplication, Table 5 lists the post-estimation tests used, their purpose, and the corresponding commands in Stata 17.0.

Table 5. Description of post-estimation tests.

Test	Purpose	Stata Command
	OLS with fixed effects model	
Modified Wald test [83]	Determine the existence of group-wise heteroscedasticity. This test assumes homoscedasticity as the null hypothesis.	*xttest3*
Pesaran test [71]	Assess the existence of contemporaneous correlations among cross-sectional observations. In this test, the null hypothesis assumes that the residuals are uncorrelated and have a normal distribution.	*xtcsd, pesaran abs*
	OLS with fixed effects and MM-QR models	
Wald test [84]	Evaluate the global significance of the estimated models. In this test, the null hypothesis is that none of the coefficients is significantly different from zero.	*testparm*

Notes: This table was created by the authors.

4. Empirical Results

This section shows the results of the preliminary tests, OLS with fixed effects, MM-QR models, and post-estimation tests.

4.1. Results of Preliminary Tests

The initial step in conducting the preliminary tests involves examining the statistical properties of the variables that are included in the econometric model. This result can be achieved by calculating the descriptive statistics of the variables. Table 6 below displays the descriptive statistics of the variables in levels and first-differences.

Table 6. Descriptive statistics of variables.

Variables	Obs	Mean	Std. Dev.	Min	Max
ENERGY_POVERTY	126	595.881	719.3409	21	5064
GDP	126	1.11×10^{13}	4.62×10^{13}	416,737.8	2.26×10^{14}
REGU_POLI	126	16.85714	0.99369	15	18
HC	126	1,746,426	3,798,354	0	1.95×10^{7}
CD	126	99.23492	93.25564	1	481.6667
CR	126	1.4875	4.3924	−1.1333	33.3
D_ENERGY_POVERTY	108	−10.2963	400.837	−1430	2888
D_GDP	108	4.49×10^{11}	1.93×10^{12}	15,759.71	1.04×10^{13}
D_REGU_POLI	108	−323,677.4	1,954,231	-1.95×10^{7}	2,360,673
D_HC	108	0.3333	0.7488	−1	1
D_CD	108	16.2370	49.1361	−157	250
D_CR	108	−0.0960	3.6353	−20	15.2

Notes: "D" denotes variables in the first-differences.

The descriptive statistics of the variables indicate that the panel data in this study are highly balanced, where all variables have the same number of observations. A highly balanced panel is required to perform some preliminary tests developed for the panel data (e.g., the cross-sectional dependence (CSD) test, the panel unit root test, and the Westerlund panel data cointegration test, among others). Furthermore, the presence of heteroskedasticity in the model can be indicated through visual analysis. However, this phenomenon can be confirmed by performing the modified Wald test.

The second step in performing the preliminary tests is identifying the presence of normal distributions in the variables in levels and first-differences. For this purpose, the Shapiro–Francia and Shapiro–Wilk tests, which verify the normal distributions of the variables, are used. Table 7 below shows the results of the normal distribution tests.

Table 7. Normal distribution tests.

Variables	Shapiro–Francia Test		Shapiro–Wilk Test		Obs
	Statistic		Statistic		
ENERGY_POVERTY	0.5954	***	0.6038	***	126
GDP	0.2409	***	0.2455	***	126
REGU_POLI	0.9845	*	0.9796	*	126
HC	0.4127	***	0.4014	***	126
CD	0.8392	***	0.8341	***	126
CR	0.5393	***	0.5484	***	126
D_ENERGY_POVERTY	0.6099	***	0.6322	***	108
D_GDP	0.2354	***	0.2419	***	108
D_REGU_POLI	0.9980	*	0.9839	*	108
D_HC	0.2126	***	0.2297	***	108
D_CD	0.9086	***	0.9220	***	108
D_CR	0.6786	***	0.6982	***	108

Notes: ***, * denotes statistically significant at (1%) and (10%) levels; "D" denotes variables in first-differences.

The results above indicate that all variables in levels and first-differences used are not normally distributed, where the null hypothesis of both tests can be rejected. Moreover, the non-normally distributed variable is a requirement for the realisation of MM-QR model regression.

The third step in realising the preliminary tests is to identify the level of multicollinearity between the variables in the model. Therefore, the VIF test is computed in this investigation to accomplish this verification. Table 8 below shows the results of the VIF test.

Table 8. VIF test.

VIF Test	
Mean VIF:	1.53

The VIF test results indicate no concern for multicollinearity in the econometric model, as the mean VIF values are low, which are below the commonly accepted benchmark of six [82]. Therefore, the fourth step in conducting the preliminary tests involves identifying the presence of cross-sectional dependence in the variables in levels and first-differences. The results of the CSD test can be seen in Table 9.

Table 9. CSD-test.

Variables	CD-Test			Obs
ENERGY_POVERTY	26.02		***	126
GDP	32.71		***	126
REGU_POLI	29.82		***	126
HC	32.73		***	126
CD	18.73		***	126
CR		N.A		126
D_ENERGY_POVERTY	26.98		***	108
D_GDP	29.17		***	108
D_REGU_POLI	30.30		***	108
D_HC	25.55		***	108
D_CD	8.51		***	108
D_CR		N.A		108

Notes: *** denotes statistical significance at (1%) level. N.A denotes unavailable; "D" denotes variables in first-differences.

The results in the table above suggest that all variables in levels and first-differences have *p*-values significant at the 1% level, indicating that the null hypothesis is not rejected and that cross-sectional dependence (CSD) is present in all variables. However, the CSD test does not show any results for the variable CR. The fifth step in conducting the preliminary tests involves determining the presence of unit roots in the variables. This result is achieved by using the Fisher-type unit-root test. The results of this test are displayed in Table 10 below.

The results indicate that the variables ENERGY_POVERTY, GDP, REGU_POLI, and DR exhibit boundary behaviour between I(0) and I(1), and the variables HC and CD are stationary. In the first-difference, the test indicates that the variables ENERGY_POVERTY, CD, and CR are stationary, whereas the variables GDP, REGU_POLI, and HC are non-stationary. In the presence of non-stationary variables, it is necessary to check for cointegration. Additionally, this study chooses not to utilise the Pesaran Unit Root test (CIPS) and Modified CADF tests due to their requirement of a minimum of eight observations by crosses, one lag, and the inclusion of both constant and trend terms, which was not feasible for this analysis. Hence, the sixth step in the preliminary tests involves examining the cointegration between the non-stationary variables using the Kao cointegration test. This investigation chooses not to utilise the Westerlund and Pedroni cointegration tests due to their requirement of a minimum of 14 observations by crosses, which was not feasible for this analysis. The results of the test are presented in Table 11.

The null hypothesis of no cointegration is rejected. This is true for the five tests' statistics reported in the tables and provides strong evidence that the non-stationary variables are cointegrated in all panels. The seventh step in carrying out the preliminary tests is to identify the nature of the panel data regarding whether it has random or fixed effects. The Hausman test is used to determine this. The results from the Hausman test are shown in Table 12 below.

Table 10. Fisher-type unit-root test.

Variables	Fisher-Type Unit-Root Test (Based on Phillips–Perron Test)				
		Without Trend		With Trend	
	Lags	Inverse Normal (Z)		Inverse Normal (Z)	
ENERGY_POVERTY	0	−2.4727	**	2.7691	
	1	−2.3429	**	3.5231	
GDP	0	10.0311		−1.5948	**
	1	9.8403		−2.7589	**
REGU_POLI	0	−4.5526	***	10.3190	
	1	−5.4849	***	11.6394	
HC	0	7.1009	***	6.3607	***
	1	8.5837	***	−3.1858	***
CD	0	2.0857		−2.2404	**
	1	2.1062		−3.1858	***
CR	0	−7.2546	***	−6.7405	***
	1	−7.6648	***	−8.0785	***
D_ENERGY_POVERTY	0	−7.5856	***	−20.4524	***
	1	−7.1415	***	−21.4559	***
D_GDP	0	−0.6467		8.8235	
	1	−0.7081		9.9780	
D_REGU_POLI	0	3.9894		1.7041	
	1	5.3371		2.1048	
D_HC	0	4.9910		7.5246	
	1	3.0367		7.7575	
D_CD	0	−6.6924	***	−2.9975	***
	1	−7.5698	***	−4.7122	***
D_CR	0	−10.4268	***	−4.7763	***
	1	−11.3560	***	−5.5251	***

Notes: ***, ** denotes statistically significant at (1%) and (5%) levels; "D" denotes variables in first-differences.

Table 11. Kao cointegration test.

Kao Test for Cointegration	Statistic	*p*-Value	
Modified Dickey–Fuller t	2.7635	0.0029	***
Dickey–Fuller t	2.6313	0.0043	***
Augmented Dickey–Fuller t	−2.2554	0.0121	**
Unadjusted modified Dickey–Fuller t	2.6740	0.0037	***
Unadjusted Dickey–Fuller t	2.4911	0.0064	***

Notes: ***, ** denotes statistically significant at (1%) and (5%) levels.

Table 12. Hausman test.

Models	Chi2(2/3)	Prob.	
Model I	45.64	0.0000	***

Notes: *** denotes statistically significant at (1%) level.

The results in the table above indicate the rejection of the null hypotheses; thus, the model has fixed effects. Therefore, in this investigation, the FE estimator is used.

4.2. Results of OLS with Fixed Effects and MM-QR

After conducting the preliminary tests, OLS with fixed effects and MM-QR regressions can be performed. As previously mentioned, this investigation uses OLS with fixed effects with robust standard errors (FE Robust) and OLS with fixed effects with Driscoll–Kraay standard errors (FE D.-K). The FE D.-K method is chosen due to heteroskedasticity (seen in

Table 2) and cross-sectional dependence (seen in Table 5). In addition, MM-QR based on the 25th, 50th, 75th, and 90th quantiles is also used to ensure the robustness of the OLS results. The 25th, 50th, 75th, and 90th quantiles are used to identify the effect of the independent variables on the dependent variables. Moreover, this empirical investigation opts to use the variables in levels instead of first-differences due to the loss of observations, where a panel with variables in first-differences drops from 126 observations to 108. This reduction impacts the results of the estimations. Table 13 below presents the results of the OLS with fixed effects and MM-QR regressions.

Table 13. Results of OLS with fixed effects and MM-QR.

Independent Variables	Main Model			Robustness Check			
	OLS with Fixed Effects			MM-QR			
	Dependent Variable (ENERGY_POVERTY)			Dependent Variable (ENERGY_POVERTY)			
	Estimators			Quantiles			
	FE	FE Robust	FE. D.-K	0.25Q	0.5Q	0.75Q	0.90Q
GDP	−0.0002 ***	***	**	-1.10×10^{-11}	-9.52×10^{-12}	-8.40×10^{-1}	-6.88×10^{-12}
REGU_POLI	101.9252 **	***	***	110.5071 ***	100.2995 ***	92.8477 *	82.6898
HC	0.0001 ***	***	***	0.0001 **	0.0001 **	0.0001 **	0.0001 *
CD	−0.8075 ***	**	*	−0.5744	−0.8516 **	−1.0540	−1.3298
CR	−41.2240 ***	***	*	22.8081	−44.71244 *	60.7030	82.5007
Constant	-1.1×10^{3} ***	***	***	N.A	N.A	N.A	N.A
Obs	126	126	126	126	126	126	126

Notes: ***, **, * denote statistically significant at (1%), (5%), and (10%) levels, respectively. N.A denotes unavailable.

The OLS regression model indicates that the independent variable GDP has a negative impact (−0.0002) on the dependent variable ENERGY_POVERTY. Conversely, the independent variable REGU_POLICY has a positive impact (101.9252) on the dependent variable. Additionally, the independent variable HC has a positive impact (0.0001), whereas the independent variables CD and CR have negative impacts of −0.8075 and −41.2240, respectively, on the dependent variable, ENERGY_POVERTY.

The MM-QR regression model demonstrates that the independent variable REGU_POLI has a positive effect on the dependent variable at the 25th, 50th, and 75th quantiles. The independent variable HC also exhibits a positive influence on the dependent variable across all quantiles. Conversely, the independent variables CD and CR have a negative impact on the dependent variable in the 50th quantile. Figure 9 below summarises the impact of the independent variables on the dependent variables.

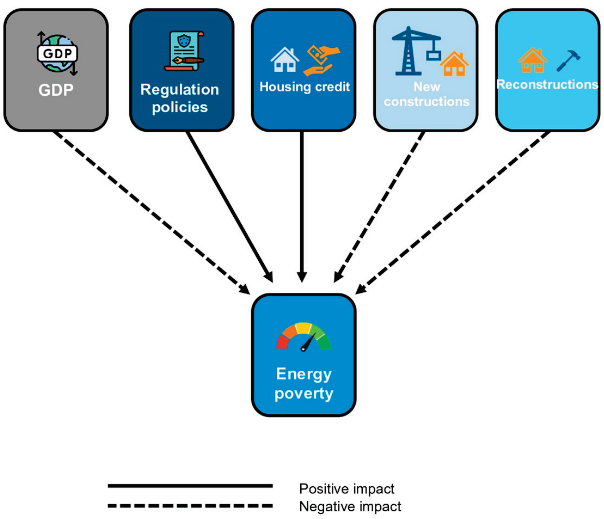

Figure 9. Summary of the effects of independent variables on the dependent ones.

4.3. Results of Post-Estimation Tests

After conducting regression models, it is necessary to perform post-estimation tests. These tests verify the presence of group-wise heteroscedasticity and contemporaneous correlations among the cross-sections of the OLS model. They also give the overall significance of the results in the OLS with fixed effects and MM-QR models. The results of the post-estimation tests are shown in Table 14 below.

Table 14. Post-estimation tests.

OLS with Fixed Effects			MM-QR			
Modified Wald Test	Pesaran Test	The Wald Test	The Wald Test			
			0.25Q	0.50Q	0.75Q	0.90Q
chi2 (18) = 1375.63 ***	11.859 ***	F(4103) = 17.05 ***	chi2(4) = 13.95 ***	chi2(4) = 12.14 ***	chi2(4) = 7.53 **	chi2(4) = 4.98 *

Notes: ***, **, * denote statistically significant at (1%), (5%), and (10%) levels, respectively.

The results of the Modified Wald test indicate the presence of group-wise heteroskedasticity in the OLS with a fixed effects model, and the null hypothesis can be rejected. The Pesaran test shows the contemporaneous correlation among the cross-sections, and the null hypothesis can be rejected in the OLS with a fixed effects model. Additionally, the Wald test suggests that the hypothesis cannot be rejected, indicating that time-fixed effects are necessary for both models.

5. Discussion

This section presents possible explanations for the results found in Table 13 above, which point to a positive answer to the research question and provide valuable insights on the control variables. First, the independent variable, GDP, negatively impacts the dependent variable, ENERY_POVERTY, by a factor of −0.0002. This finding means that, as GDP becomes higher, the energy poverty in the Lisbon metropolitan area becomes lower, but the impact is not very significant.

One reason for the low capacity of income to mitigate energy poverty in the Lisbon metropolitan area could be due to the high cost of living caused by factors such as tourism, property speculation, and a housing shortage, which have led to a property boom [85]. The monthly cost of living in the Lisbon metropolitan area for a single person is estimated to be EUR 1846 [86], whereas, for a family of four, it is around EUR 3477 [86]. Moreover, the minimum wage in Portugal is EUR 705 per month [87], which is not enough to cover these costs. Furthermore, a quarter of workers only earn the minimum wage, making it difficult for them to access credit to improve the energy efficiency of their homes, purchase energy-efficient appliances, or acquire green energy technologies.

Households and individuals are faced with a difficult choice between paying for basic necessities, such as rent, food, and energy bills, and improving the energy efficiency of their homes. An inquiry by the Lisbon Energy and Environment Agency found that 40% of Lisbon residents admitted to discomfort with the temperature in their homes during winter, and 32% reported discomfort during summer [50].

Research by Fuinhas et al. [76] found evidence that a low income contributes to energy poverty. The authors found that a low income in Portugal limits investment in energy-efficient homes, causing consumers to choose lower-efficiency homes with low-energy-efficiency performance certificates (e.g., D, E, and F). The high prices of new homes with high energy efficiency standards, caused by factors such as tourism, property speculation, and housing shortages, also make it difficult for low-income households to purchase these homes.

The independent variable REGU_POLICY has a positive impact of 101.9252 on the dependent variable ENERY_POVERTY, i.e., the variable REGU_POLICY increases energy poverty in the Lisbon metropolitan area, and the impact is very high. Indeed, this result could indicate that the implemented regulation policies are inefficient in mitigating energy poverty in the Lisbon metropolitan area and Portugal as a whole. Therefore, this inefficiency could be related to barriers such as economic, institutional, and behavioural ones. These barriers widely limit the achievement of regulation policy goals [88]. Economic barriers refer to difficulties in accessing credit to improve the energy efficiency performance in dwellings and buildings, insufficient and unstable available funding, high risk for investors and financial institutions, building stock characteristics, and split incentives [88–90]. In Portugal, accessing government support to improve energy efficiency in dwellings and buildings is very bureaucratic, limited, and insufficient. For example, "*Programa de Apoio Edifícios + Sustentáveis* 2021" (Sustainable Buildings Support Programme 2021) has a contribution rate of eligible expenditures supported by the programme between 65–85%, and a limit of eligible expenditures supports a value until EUR 4500 (Euros) [91]. In the case of "*Programa Casa Eficiente 2020*" (Efficient House 2020 Programme), the programme only applies in the case of interventions for replacing existing household appliances. Individual expenditure cannot exceed 15% of the total eligible investment amount of the operation [92]. These offered values are shallow and insufficient for households and individuals with low incomes, budgets, and credit restrictions that intend to improve the energy efficiency performance of their dwelling.

Institutional barriers are related to complex/inadequate regulatory procedures, conflicting guidelines in the governance structure, political obstruction, and a lack of policy coordination [88,93,94]. For example, in Portugal, the complexity of regulatory procedures and their bureaucracies make it difficult for individuals to receive government support to improve the energy efficiency of their houses. In addition, the change in political power in Portugal and Brussels, as well as in the European Parliament and the Council of the European Union, where all directives related to energy efficiency in dwellings and buildings in the European Union are elaborated, impacts the efficiency of regulation policies. Moreover, corruption and conflicts of interest in Portugal, Brussels, the European Parliament, and the Council of the European Union contribute to this inefficiency. Indeed, institutional barriers are a significant limitation to the diffusion and promotion of energy efficiency and renewable energy technologies, undermining the success of government regulation [88,95].

Behavioural barriers are related to the misperception of economic returns, household and individuals consumption practices, limited trust in local and national public administration, different purchasing choices, and financial restrictions due to low incomes [88,89]. According to Al-addous and Albatayneh [96], those barriers are linked to knowledge gaps affecting energy efficiency improvement and energy-efficient and green energy technologies implementation. In the Lisbon metropolitan area and Portugal as a whole, low incomes, high living costs and taxes, and the high level of demographic ageing have reduced the awareness of households and individuals on energy savings and have limited the diffusion of a culture of saving both at the individual and community level. In the literature, regulation policies have been incapable of mitigating the number of dwellings and buildings with low energy efficiency (e.g., D, E, and F) in Portugal as a whole [9,10].

The independent variable HC has a positive impact of 0.0001 on the dependent variable ENERY_POVERTY, meaning that HC increases energy poverty in the Lisbon metropolitan area. However, the impact is small. The cause of this impact could be the difficulty in accessing housing credit due to a budget constraint caused by low household and individual incomes, as suggested by Fuinhas et al. [76]. Another factor that may contribute to this result is (i) the bureaucracy involved in housing credit agreements, (ii) the expenses and taxes associated with a mortgage, (iii) the high down payment required, which can be 10–20% of the property value, and (iv) high property prices due to the tourism boom, property speculation, and housing shortages, which make it difficult for low-income households and individuals to purchase a dwelling with high energy efficiency standards in the Lisbon metropolitan area. Another important factor may be the lack of information about alternative housing credit and government support, such as the "*Programa Casa Eficiente 2020*" (Efficient House 2020 Programme) [92] and the "*Programa de Apoio Edifícios + Sustentáveis 2021*" (Sustainable Buildings Support Programme 2021) [91], which can help in the reconstruction of permanent or secondary dwellings with low energy efficiency by, for example, improving space cooling and heating or purchasing appliances with high energy efficiency standards and renewable energy technologies, such as photovoltaic panels and solar thermal systems.

The independent variable CD has a negative impact of −0.8075 on the dependent variable ENERY_POVERTY, meaning that it helps to mitigate energy poverty in the Lisbon metropolitan area. However, its impact is low compared to the results of the independent variable CR. This result may be due to mandatory regulations that promote the improvement of energy efficiency in new dwellings and buildings, such as the Heating, Ventilation, and Air Conditioning (HVAC) regulation, the Energy Certification System of Buildings regulation, the Certificate of Energy Performance and Indoor Air Quality regulation, and the Environmental Fund program's Sustainable Buildings regulation, as mentioned in Section 3.1. Another factor contributing to this negative impact is the tourism boom, property speculation, housing shortages, and tax incentives for foreigners through the "Golden Visa", which have influenced the construction of new, energy-efficient dwellings and buildings following the mandatory regulations for energy efficiency.

However, the increase in new dwellings and buildings with high energy efficiency standards is not for everyone. For example, only a tiny proportion of the population in the Lisbon metropolitan area with high income and access to credit (national or international) without bureaucracy and restrictions, as well as tax incentives (e.g., foreigners through the "Golden Visa"), have access to these dwellings and buildings. This result has a negligible impact on the independent variable, CD. Another factor contributing to this low impact could be the high construction costs of these high-energy-efficiency dwellings or buildings. These dwellings or buildings can cost 20% more than conventional dwellings or buildings with low-energy-efficiency performances. This increase in cost is reflected in the prices of dwellings or buildings with high energy efficiency standards [55]. As a result, these dwellings become inaccessible to households and individuals with low incomes and limited access to government support, such as the EUR 4500 (Euros) housing credit offered in [89]. This result leads these households and individuals to buy conventional dwellings with low energy efficiency standards (e.g., D, E, and F) and make necessary energy efficiency improvements.

Finally, the independent variable CR negatively impacts the dependent variable ENERY_POVERTY with a coefficient of −41.2240. This finding means that the independent variable CR reduces energy poverty in the Lisbon metropolitan area, and its impact is much higher than the independent variable CD. This result could be attributed to mandatory regulations promoting energy efficiency improvements in existing dwellings and buildings, as discussed in Section 3.1. Another factor that may contribute to this negative impact is the tourism boom, property speculation, housing shortages, and tax incentives for foreigners through the "Golden Visa," which influences the rebuilding or renovating of permanent or secondary dwellings with low energy efficiency.

The high cost of new dwellings and buildings, with and without high energy efficiency standards, has prevented low-income households and individuals and foreigners with limited budgets from obtaining housing loans. They have instead opted to purchase used or old dwellings and buildings with low-efficiency standards (e.g., D, E, and F) and renovate them to improve energy efficiency. Another factor that may have contributed to this high impact is the fiscal benefits offered for urban regeneration areas, or "*Áreas de Reabilitação Urbana* (ARU)" in Portuguese [97]. Each municipality in the Lisbon metropolitan area provides tax benefits for individuals who buy and renovate damaged dwellings or buildings [97]. These tax benefits include (i) a three-year exemption from municipal property tax, (ii) a three-year exemption from municipal tax on property transfers, (iii) a reduction in income tax, (iv) a reduction in value-added tax (IVA), and (v) a reduction in other taxes [95].

Moreover, the existence of government support, such as the "*Programa Casa Eficiente 2020*" (Efficient House 2020 Programme) [92], and "*Programa de Apoio Edifícios + Sustentáveis 2021*" (Sustainable Buildings Support Programme 2021) [91] to improve the energy efficiency of dwellings and buildings, also could be related to this high impact.

6. Conclusions and Policy Implications

This research aims to contribute to enhancing the understanding of (i) efforts to combat global warming, (ii) requirements to decrease greenhouse gas emissions, and (iii) the need to restrict the environmental impact of human activities on the environment. Few studies have focused on the effect of energy efficiency on energy consumption in Portugal. Hence, this study aims to fill this gap and discover appropriate energy policy measures in the residential sector in Portugal. This research's objective is to provide a supported answer to the following question: Do energy efficiency regulations help to reduce energy poverty in residential dwellings in Portugal?

Despite its small size, Portugal has significant geographical differences, which may hinder clear comprehension of the relationships between variables. This particularity is kept in mind, and the research focuses on the impact of energy efficiency regulations on energy poverty in the residential dwellings of 18 municipalities in the Lisbon metropolitan area, which is considered the wealthiest region of Portugal.

This study uses well-established econometric methods, including Ordinary Least Squares with fixed effects and method of moments quantile regression, to examine data from 2014 to 2020. The aim is to determine the variables that have a significant impact on energy poverty, which is represented by homes with low energy efficiency (rated D, E, and F on the energy efficiency certificate). The following variables are selected for analysis: (i) GDP, (ii) national regulations on energy efficiency for residential properties, (iii) credit agreements for the purchase, construction, or renovation of permanent or secondary homes, or rent and land purchases for owner-occupied homes, (iv) the number of completed homes in new family housing constructions, and (v) the number of completed renovations relative to 100 completed new constructions.

The answer to the research question ("Do energy efficiency regulation policies mitigate energy poverty in residential dwellings in Portugal?") is positive. The OLS and MM-QR estimations show that energy efficiency regulations for the residential sector positively impact (101.9252) energy poverty. This finding suggests that energy efficiency regulations for the residential sector increase energy poverty in the Lisbon metropolitan area and have a very high impact. However, this result could also indicate that regulations are inefficient in reducing energy poverty in the Lisbon metropolitan area or Portugal as a whole, due to various economic, institutional, and behavioural barriers that limit the effectiveness of the regulations.

Policy Implications

The results of this research serve as a warning to policymakers regarding implementing policies that maximise economic and social benefits from enhancing the energy efficiency of dwellings. Firstly, energy efficiency regulations should be revised; despite the positive impact of energy efficiency regulations on reducing energy poverty, there are still barriers that limit their effectiveness. Thus, it is necessary to review these regulations and identify the areas that need improvement to enhance their effectiveness in reducing energy poverty. Secondly, policies targeting households with low energy efficiency should be developed; this study finds that energy efficiency regulations have a positive impact on reducing energy poverty. However, it is essential to identify households with low energy efficiency ratings and provide them with targeted assistance, such as financial aid, to help them upgrade their energy efficiency and reduce their energy costs. Thirdly, financial incentives should be promoted; this study finds that credit agreements have a significant impact on reducing energy poverty. Hence, there is a need to promote financial incentives, such as loans and grants, to support households that want to improve their energy efficiency.

Fourthly, awareness and education should be increased; social and cultural factors are found to play a significant role in energy poverty, which highlights the importance of increasing awareness and education about energy efficiency and conservation. It is essential to develop educational programs that target different segments of society, including schools, communities, and households, to raise awareness about the benefits of energy efficiency and conservation. Fifthly, the effectiveness of policies should be monitored and evaluated;

it is crucial to monitor and evaluate the impact of policies implemented to reduce energy poverty regularly. This can help identify the effectiveness of the policies and determine whether they need to be revised or improved to achieve the desired outcomes.

Sixthly, improvements in efficiency in the housing sector contribute to the pressing need to transition from fossil fuels to renewable energy sources, reducing emissions of harmful gases. This result is achieved by reducing the energy consumption required to cool dwellings and using more environmentally friendly construction materials, some of which emit significant amounts of pollution, such as mortar. Seventhly, efficiency gains can be linked to the generation of clean energy in dwellings, such as solar or thermal. Eighthly, policies should be designed to achieve economies of scale by recycling residuals from dwelling renovations. Ninthly, transient phenomena, such as tourism, should be limited or isolated from dwellings. Tenthly, efficient dwellings should be linked to the effort to smooth energy demand by managing the energy demand side. Finally, preventive measures should be implemented to limit the rebound effect, also known as the Jevons Paradox, which occurs when increased energy efficiency leads to increased overall energy consumption. Additionally, greater energy efficiency in dwellings can make energy-consuming activities more affordable, increasing their usage.

7. Limitations and Future Research

7.1. Study Limitations

This study has several limitations stemming from the contingencies that typically challenge empirical research. Firstly, the short data period makes it challenging to identify underlying trends and decompose the total effect into short-term and long-term impacts. Secondly, this study is limited by the variables available, and the complexity and theoretical uncertainty of the determinants of dwellings' energy efficiency likely require the inclusion of qualitative variables, which is challenging to model using longitudinal data. Thirdly, the results may not be generalisable to other situations due to the limited capacity to generalise from specific circumstances, as this study is conducted in a wealthy area of a not-so-wealthy country. Fourthly, EPCs do have limitations as a proxy for energy poverty. They only provide information on the energy efficiency of buildings and do not take into account other factors that can contribute to energy poverty, such as household income, energy prices, and the quality of heating systems. Therefore, although EPCs can be a valuable tool in assessing energy poverty, they should be used in conjunction with other indicators to provide a more comprehensive understanding of the issue. Finally, the lack of literature on the topic in Portuguese economic and social realities has resulted in a lack of fundamental research that would allow for the identification of the underlying factors driving the economy, making it challenging to research ways to improve dwellings' energy efficiency.

7.2. Future Research

Deploying energy-efficient dwellings in challenging times requires a thorough understanding of the complex relationships among the variables involved. One approach is to enhance traditional econometric methods with fuzzy-set qualitative comparative analysis (fsQCA), which is equipped to handle small samples and qualitative variables. Another approach is to investigate the relative effectiveness of different policy measures, such as financial and regulatory incentives, and to consider factors such as income inequality, low wages, interest rates in financing energy transitions, and housing market speculation when examining the ability to renovate dwellings.

Moreover, it is necessary to develop more comprehensive indicators of energy poverty that take into account multiple factors, such as household income, energy prices, and the quality of heating systems. This would help provide a more holistic understanding of energy poverty and its underlying causes. Examining the relationship between EPC ratings and other indicators of energy poverty, such as fuel poverty and energy expenditure, could help establish the validity of EPCs as a proxy for energy poverty and determine how they can be used in conjunction with other indicators to better understand the issue.

Exploring the effectiveness of policies and programs designed to address energy poverty, particularly those that focus on improving the energy efficiency of buildings, could involve assessing the impact of different types of interventions on energy consumption, energy costs, and the well-being of households. Investigating the role of social and cultural factors in energy poverty, including how social norms and attitudes towards energy use and conservation may impact energy consumption and energy poverty, could help to identify new approaches to addressing energy poverty that are more attuned to the needs and values of different communities.

Finally, it is recommended to validate these findings through cross-validation by applying the same approach to other contexts, such as metropolitan areas or panels of countries and different types of buildings.

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sustainability

Article

How Renewable Energy and CO_2 Emissions Contribute to Economic Growth, and Sustainability—An Extensive Analysis

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Abstract: Using energy efficiently is crucial for economic development and sustainability. However, excessive use of fossil fuels impedes sustainable economic growth, and the released emissions have a negative impact on the environment. Still, there is no consensus in the literature as to the side effects or even regarding the determinants used to assess this relationship. As such, this article explores the effects that CO_2 (carbon dioxide) emissions and renewable energy consumption have on economic growth, using fixed assets, human capital, research and development, foreign direct investment, labor force, and international trade as controls, on a sample of 27 EU (European Union) countries between 1994 and 2019. Four different methodologies were applied to the sample, namely ordinary least squares, fixed effects, random effects, and the generalized method of moments in first differences, allowing endogeneity to be accounted for. Results show that gross fixed capital, human development, and trade contribute positively to economic growth; however, even though these contributions increase due to renewable energy consumption, that increase occurs at the expense of more CO_2 emissions. This expense may be justified by the high dependency on fossil fuels in the EU 27 group. Policy implications are presented for policymakers, namely governments, in light of sustainability and climate change.

Keywords: renewable energy; economic growth; CO_2 emissions; human capital; investment; sustainability

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1. Introduction

Renewable energy emits fewer (or no) greenhouse gases, and at the same time, countries need to ensure proper economic growth. Economic growth needs to be achieved sustainably, and ensuring lower pollution levels is necessary for climate change agreement goals to be met. At the same time, higher fossil fuel energy prices, increased inflation levels, higher living standards, and increased difficulties faced by families also justify a stronger use of renewable energy. By reviewing the existent literature between 2010 and 2021 [1], this study highlights that renewable energy does not hinder economic growth in either developed or developing countries.

Since [2] examines the relationship between renewable energy consumption and economic growth, many researchers have explored this link. However, no consensus has yet been reached. Despite recent efforts to conform with COP-27 (the 27th Conference of the Parties of the UNFCCC—United Nations Climate Change Conference) and increased energy prices due to the full-scale aggression of the Russian Federation against Ukraine, there are still doubts as to the real effects of renewables consumption on economic growth [3]. The quest for greener energy consumption emerged worldwide due to the related projections for fossil fuel depletion, turning the energy-led economic growth nexus into an interesting area of research to ensure a sustainable environment [4].

There are limited sources available for conventional energy, but that energy is highly necessary to create production levels that justify economic growth, even if the negative effects of the energy sources are far worse than the economic benefits [5]. This situation is forcing the world to move towards renewable energy consumption and production to decrease fossil-energy dependency [3,6,7]. Additionally, the current concerns about fossil fuels depletion are related to their frequent use and high consumption rates. Fossil fuels are also associated with greenhouse gas effects, which lead to global warming [2,4]. Meanwhile, green energy is naturally replenished and fosters sustainable development [7,8].

The present article intends to contribute to the debate about how CO_2 emissions and renewable consumption effect economic growth. Since there is no consensus in the literature, we intend to highlight the effects of both CO_2 emissions caused by the burning of fossil fuels and the consumption of renewable energies on economic growth of the 27 countries of the European Union in the period between 1994 and 2019. We added six variables to the analysis, which serve to control the results obtained, namely: investment in fixed assets (gross capital formation) as a percentage of GDP (Gross Domestic Product); research and development expenditure as a percentage of GDP; labor force participation; school tertiary enrollment to represent the level of human capital qualifications; foreign direct investment; and involvement in a country's international trade. As such, a broader spectrum of exogenous variables was included in the analysis, allowing us to reach further than the justifications that already exist in the literature. We assume a log–log model specification, with the estimated coefficients representing the constant elasticities. Thus, coefficients represent the percentage change in the dependent variable due to a percentage change in the explanatory variables. Moreover, both models, ignoring endogeneity and those variables which account for it, are used for estimations and robustness checks. Finally, a balanced panel dataset was composed. It is believed that, with more complete information, the paper results will contribute more efficiently to the contradictory findings that are currently present in the literature.

As pointed out by [1,3], we may group empirical literature about energy consumption and its impact on economic growth into positive and negative influences, but there is still no formal conclusion. The energy-led economic growth hypothesis points to an indispensable role of energy in economic growth [8]. However, results mentioning a negative impact of renewable energy consumption over economic growth also exist [9]. Based on these contradicting results, we intend to shed more light on the existing literature. Moreover, while current studies do explore the variables we include in our analysis, they are not explored jointly. This is true even though many of the existing empirical works are concentrated in individual countries or small groups of countries and present inconclusive results. Contradictory evidence could lead to ineffective policy definition and subsequent implementation. Therefore, this research manages to contribute to this ongoing debate and entice scholarly interest in the subject, focusing not on a specific country or small group of countries, but on the EU27 and while considering European energy policies that are being implemented. Trade openness and economic growth studies also demonstrate ambiguous results, with final reported impacts that are dependent on economic conditions. Positive effects are found by [10], whereas, considering Indonesia, [11] points to an inverse relationship. Based on these inconclusive results, the joint energy policies being implemented in EU27, increased energy prices, COP 27 decisions, and joint climate change efforts, the present work tries to shed new light on the CO_2 emissions–renewables–growth nexus, accounting for endogeneity problems empirically. In the literature, we find the work of [12], whose results suggest that trade openness and renewable energy use promote economic growth by applying FMOLS (full modified ordinary least squares) and DOLS (dynamic ordinary least squares) econometric techniques in EU 28 countries. Our work is different from existing studies in three aspects at least: we use different methodologies, extended the period of analysis, and also, by including other control variables, we are able to explain the relationship between CO_2 emissions–growth–renewables.

The rest of the article is presented as follows. Section 2 presents a brief review of the recent literature on the topic. Section 3 presents the data, variables, main statistics, and correlations, highlighting the relevant results. Section 4 provides the empirical findings, whereas in Section 5 we discuss the results and provide some policy implications. Finally, Section 6 concludes this work.

2. Literature Review

For OECD (Organisation for Economic Co-operation and Development) countries and using panel data methodology, starting from a Cobb–Douglas type production function, [13] concluded that there is a long-term equilibrium relationship between real GDP and GDP per capita, and from the ratio of renewable energy consumption to total energy consumption, investment, employment, and R&D (research and development), thus confirming the importance of these variables in economic growth. For a wide range of countries, using Multivariate Panel Data Analysis, [14], concluded that there is a statistically significant relationship between the production and consumption of renewable energy, both for developed and developing economies, suggesting that renewable energy can be an important source of sustainable economic growth in the future.

By verifying the relationship between renewable energy consumption and economic growth for a set of 103 countries between 1995 and 2015, [15] found that, for OECD countries, there is a positive and significant relationship between this consumption and economic growth. For non-OECD countries, a positive and significant relationship starts to occur when these countries intensify the use of renewable energies. For low renewable energy consumption, the effect on economic growth is negative. In other words, the negative effect of consumption on economic growth in the early stages of renewable energies can be compensated for in the long term, when these countries start to intensify the level of consumption of renewable energies. For [15] the use of the variable renewable energy consumption divided by total energy consumption is also preferable to the use of the variable renewable energy production with respect to total energy production, because renewable energy production prices differ depending on the specific alternative source used.

In Ghana, a country considered blessed for the use of renewable energy, the reality is that consumption of this type of energy has a significant and positive bidirectional relationship with economic growth. The variables trade, investment, and FDI (foreign direct investment) also have positive and significant impacts on economic growth. These results are verified in both the short and the long term [16]. The increased energy usage creates new jobs, and the labor force needs to respond to these demands [1]. Moving towards renewable energy leads to economic development beyond economic growth by reducing carbon emissions [17,18].

Considering energy consumption as the backbone of economic growth and studying the effect of consumption of bioenergy from biomass as an alternative and sustainable source for energy production (considering the hypothesis of economic growth within a production function type Cobb–Douglas), [19] found that renewable energy consumption from biomass has a positive and significant impact on economic growth in the countries of the European Union. These authors also found that this relationship is stable in the long term. Therefore, fossil fuels are a considerable source of carbon emissions and environmental degradation [1]. Using non-renewable energy sources enhances economic growth but increases the dilemma in policy priorities. Should countries promote economic growth, or bet on renewables and promote sustainable growth? It should be borne in mind that renewable sources demand sophisticated energy technologies, an appropriate workforce, and gross fixed investment beyond R&D. Supplying energy from renewable sources is also time-consuming and costly, demanding balanced spending from governments to maintain economic growth and simultaneously enhance sustainable development by embracing the necessary climate change mitigation. Economic growth depends heavily on energy consumption [14,17]. In turn, energy consumption is highly responsible for greenhouse gas emissions, particularly CO_2 emissions [20].

Increased economic growth is positively correlated with increased pollution levels. Higher carbon emissions are associated with non-renewable energy consumption and globalization [21], and are also considered harmful to human health [22]. Research points out that R&D expenditure, international trade, technology, innovation, and trade-adjusted carbon emissions are suitable for environmental recovery, without impeding economic growth [23,24]. Thus, many studies claim that renewable energy is a good strategy for environmental sustainability [3]. Chang and Fang [25] confirm a positive association between renewable energy consumption and economic growth in BRICS (Brazil, Russia, India, China, and South Africa). Moshin et al. [8] found bi-directional causality in 25 Asian countries, and that renewable energy decreases both emissions and environmental degradation. For 29 European countries, [26] suggests that renewables enhance economic growth while reducing emissions. Results from [27] for 75 economies, from [28] for G7 countries (Canada, France, Germany, Italy, Japan, United Kingdom, and the United States), and from [15] for 103 world economies, point to mixed results depending on economic conditions faced by countries. Chen et al. [15] found a positive influence in developing and non-OECD countries when they exceed a certain threshold level; however, they found a negative influence whenever the countries used renewable energy below that threshold.

For G7 countries, [29] highlights that green growth decreases CO_2 emissions, as human capital is necessary to simultaneously achieve sustainable growth. As pointed out by [1], prior research uses essential and more sophisticated methodologies to examine emission levels and economic growth, energy structure, energy efficiency, financial development, technological development openness, and population. Few studies simultaneously examine CO_2 emissions, renewable energy consumption, economic growth, investment in fixed assets, human capital, R&D, labor force participation, foreign direct investment, and international trade, as we do in this study; we also consider a larger data span (1994–2019) for all EU 27 countries.

Fang et al. [30] measured the development of green economic growth, R&D, and green finance in the South Asian region between 2008 and 2020, suggesting that R&D reduces carbon emissions, allowing for a green economic recovery. They also conclude that, to minimize tiers of CO_2 emissions and technology spillovers, industrial structural change is needed, especially in developing economies. The findings of Hussain et al. [31] confirm that green technology enhances green growth, and that emissions harm green growth in high-GDP countries. Economies that adopt advanced technologies make productivity progress in the environment [32]. Grafström et al. [33] address the importance of government support for renewable energy R&D for 12 EU countries. Their findings defend the view that countries with less energy-import dependence and deregulated electricity markets receive less government R&D support. Topcu et al. [34] confirm that energy consumption, gross capital formation, urbanization, and natural resources have different impacts on GDP by income level.

Infrastructure investment is needed to meet renewable energy demands for human capital, labor force participation, gross capital formation, and the associated research and development required for sustainable economic growth; a positive association on these items is easier to observe in high-income countries [34]. Foreign direct investment increases when countries have sufficient natural resources or can manage the available resources more efficiently, decreasing their dependence on other countries. For the MENA region (countries situated in and around the Middle East and North Africa), [35] found that FDI plays a key role in promoting economic development by leading to beneficial impacts on environmental sustainability and economic growth. In a panel of 105 countries, FDI was found to aggravate CO_2 emissions, as did economic growth, industrialization, and trade openness [36]. Again, the impacts of different variables depend on the country's income level, making it relevant whether additional variables are included in the study, and verifying whether results from countries that have relatively high income growth, or are at least developed, apply in other countries.

Capital accumulation stimulates economic growth, and economic growth promotes physical capital stocks by proportionating capital investments [33,34]. Mahmood et al. [37] conclude that trade openness increases CO_2 emissions, whereas human capital mitigates emissions in Pakistan. However, [38] infers that, in China, increasing human capital leads to the escalation of emissions and environmental degradation, demonstrating that the Chinese economy is sustained through pollution-embedded trade. As mentioned by [39], education (as the basis for human capital) creates the necessary conditions for higher social welfare concerns, encouraging people to behave in a more environmentally friendly way through environmental-oriented behaviors [38]. Not many studies include this variable in the renewables–CO_2-emissions–growth nexus exploration, and the few studies that have been conducted have mixed results.

3. Data, Variables, Main Statistics, and Correlations

The sample used in this study comprises the period 1994–2019 for the 27 countries of the European Union. Since there are no missing observations, the panel is balanced with a total of 702 observations. The database was obtained through access to the World Development Indicators (WDI), which is the primary World Bank collection of development indicators and is compiled from officially recognized international sources.

Table 1 shows the variables used in the empirical analysis, their definitions, the objectives of each variable, and the unit. Except for GDP per capita which is expressed in USD, and CO_2 emissions expressed in tonnes per capita, all other variables are expressed in percentages. Table 2 shows the average of the same variables by country.

Table 1. Variables definition and data sources.

Variable Acronym	Definition	Objectives	Unit
$GDPpc_{it}$	Gross domestic product per capita, in the country i and year t (constant, 2015)	Achieving the growth of an economy	USD
CO_{2it}	CO_2 emissions, in the country i and year t	Quantify CO_2 emissions from burning fossil fuels	Tons per capita
REC_{it}	Renewable energy consumption in the country i and year t	Measure renewable energy consumption concerning final energy consumption	Percentage
GCF_{it}	Gross capital formation, in the country i and year t	Investments made in fixed assets concerning GDP	Percentage
$R\&D_{it}$	Research and development expenditure, in the country i and year t	Measuring investment in R&D concerning GDP	Percentage
LFP_{it}	Labor force participation, in the country i and year t	Amount of population providing labor for the production of goods and services	Percentage
ST_{it}	School tertiary enrollment, in country i and year t	Level of human capital qualifications	Percentage
FDI_{it}	Foreign direct investment, in country i and year t	Amount of foreign investment in a country	Percentage
$Trade_{it}$	International trade, in country i and year t	Involvement in a county's international trade	Percentage

Source: Authors' elaborations.

As we can see, for the period under review, the country with the highest average GDP per capita (constant, 2015) is Luxembourg (€99,152), with Bulgaria (€5592) as the country where this variable is the lowest. Between these two countries, there is an impressive disparity of €93557 in GDP per capita, which demonstrates the wide range of income in the EU. In terms of emissions of tons of CO_2 per capita, the lowest average is found in Latvia (3597) and the highest in Luxembourg (20,324). The most polluting country in the EU on average is the one with the highest level of per capita wealth. In terms of renewable energy consumption, the country with the highest average is Sweden (41,893), and Malta (2027) has the lowest average, even though this country has been intensifying its energy consumption from renewable sources in recent years. Other northern European countries such as Finland (34,133) and Latvia (36,125) also have high per capita energy consumption from renewable sources.

Table 2. Average of variables for each EU country (1994–2019).

Country	GDPpc	CO_2	REC	GCF	R&D	LFP	ST	FDI	Trade
Austria	41,204	8.055	28.970	24.693	2.462	59.708	66.872	2.175	92.095
Belgium	37,825	9.982	4.622	23.214	2.165	52.533	64.547	11.983	144.296
Bulgaria	5595	6.091	11.088	21.234	0.576	52.680	52.691	7.066	103.031
Croatia	11,036	4.277	28.752	22.703	0.906	49.025	47.452	3.516	80.031
Cyprus	23,866	6.883	5.936	20.754	0.403	62.521	40.771	64.014	125.181
Czechia	15,133	10.981	9.624	29.465	1.397	59.873	47.183	4.821	118.034
Denmark	50,666	9.045	19.124	21.287	2.587	64.054	69.437	2.382	90.163
Estonia	14,341	12.202	21.670	29.150	1.261	60.953	61.080	7.531	142.369
Finland	40,499	10.563	34.133	22.873	3.125	60.828	83.974	3.523	73.246
France	34,719	5.525	11.137	22.157	2.170	55.841	55.088	5.034	54.849
Germany	37,010	9.713	8.838	21.531	2.639	59.004	57.513	2.257	70.560
Greece	19,426	7.832	10.921	19.937	0.761	51.828	82.410	0.837	55.132
Hungary	10,843	5.114	9.692	24.754	1.055	51.390	48.631	10.578	136.160
Ireland	47,770	9.458	4.908	25.624	1.280	60.461	58.504	17.200	174.861
Italy	31,598	6.913	9.985	19.702	1.175	48.672	58.091	1.011	51.015
Latvia	10,724	3.597	36.125	26.425	0.513	59.214	64.411	3.874	100.841
Lithuania	10,780	3.801	20.547	21.140	0.780	58.963	64.819	3.347	117.211
Luxem.	99,152	20.324	5.802	19.984	1.436	55.904	13.357	17.631	283.791
Malta	19,298	5.661	2.027	22.431	0.463	51.221	35.014	73.541	261.071
Poland	9573	8.087	8.604	21.487	0.771	57.083	59.334	3.304	74.716
Portugal	18,848	5.245	24.245	21.921	1.063	60.183	55.761	3.554	69.749
Romania	6676	4.274	18.601	24.347	0.470	58.081	41.250	3.387	66.841
Slovakia	12,498	6.783	8.180	26.284	0.717	59.604	40.247	3.591	146.964
Slovenia	19,228	7.425	17.480	24.431	1.742	58.245	68.900	1.960	122.914
Spain	24,758	6.398	11.721	23.500	1.118	55.940	69.351	2.871	56.592
Sweden	45,214	5.267	41.893	22.881	3.328	66.521	66.614	4.530	80.731
TheNether.	42,151	9.937	3.595	21.224	1.900	63.565	63.804	18.124	129.922

Source: Authors' calculations.

In terms of average investment as a percentage of GDP, the country that invests the most is Czechia (29.465%), and the country that invests the least is Greece (19.936%). We can also see that in general terms, all countries have average investments between 20% and 30% of their GDP.

As regards average investment in terms of R&D as a percentage of GDP, it is highest in Sweden (3.328%) and lowest in Cyprus (0.403%). Finland (3.125%) and Germany (2.639%) also show high investment values in R&D as a percentage of GDP, but Romania (0.470%) and Bulgaria (0.576%) have few investments in R&D. Labor force participation is highest in Sweden (66.521%) and lowest in Italy (48.672%) and Croatia (49.025%), where more than half of the population aged over 15 who can be considered economically active do not participate in the labor force.

The gross enrollment ratio is the ratio of total enrollment, regardless of age, to the population of the age group that officially corresponds to the level of tertiary education. The average is higher in Finland (83.974%) and lower in Luxembourg (13.357%). Foreign direct investment as a percentage of GDP is highest in Malta (73.541%) and Cyprus (64.014%) and lowest in Greece (0.837%), Ireland and Luxembourg still show values around 17%. The degree of openness to the outside world in average terms is highest in Luxembourg (283.291%) and Malta (261.071%) and lowest in Italy (only 51.015%). We can also see in Table 2 that the economics of Spain, Greece, and France have a degree of openness to the outside, below 60%.

Table 3 contains the main descriptive statistics, namely the maximum and minimum values, means, and standard deviations of the variables used.

The highest GDP per capita value occur in Luxembourg in 2006 and the lowest in Bulgaria in 1999; meanwhile, CO_2 emissions were highest in Luxembourg in 1994 and lowest in Latvia in 2000. The variable renewable energy consumption assumes the maximum value in Sweden in 2019 and the minimum value in Malta for several years. Gross capital formation reaches its maximum value in Ireland in 2019 and its minimum value in Bulgaria in 1996.

In turn, expenditure on investment in research and development was higher in Sweden in 2000 and lower in Cyprus in 1997. Labor force participation variable was higher in 2019 in Sweden and the lowest value occurred in Croatia in 1995. School tertiary enrollment is highest in Greece in 2019 and lowest in Luxembourg in 1994.

Finally, foreign direct investment reached its peak in Malta in 2007, and in the same year, the minimum was verified in Luxembourg, while the trade variable reached its maximum value in Luxembourg in 2019 and the minimum value in Greece in 1994.

Table 3. Main descriptive statistics.

	Maximum	Minimum	Average	Std Deviation
GDPpc	112,417	3537	27,435	20,163
CO_2	26.829	2.927	7.7569	3.575
REC	52.880	0.010	15.490	1.600
GCF	54.955	1.157	23.152	4.556
R&D	3.873	0.203	1.417	0.882
LFP	73.360	36.211	57.554	5.284
ST	148.531	7.038	57.185	21.375
FDI	449.081	−57.532	10.395	34.669
Trade	377.842	36.163	111.941	60.145

Source: Authors' calculations. GDPpc—Gross domestic product per capita; CO_2—CO_2 emissions; REC—Renewable energy consumption; GCF—Gross capital formation; R&D—Research and development expenditure; LFP—Labor force participation; ST—School tertiary enrollment; FDI—Foreign direct investment; Trade—International trade.

Table 4 contains Pearson's correlation coefficients. To obtain accurate results from the empirical analysis, we also consider the problem of multicollinearity. The Pearson's correlation test, applied to our variables, showed that there is no multicollinearity between the variables considered, considering that we used the value of −0.80 or 0.80 as a limit, like other studies [40].

Table 4. Correlations.

	GDPpc	CO_2	REC	GCF	R&D	LFP	ST	FDI	Trade
GDPpc	-	0.6525	−0.0333	−0.1541	0.5443	0.2404	−0.0242	0.0890	0.4221
CO_2	-	-	−0.3595	0.0508	0.2405	0.1025	−0.2458	0.0573	0.3973
REC	-	-	-	0.0331	0.3817	0.2949	0.4470	−0.1973	−0.2681
GCF	-	-	-	-	−0.091	0.1007	0.1428	−0.0520	0.0077
R&D	-	-	-	-	-	0.3763	0.4215	−0.1408	−0.1227
LFP	-	-	-	-	-	-	0.1497	−0.1276	−0.2642
ST	-	-	-	-	-	-	-	−0.1276	−0.2642
FDI	-	-	-	-	-	-	-	-	0.3353
Trade	-	-	-	-	-	-	-	-	-

Source: Authors' calculations. GDPpc—Gross domestic product per capita; CO_2—CO_2 emissions; REC—Renewable energy consumption; GCF—Gross capital formation; R&D—Research and development expenditure; LFP—Labor force participation; ST—School tertiary enrollment; FDI—Foreign direct investment; Trade—International trade.

4. Empirical Analysis, Model Specification, and Estimation Methods

As we explained before, we use balanced panel data to estimate the model which seeks to explain the effects that CO_2 emissions caused by the burning of fossil fuels and the consumption of renewable energies have on the economic growth of the 27 countries of the European Union, in the period between 1994 and 2019. Additionally, we added six variables to the analysis, which serve to control the results obtained. We assumed a log–log model specification; therefore, the estimated coefficients represent the constant elasticities showing the percentage change in the dependent variable due to a percentage change in the explanatory variables. The model takes the following form:

$$\begin{aligned} \mathrm{lnGDPpc_{it}} &= \alpha_i + \beta_1\, \mathrm{lnCO_{2it}} + \beta_2\, \mathrm{lnREC_{it}} + \beta_3\, \mathrm{lnGCF_{it}} + \beta_4\, \mathrm{lnR\&D_{it}} + \beta_5\, \mathrm{lnLFP_{it}} + \beta_6\, \mathrm{lnST_{it}} \\ &+ \beta_7\, \mathrm{lnFDI_{it}} + \beta_8\, \mathrm{lnTrade_{it}} + u_{it} \end{aligned} \quad (1)$$

Equation (1) regresses the lnGDP per capita as a function of the ln of CO_2 emissions, the ln of renewable energy consumption, and the ln of six control variables: gross capital formation; research and development expenditure; labor force participation; school tertiary enrollment; foreign direct investment; and international trade.

Three methods of estimation can be used to estimate Equation (1) with panel data. The simple OLS (Ordinary Least Squares) approach on the pooled model assumes no country and time-specific effects. However, this method of estimation is more appropriate to a set of homogeneous countries; this is not appropriate for our study since our sample includes both more and less advanced countries with different structures and levels of development. An alternative estimation approach that captures country-specific heterogeneity is the fixed effects (FE) model capturing the country-specific heterogeneity in the constant part (as it is different from country to country) as it is shown in Equation (1). This model can be estimated by the LSDV (least squares dummy variables) method, either assuming country-specific dummy variables or by the time-demeaned estimation approach [41]. Using the FE (fixed effects) method, an explicit hypothesis is made that fixed effects are not correlated with the explanatory variables, and FE estimates are not consistent under this condition. The third estimation method applied to panel data is the random effects (RE) approach, which considers that the country´s heterogeneity is not observable and captured in the error term. The estimation method used is GLS (generalized least squares) applied to the partially demeaned model [41]. Using this method, the hypothesis that the unobserved error term is not correlated with the explanatory variables is crucial to obtain unbiased and consistent estimates.

To decide which estimation method to perform (OLS, LSDV, or GLS) three statistical tests are normally used. The F-test tests the pooled model versus the FE model, the Breush–Pagan LM test tests the pooled model versus the RE model, and the Hausman test tests the RE model versus the FE model. Performing the three statistical tests, the FE model is the most appropriate specification to adopt (p-value of F-test = 0; p-value of the Breush–Pagan LM test = 0; p-value of the Hausman test = 1.55838×10^{-3}).

A very common problem in panel data is endogeneity, which is often not verified and corrected. As we can see in Table 5, the results of the Hausman Test show that several variables can be considered endogenous (p-value less than 0.05). In this case, the null hypothesis that there is no correlation with the error term is rejected, so the estimation approach using instrumental variables should be used to obtain consistent estimators, for example, by dynamizing the model [40], because in presence of endogeneity, the estimation may provide biased results.

According to [42–44], the inclusion of the lagged dependent variable streamlines the model but causes problems of endogeneity, which cannot be solved by traditional methods (for example 2SLS (two-stage least squares), 3SLS (three-stage least squares) or SUR (seemingly unrelated regression)). So, according to these authors, in this case, the best estimation method should be the GMM (generalized method of moments) method in the first differences.

Table 5. Hausman test specification results.

GDPpc—*p*-value = 0.5132	LFP—*p*-value = 0.0147
CO_2—*p*-value = 0.0425	ST—*p*-value = 0.4478
REC—*p*-value = 0.0832	FDI—*p*-value = 0.3547
GCF—*p*-value = 0.0354 R&D—*p*-value = 0.4587	Trade—*p*-value = 0.0254

Source: Authors' calculations. GDPpc—Gross domestic product per capita; CO_2—CO_2 emissions; REC—Renewable energy consumption; GCF—Gross capital formation; R&D—Research and development expenditure; LFP—Labor force participation; ST—School tertiary enrollment; FDI—Foreign direct investment; Trade—International trade.

The estimation using the GMM method in the first differences (as recommended by [42,44]), for the variables that seek to justify the growth rate of GDP per capita, allows the persistence of the dependent variable in time to be considered, in addition to solving potential problems caused by endogeneity.

The GMM model in the first difference takes the following form:

$$\ln GDPpc_{it} = \alpha_i + \beta_1 \ln GDP(-1)pc_{it} + \beta_2 \ln CO_{2it} + \beta_3 \ln REC_{it} + \beta_4 \ln GCF_{it} + \\ + \beta_5 \ln R\&D_{it} + \beta_6 \ln LFP_{it} + \beta_7 \ln ST_{it} + \beta_8 \ln FDI_{it} + \beta_9 \ln Trade_{it} + u_{it} \quad (2)$$

Equation (2) regresses the lnGDP per capita as a function of the lnGDP per capita lagged in one year, the ln of CO_2 emissions, the ln of renewable energy consumption, as well as the ln of six control variables: gross capital formation; research and development expenditure; labor force participation; school tertiary enrollment; foreign direct investment; and international trade.

Table 6 reproduces the estimated results through the panel data fixed effects methodology and the GMM methodology in the first differences. The first major conclusion we can draw is that, since the coefficient of the dependent variable lagged in a period is 0.91 (in model 3), it reveals the high persistence of the effect of the previous year's economic growth, that is, only about 9% of the economic growth is adjusted the following year. In the case of model 4, the coefficient of the dependent variable lagged is 0.93; this also reveals the high persistence of the economic growth of the previous year because, in this case, only about 7% of the economic growth is adjusted the following year.

In the fixed-effects model, there is a greater number of variables with statistical significance than in the GMM model, but the GMM model does not present endogeneity; therefore, it does not compromise the reliability of the estimated coefficients or its statistical inference.

Models 1 and 3 consider all variables, but model 2 does not consider CO_2 emissions, and in model 4, the variables that do not present statistical significance in model 3 were removed, as they included renewable energy consumption without considering CO_2 emissions and without statistically insignificant variables.

In model 2, we found that all variables that were statistically significant in model 1 remained so, with the variables gross capital formation, research and development expenditure, labor force participation, and international trade still reinforcing their contribution to economic growth. Concerning model 4, the variables that had statistical significance in model 3 maintained their significance. The previous results found that, in the case of renewable energy consumption, the effects of the persistence of the dependent variable over time are reinforced.

Table 6. Results from the estimations.

	Dependent Variable: lnGDPpc			
	Fixed Effects		**GMM First Differences**	
	Model 1 Coefficients	**Model 2 Coefficients**	**Model 3 Coefficients**	**Model 4 Coefficients**
Intercept	4.53741 ***	4.98322 ***	6.00215 ***	6.12148 ***
lnGDPpc (−1)			0.91416 ***	0.93148 ***
lnCO_2	0.02116 ***		0.01243 *	
lnREC	0.11850 ***	0.09212 **	0.05474 **	0.09751 ****
lnGCF	0.19670 ***	0.21579 ***	0.03409 *	0.03375 *
lnR&D	0.07503 ***	0.09505 ***	0.00413	
lnLFP	0.25339 ***	0.32933 ***	0.05123	
lnST	0.33100 ***	0.32435 *	0.03300 **	0.02784 ***
lnFDI	0.01225 ***	0.00947 *	0.00020	
lnTrade	0.43277 ***	0.44165 ***	0.09313 ***	0.01022 ***
R-Squared	0.97951	0.97818		
F-test (*p*-value)	9.90083×10^{-3}	4.72714×10^{-3}		
Breus–Pagan test (*p*-value)	0	0		
Hausman test (*p*-value)	3.65478×10^{-3}	4.65478×10^{-3}		
Observations	702	702		

Note: ***, ** and * denote statistical significance at the 1%, 5% and 10% level of significance respectively. GDPpc—Gross domestic product per capita; CO_2—CO_2 emissions; REC—Renewable energy consumption; GCF—Gross capital formation; R&D—Research and development expenditure; LFP—Labor force participation; ST—School tertiary enrollment; FDI—Foreign direct investment; Trade—International trade. Source: Authors' estimations.

5. Discussion

As we can see in Table 6, in the two estimations using fixed effects, all variables assume statistical significance for normally considered levels. The two main independent variables of this study (CO_2 emissions from burning fossil fuels and renewable energy consumption in relation to final energy consumption) contribute statistically significantly to the per capita economic growth of the European Union countries, as already verified in other studies [12,23,31,33] (among others). In our case, an important piece of evidence must be highlighted, which is the impact of these two variables on economic growth, with the impact of renewable energy consumption with respect to total energy consumption being higher than the contribution made by CO_2 emissions from burning fossil fuels. Under that condition, ceteris paribus, a 1% increase in the renewable energy consumption–total energy consumption ratio contributes to an increase in GDP per capita of 0.1185%; in the case of CO_2, however, the increase is only 0.021%, that is, an impact of about five times less. This evidence may mean that the ongoing energy transition, which is intended to decarbonize energy consumption and replace it with renewable energy consumption, will contribute positively in net terms to economic growth, despite the loss associated with the decrease in CO_2 emissions.

In Table 6, and model 2 (without the CO_2 variable), all other variables continue to show statistical significance for economic growth in the European Union. Considering endogeneity, model 4 also reveals that removing the non-significant variables R&D, LFP, and FDI, all the others keep their significance and positiveness in estimations.

Still, regarding the two models with endogeneity, the variable that most contributes to economic growth is the degree of the economy's trade openness to the outside (Trade), and in this case, under ceteris paribus condition, it is estimated that an increase of 1% in this variable causes an increase of more than 0.4% of GDP per capita, showing it as a significant variable for the sample of EU 27 countries and the period of analysis. Its significance appears jointly with the representative variables used for human capital and gross capital formation. Even though previous literature highlights the clear role of trade openness on economic growth, in the context of renewable consumption, a well-trained and highly skilled domestic labor force is required for the adoption of new technology through international trade, especially sustainable technology, that is able to provide sustainable economic growth [45]. However, CO_2 emissions also increase GDP per capita, which could be explained by the EU 27's high dependence on fossil fuels as considered in our sample. Another very impactful variable in economic growth (which is verified in the four models) is the tertiary school (ST), which once again reveals the important role that tertiary education plays in preparing students to enter the job market. More educated students increase work productivity, which impacts the profitability of companies and economic growth, in addition to the workers enjoying higher wages. It is also important to mention the positive externalities that occur when these more qualified workers spill over to other workers, triggering a virtuous cycle in companies and nations [46]. Thus, policymakers and governments should regard trade and human capital as clean energy-fostering mechanisms when developing energy demand policies that are environmentally friendly.

In the same sense, the variable labor force participation (LFP) also has a high impact on economic growth, when disregarding endogeneity, along with investment in fixed assets (GCF). In a global environment of intense competitive changes, correct and appropriate investments become economic results in the future, improving the performance of companies and economies. Moreover, a lack of awareness regarding the adversities associated with environmental pollution that is caused by non-educated populations or lack of sufficient human capital may trigger negative environmental consequences [37,39]. Still, as shown by the results in Table 6, all independent variables coefficients are positive, indicating that more efforts are necessary to promote economic growth in a sustainable way. Based on the sample analyzed here, substitution of fossil fuels by renewable energy sources may seem to be the best solution.

Concerning the FDI variable, it is considered to be an important driver in the economic growth of the countries that receive it for several reasons. According to [47], FDI is a fundamental factor in international economic integration, as it allows companies to organize their production across countries and form global value chains that contribute to the creation of a more competitive business environment [36]. Globalization, through participation in international trade and attraction of foreign direct investment, may lead to the expansion of pollution-intensive industries, especially in developing countries, where these nations are at risk of turning into pollution havens [36]. Other authors found opposing results [35], suggesting that FDI plays a key role in economic growth and simultaneously drives environmental sustainability. Our results are consistent with authors who are defending a positive role of FDI over GDP per capita, but the significance of the variable is not kept when endogeneity issues are addressed.

Finally, regarding R&D, the effect on GDP per capita is the smallest of all, but it also has a positive and significant effect. When endogeneity is addressed, the sign is kept but the significance is lost. Grafström et al. [33] mention that countries with deregulated energy markets and with lower energy-import dependence receive less government R&D support. In the EU 27 group, energy markets are becoming more deregulated, and policies are being redirected to decrease fossil fuel energy dependence and increase quotas for renewable energy productions. Still, more efforts in R&D support and the associated clean technologies and gross capital investment are necessary to reach independence in terms of energy production and consumption, and the necessary infrastructures to support renewables are needed to ensure sustainable economic growth [48].

One of the biggest differences between the two types of estimation is that, in the GMM in the first differences, some control variables lose their statistical significance, including R&D, LFP, and FDI. However, it should be noted that in these estimates (model 3) the variable that quantifies CO_2 emissions from burning fossil fuels does not show statistical significance, but renewable energy consumption in the country continues to maintain this significance. In models without endogeneity, the control variables ST, Trade, and GFC continue to maintain statistical significance, although their contribution to the formation of GDP per capita has decreased in relation to models with endogeneity. This is because the persistent effect from the previous year was excluded due to the small adjustment made in the following year.

It can be expected that a low economic growth level, alongside predominant fossil fuel dependency and technological backwardness, is responsible for environmental distress, which should be more visible in developing countries [33,34,36]. In EU 27, we are still noticing economic growth at the expense of more CO_2 emissions, even if renewable energy consumption is demonstrated to improve economic growth. Thus, policymakers should redirect and focus their attention on the promotion of lower energy dependence which we believe to be the highest problem in this group of countries. As pointed out by [1], fossil fuels are a considerable source of carbon emissions and environmental degradation. This result causes us to return the introduction, where the question of policy priorities has been addressed. Considering the type of countries under analysis, the current priority should be in the promotion of renewable sources, reducing EU 27 energy dependency, and ensuring sustainable growth as is necessary for agreements designed to fight climate change and environmental degradation.

If, as pointed out by [17] and by [18], moving towards renewable energy leads to economic development besides economic growth by reducing carbon emissions, our results indicate that the EU 27 group is on the correct track, but is still far from reaching the necessary goals of climate change neutrality, considering the simultaneously found positive impact of CO_2 emissions on economic growth. Globalization and trade foster the flow of eco-friendly technologies and modern innovative methods of production, namely in terms of renewable energy product development, ensuring low carbon emissions. For developing nations, technology stock is already low and globalization can promote technology spillovers, helping them to protect their environmental attributes. Additionally, the usual bad management of natural resources delays development in these countries, thereby decreasing economic growth. However, in the majority of the EU 27, we are dealing with supposedly developed economies, and in face of these results, we can argue that policymakers and governments should promote a more effective and aggressive policy of renewables promotion, adopting technologies that: enable the production and consumption of renewables; continue to promote and support R&D expenses, namely in renewable sources of energy; betting on human capital development (and being open-minded about new technologies and environmental awareness); and promoting gross capital investment and trade. Only then will we be able to observe lower levels of energy dependency in Europe. Additionally, governments and policymakers should create the necessary conditions for a globally deregulated energy market in Europe, which clearly demands the necessary connecting infrastructures and the funds that could be obtained through the European CO_2 emissions licenses market to turn effective the principles of pollutant–payer. For an equilibrium to be reached, and for reasons of fairness, this market should embrace all the economic activity sectors in the economies of the EU 27 group.

6. Conclusions

This study explores the impacts of: renewable energy consumption; CO_2 emissions from burning fossil fuels; investments made in fixed assets; investment in R&D; amount of population providing labor force for the production of goods and services; the level of human capital qualifications; amount of foreign investment in a country; and involvement in a country's international trade, based on the economic growth for the group of EU 27 countries during 1994 and 2019. We tried to address the identified gap in the literature regarding the lack of consensus respecting the effects of these variables on economic growth and the contradictory findings for the different variables. A more complete approach includes six variables simultaneously in the study of the nexus of CO_2 emissions–renewables–growth for an extended period of analysis and considering endogeneity in the empirical applications.

Results highlight the positive persistent and significant effects of CO_2 emissions, renewables energy consumption, gross fixed capital investment, human capital, and trade, on economic growth, which we justify by the still high dependency of the EU 27 group on fossil fuels. Since energy is an important source of economic growth in worldwide economies, sustainable economic growth can only be achieved through prior creation of the conditions necessary to expand the production and consumption of renewables. This can only be achieved through human capital, innovative technologies able to respond to the demand, imposition of the necessary renewable sources, and continued trade openness (and here we include the unique desired electricity market network in Europe). Only then will Europe be able to grow in a sustainable way that ensures the necessary reduction of CO_2 emissions.

Despite the interesting findings, namely, that the impact of renewable energy consumption concerning total energy consumption is higher than the contribution made by CO_2 emissions from burning fossil fuels, this work presents some limitations regarding the impossibility of extending the period of analysis to provide an individual country analysis. Consequently, policies associated with the particular macroeconomic and microeconomic conditions that exist within a particular country are difficult to include as they relate to specific energy or governmental impositions. Still, the evidence provided here may mean that the ongoing energy transition, which is intended to decarbonize energy consumption and replace it with renewable energy consumption, will contribute positively in net terms to economic growth, benefiting from the associated decrease in CO_2 emissions.

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Article

Moderating Impacts of Education Levels in the Energy–Growth–Environment Nexus

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Abstract: The world's environment has deteriorated significantly over the years. Pollution's impact on the ecosystem is undeniably alarming. Many factors have been found in the literature to impact environmental pollution. However, there is a dearth of literature on the impacts of education levels on environmental pollution. This study, therefore, examines the effects of education levels and their moderating impacts on the energy–growth–environment nexus. Fundamentally, the study investigates the effects of economic growth, natural resources, and the marginal effects of energy consumption on environmental pollution at various levels of education in Africa from 1990 to 2017. The cross-sectional dependence test, unit root test, cointegration test, fixed effect estimation, Driscoll–Kraay standard errors, fully modified least ordinary least square estimator and dynamic ordinary least square estimator are employed for the analyses. The findings reveal that education increases environmental pollution and that the marginal impacts of energy consumption at various education levels adversely impact environmental pollution, implying that increased school enrollments exacerbate the adverse effects of energy consumption. The findings also show that economic growth, population, and trade openness degrade the environment, whereas natural resources promote environmental sustainability. We deduce several policy implications to improve environmental quality in Africa based on the findings.

Keywords: carbon emissions; economic growth; energy consumption; education; environmental pollution

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1. Introduction

Environmental pollution and climate change are the main challenges to sustainable global development and growth [1]. The environment of the world has deteriorated significantly over the past several decades. The environmental pollution impact on the planet's geography is profound, and environmental stakeholders are incredibly concerned. As a result, countries are being pushed to solve environmental issues while sustaining economic growth [2]. Environmental destruction in many countries is attributed mainly to human activities such as rapid industrialization, population growth, economic expansion, urbanization, natural resources depletion and overdependence on fossil fuel consumption [3–7]. Carbon dioxide (CO2) emissions are undeniably one of the primary contributors to environmental pollution [8–12]. As a result, various studies have employed CO2 emissions to measure the environmental impacts of human activities [7,13–16].

Understanding the mechanism of CO_2 emissions is crucial for energy decarbonization and climate change mitigation. Therefore, countries are devoting their resources to mitigating the effects of climate change and reducing the inherent vulnerabilities associated with frequent natural disasters. The countries are implementing new environmental strategies and regulations to alter their energy consumption patterns, rely more on renewable energy sources, and meet stricter environmental standards through advanced technologies in their manufacturing and consumption activities. Additionally, they are implementing various climate policies and coordinating several global efforts to mitigate the adverse effects of global warming [17,18]. Some of these notable efforts are the Kyoto Protocol of 1997, the Paris Convention of 2015, and the Sustainable Development Goals (SDGs) of 2015. However, education is required for the potential positive impacts of government regulations, strategies, and policies on environmental quality. Without education, government regulatory measures, efforts, and policies will not be enough to promote environmentally friendly behaviors and accomplish environmental benefits [19].

Education can impact the environment by raising awareness and motivating people to protect it. It helps people reconsider their habits that are harmful to the environment, allowing them to utilize resources effectively and gain a deeper awareness of environmental challenges [20]. When it comes to environmental policy issues, educated people are more likely to back them. A country's reliance on a particular energy source is inextricably linked to its level of educational attainment [21]. Existing research, however, indicates that education might have two conflicting impacts on environmental quality. In societies with low levels of education, a boost in school enrollment would accelerate the consumption of non-renewable energy resources, causing environmental damage [19]. Increased knowledge in these countries increases the use of environmentally damaging products. On the other hand, when school enrollments reach certain levels, more education will boost eco-friendly technology and environmental knowledge [22]. Furthermore, more education attracts technology, and the level of education impacts how firms employ technologies [23,24].

The argument underlying education's ability to moderate the environmental impacts of energy consumption is straightforward. Theoretically, when education levels rise, the energy consumption structure might change dramatically by enabling consumers to substitute energy sources and comprehend detailed information about energy prices and usage [25]. Additionally, increased educational levels can result in more knowledgeable customers making more informed energy usage decisions, thereby moderating the environmental impact of energy consumption. However, the direction of such a possible impact needs to be empirically examined. Hence, it is crucial to investigate education's probable effects on environmental pollution through its moderating impacts on energy consumption. Therefore, the specific objective of this paper is to examine the impacts of education levels and their moderating effects on the energy–growth–environment nexus in Africa. Fundamentally, it seeks to ascertain the effects of economic growth, natural resources, and the marginal effects of energy consumption on environmental pollution at various levels of education. We test the hypothesis that economic growth, natural resources, energy consumption and education have no impacts on environmental pollution. We also test the hypothesis that education has no moderate effects on energy consumption.

This study contributes to the literature in three ways. First, we investigate the impacts of education levels on environmental pollution. Scarce attention is given to the impacts of education on environmental pollution, particularly in Africa. Such insufficient attention is somewhat surprising since the role of education in recognizing the causes of global climate change and its consequences on the environment cannot be denied. Most environmental literature ignores the effects of education levels on the environment. This study fills the gap by examining the effects of primary, secondary, and tertiary education levels on environmental pollution. Second, we examine the moderating impacts of energy consumption and education levels on environmental pollution. Most studies on education's influence on the environment assume only a direct effect. It is vital to emphasize that when the education variable takes a direct impact, the relationship between education and environmental pollution can only go one way. As a result, education's direct and moderating impacts cannot be studied separately. The current study is novel as it uses the moderating effects of education levels on environmental pollution. Third, we examine the contingency effects of education by calculating the marginal impacts of energy consumption on environmental pollution at various levels of education. Thus, we separately estimate education impacts at mean, minimum and maximum levels. From a policy standpoint, examining what happens at the mean, minimum, and maximum levels of primary, secondary, and tertiary education is critical. Ignoring such empirical analysis may result in incorrect policy recommendations.

There is a scarcity of evidence from research that has used marginal impacts to examine the link between education levels and environmental pollution.

To the best of our knowledge, this is the first study to examine the marginal impacts of energy consumption at different levels of education on environmental pollution in Africa. Africa is particularly vulnerable to the harmful effects of climate change. Hence, it is essential to investigate these implications. Africa's temperature is expected to climb faster than the world average, reaching 4–6 degrees Celsius this century [26]. Nevertheless, according to UNESCO 2019 reports, Africa has the greatest incidence of school exclusion in the world, with more than 20% of primary school-age children denied the right to education.

The rest of the paper is organized as follows: A review of the literature is presented in Section 2. The methodologies used in the study are described in Section 3. Section 4 presents and discusses the results. Section 5 concludes the paper.

2. Literature Review and Knowledge Gap

2.1. Literature Review

Extensive research has been conducted on the link between economic growth and the environment. The environmental Kuznets curve (EKC) hypothesis proposed by Grossman and Krueger [27] has been used in the environmental literature to identify pollution causes. The EKC hypothesis postulates that environmental pollution rises in the early stages of economic growth as economic output rises. This process will continue until a certain economic growth level is reached, at which point economic growth and environmental pollution will begin to diminish. However, empirical research is ambiguous regarding evidence to validate the EKC hypothesis. Some empirical research, for example, has offered evidence supporting the EKC hypothesis. For example, some empirical studies have provided proof for the EKC hypothesis [12,28–37]. In contrast, some studies have discovered no substantial evidence to support the EKC hypothesis [11,38–40].

Additionally, several empirical investigations have demonstrated that energy consumption increases pollution levels [8,41–45]. They documented that as energy usage rises, pollutant levels rise [46,47]. However, some studies reveal that renewable energy reduces pollution [3,4,48–50]. Another variable that influences environmental pollution is natural resources. Some scholars believe that natural resources significantly influence atmospheric pollutants and have reported mixed findings. For instance, Bekun et al. [51] and Sun et al. [52] found that natural resources have detrimental effects on environmental sustainability. In contrast, Balsalobre-Lorente et al. [53], Khan et al. [15] and Shittu et al. [54] found that natural resources boost environmental quality. Danish et al. [14] discovered that while an abundance of natural resources increases CO2 emissions in South Africa, it mitigates them in Russia. Correspondingly, Ahmad and Satrovic [55] found that the direct impacts of natural resources reduce energy and carbon efficiency while positively moderating the effects of fiscal decentralization and financial inclusion on environmental sustainability.

Education-related variables have recently been incorporated into the study. For example, Chankrajang and Muttarak [56] discovered that learning about eco-friendly conduct leads to pro-environmental decisions, aiding CO2 reduction and environmental protection. Furthermore, education is required to understand the worldwide repercussions of climate change and its negative consequences. Likewise, Balaguer and Cantavella [21] discovered that education enhances environmental quality in Australia. Other studies have confirmed Chankrajang and Muttarak's conclusions about the favorable effects of education on pro-environmental attitudes and environmental quality. Meyer [57], for example, noticed that educated individuals in Europe are more aware of the external consequences of their actions and, as a result, are more concerned with societal welfare.

Similarly, it was found that education improves the environment in Turkey [5] and the OECD [58], and APEC countries [59]. Nevertheless, Zafar et al. [60] discovered that education increases environmental deterioration to some extent, which does not enhance the quality of the environment. Likewise, Mahalik et al. [19] discovered that primary education increases environmental degradation in China, Brazil, India, and South Africa, whereas secondary education enhances it. Maranzano et al. [61] discovered that the Educational EKC hypothesis holds for economies with significant income inequality and that the emissions–income elasticity seems to decrease when education is taken into account in OECD Countries. Conversely, Liu et al. [62] and Zhang et al. [63] found that education reduces environmental quality in Latin American and developing countries. Still, according to Boukhelkhal [64], education will increase environmental damage in the short run but decrease it in the long run in Algeria.

In examining the moderating effects of education, Katircioglu et al. [65] demonstrated that education's moderating function and direct influence on energy usage are harmful to the environment in Cyprus. Similarly, Osuntuyi and Lean [66] found that education worsens environmental deterioration. Its moderating influence, however, helps to mitigate energy consumption's negative effects on the environment in high- and upper-middle-income groups while amplifying them in low- and lower-middle-income groups. Similarly, Osuntuyi and Lean [67] discovered that the direct and moderating impacts of education exacerbate environmental pollution in Africa.

Education has also been employed as a proxy for human capital in other studies, with mixed results. Human capital, for example, has been demonstrated to lessen environmental degradation [23,31,68–71] without decreasing economic growth [72]. However, research by Zhang et al. [16] and Ahmed et al. [73] has established that human capital is harmful to the environment, refuting this assumption. On the other hand, Tang et al. [74] looked at the indirect and direct effects of human capital in 114 nations. They discovered that human capital has a significant impact on renewable energy use.

2.2. Knowledge Gap

The majority of studies on the impact of education on the environment [19,59,61–64] only consider direct impacts. Khan [23], Katircioglu et al. [65], Osuntuyi and Lean [66], and Osuntuyi and Lean [67] are notable exceptions. Khan [23] broadens the classic EKC model by including various levels of education variables and studying the moderating effects of economic growth and education levels on environmental quality. The study, however, did not consider the moderating roles of education and energy use. In contrast, Katircioglu et al. [65] only evaluated the moderating influence of higher education, whereas Osuntuyi and Lean [66] only examined the moderating impacts of primary education.

Additionally, there is a dearth of evidence from studies that have examined the relationship between education levels and environmental pollution by examining marginal impacts. Although Osuntuyi and Lean [67] evaluated the marginal effects of education, the study utilized only primary school education. Finally, researchers are divided on the environmental consequences of education, while its environment-moderating effects have received less attention. Variations in empirical methodology, data, time, or countries may have affected previous empirical findings.

3. Methodology

3.1. Model Specification

This study's theoretical framework is the EKC hypothesis of Grossman and Krueger [27]. Econometrically, the model is given as follows:

$$E = \beta_0 + \beta_1 Y_t + \beta_2 Y^2 + Z_t + \mu_t \quad (1)$$

where E_t is an indicator of environmental quality, Y_t is per capita GDP (as an economic growth measure), ${Y_t}^2$ is the square of per capita GDP, and μ_t is the normally distributed stochastic term. Z_t is a vector of additional variables that might influence environmental degradation. If $\beta_1 > 0$ and $\beta_2 < 0$, the link is inverted U-shaped, verifying the EKC hypothesis. However, if $\beta_1 < 0$ and $\beta_2 > 0$, it indicates the nexus is U-shaped. Thus, the hypothesis is not validated.

Following [27] model, the basic model for this study is specified as follows:

$$CO2_{it} = \delta_0 + \delta_1 GDP_{it} + \delta_2 GDP_{it}^2 + \delta_3 ENG_{it} + \delta_4 NRE_{it} + \delta_5 PRI_{it} + \delta_6 POP_{it} + \delta_7 TRD_{it} + \mu_{it} \quad (2)$$

$$CO2_{it} = \alpha_0 + \alpha_1 GDP_{it} + \alpha_2 GDP_{it}^2 + \alpha_3 ENG_{it} + \alpha_4 NRE_{it} + \alpha_5 SEC_{it} + \alpha_6 POP_{it} + \alpha_7 TRD_{it} + \mu_{it} \quad (3)$$

$$CO2_{it} = \chi_0 + \chi_1 GDP_{it} + \chi_2 GDP_{it}^2 + \chi_3 ENG_{it} + \chi_4 NRE_{it} + \chi_5 TER_{it} + \chi_6 POP_{it} + \chi_7 TRD_{it} + \mu_{it} \quad (4)$$

where *CO2* = carbon emissions (as an environmental pollution proxy), *GDP* = per capita real *GDP* (as an economic growth proxy), GDP^2 = square of *GDP*, *ENG* = energy consumption, *NRE* = natural resources, *PRI* = primary education, *SEC* = secondary education, *TER* = tertiary education, *POP* = population growth, *TRD* = trade openness, *i* = the country index and *t* = time index. Population and trade openness are added as control variables.

The literature has established that education determines how energy consumption choices affect the environment [25]. Therefore, to investigate the moderating roles of education, we first model the interaction between energy consumption and education variables as follows:

$$CO2_{it} = \gamma_0 + \gamma_1 GDP_{it} + \gamma_2 GDP_{it}^2 + \gamma_3 ENG_{it} + \gamma_4 NRE_{it} + \gamma_5 PRI_{it} + \gamma_6 (ENG * PRI)_{it} + \gamma_7 POP_{it} + \gamma_8 TRD_{it} + \mu_{it} \quad (5)$$

$$CO2_{it} = \eta_0 + \eta_1 GDP_{it} + \eta_2 GDP_{it}^2 + \eta_3 ENG_{it} + \eta_4 NRE_{it} + \eta_5 SEC_{it} + \eta_6 (ENG * SEC)_{it} + \eta_7 POP_{it} + \eta_8 TRD_{it} + \mu_{it} \quad (6)$$

$$CO2_{it} = \lambda_0 + \lambda_1 GDP_{it} + \lambda_2 GDP_{it}^2 + \lambda_3 ENG_{it} + \lambda_4 NRE_{it} + \lambda_5 TER_{it} + \lambda_6 (ENG * TER)_{it} + \lambda_7 POP_{it} + \lambda_8 TRD_{it} + \mu_{it} \quad (7)$$

Following that, we investigate energy consumption's marginal impacts on environmental pollution at various levels of education. We employ the partial derivatives of Equations (5)–(7) with respect to energy consumption to capture the marginal effects. The equations are specified below:

$$\frac{\partial CO2_{it}}{\partial ENG_{it}} = \gamma_3 + \gamma_6 PRI_{it} \quad (8)$$

$$\frac{\partial CO2_{it}}{\partial ENG_{it}} = \eta_3 + \eta_6 SEC_{it} \quad (9)$$

$$\frac{\partial CO2_{it}}{\partial ENG_{it}} = \lambda_3 + \lambda_6 TER_{it} \quad (10)$$

3.2. Data

The study uses annual time-series data from thirty-one African countries from 1990 to 2017. Data availability for a handful of selected nations over a long period determines the estimation timeframe. The countries are Algeria, Botswana, Benin Republic, Burkina Faso, Burundi, Cameroon, Côte d'Ivoire, Congo Republic, Egypt, Eswatini, Ethiopia, Ghana, Gambia, Guinea, Kenya, Lesotho, Madagascar, Mali, Mauritania, Mauritius, and Morocco. Others are Niger, Nigeria, Rwanda, South Africa, Senegal, Tanzania, Tunisia, Togo, Uganda and Zambia. Table 1 describes and provides the data sources for the study.

Table 1. Description of variables and sources of data.

Variables	Measurement	Sources
CO2	Thousand metric tons of CO2	WDI [75]
EFP	Measured in global hectares	EFP [76]
GDP	Constant 2010 US dollar	WDI [75]
ENG	British thermal units (Btu)	EIA [77]
NRE	A composite index of oil rents, natural gas rents, coal rents (hard and soft), mineral rents, and forest rents. Measured as a share of GDP	WDI [75]
PRI	Percentage of gross primary school enrollment	WDI [75]
SEC	Percentage of gross primary school enrollment	WDI [75]
TER	Percentage of gross tertiary school enrollment	WDI [75]
TRD	The sum of exports and imports of goods and services. Measured as a share of GDP	WDI [75]
POP	Midyear estimates	WDI [75]

Note: WDI = World Bank Development Indicator, EIA = Energy Information Administration.

Figure 1 reveals that all variables, including economic growth and its squared term, energy consumption, natural resources, education, population, and trade openness, as well as the moderating term between education variables and energy consumption, show either a positive or negative influence on environmental pollution in Africa.

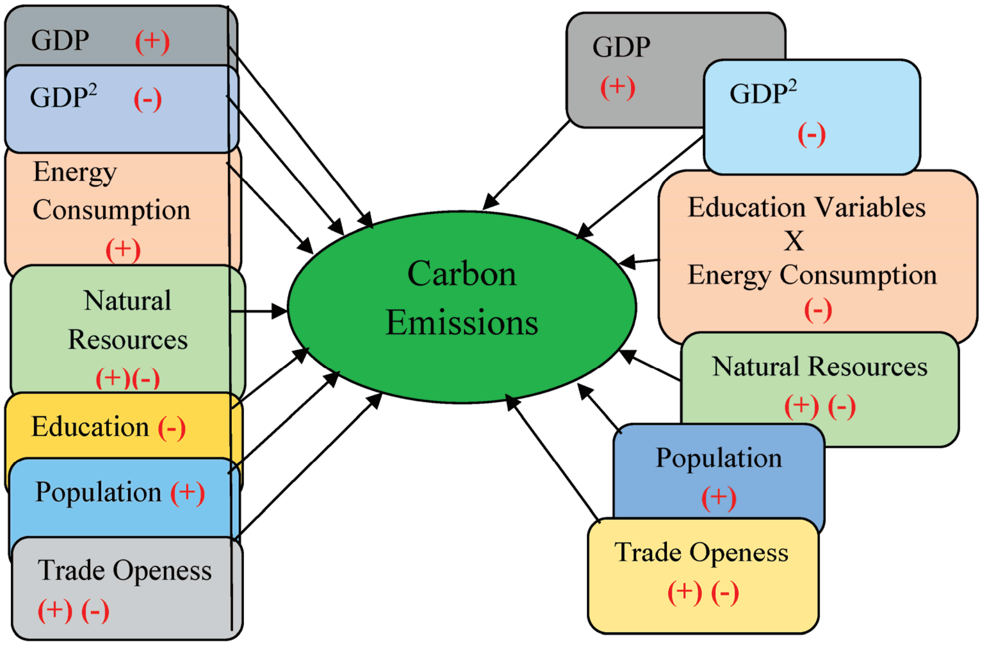

Figure 1. Conceptual framework of the variables.

3.3. Estimation Strategy

Descriptive and correlation analyses are the first steps in this study. Cross-sectional dependence (CSD), cointegration, and panel unit root tests are also investigated. We employ the Breusch and Pagan [78], Baltagi et al. [79] and Pesaran [80] tests. Second-generation stationarity tests are employed. The tests are the cross-sectionally augmented Dickey-Fuller test (CADF) and the cross-sectionally augmented IPS (CIPS) statistic [80,81]. The Westerlund [82] cointegration test is used to determine the cointegration among the variables. The test accounts for cross-section dependencies and non-strictly exogenous regressors.

We employ the variance inflation factor (VIF) to identify potential multicollinearity in all the models. The VIF values are less than 10, suggesting the absence of multicollinearity [83]. We also conducted the Breusch–Pagan/Cook–Weisberg and Wooldridge tests.

The results show the presence of heteroskedasticity and serial correlation in all the models. Thus, we employ the Driscoll and Kraay [84] (DK) standard errors (based on fixed effects estimation) for panel regressions because of heteroskedasticity, autocorrelation, and cross-sectional dependence in our models. The DK standard errors [85] are autocorrelation consistent and robust to heteroskedasticity and general forms of cross-sectional and temporal dependence [32,86,87]. The DK estimator works well with balanced and unbalanced panels and can deal with missing values [45,88,89]. Driscoll and Kraay [84] show, using large T asymptotics, that the basic non-parametric time-series covariance matrix estimator may be improved to be resilient to extremely general types of cross-sectional and temporal dependence. The adjustment of the standard error estimates ensures that the covariance matrix estimator is consistent, regardless of the cross-sectional dimension N. As a result, DK's technique avoids the shortcomings of other approaches, often inapplicable when the cross-sectional dimension N of a micro-econometric panel is high [85].

We employ the FMOLS and DOLS techniques for robustness checks. Pedroni [90] proposed the FMOLS heterogeneous panel cointegration method. The FMOLS is consistent and employs a non-parametric approach to endogeneity issues and autocorrelations [91,92]. It does not suffer significant distortions when endogeneity and heterogeneity exist [93]. It corrects serial correlation and simultaneous bias [94]. It also considers the issues related to the intercept and eliminates the missing variables biases and homogeneity restrictions [95]. On the other hand, the DOLS technique, developed by Kao and Chiang [96], is based on a parametric dynamic panel. The DOLS corrects endogeneity, simultaneity and serial correlation issues. It generates unbiased long-run estimates and supplements the static regression with leads, lags and regressors' contemporaneous values in the first difference [91,97,98]. It also has asymptotic efficiency and robustness in a small sample [97]. It also yields reliable estimates of explanatory variable coefficients in small samples [98]. Finally, we calculate the marginal impacts and compute the new standard errors based on Brambor [99]. The methodological framework of the study is show in Figure 2.

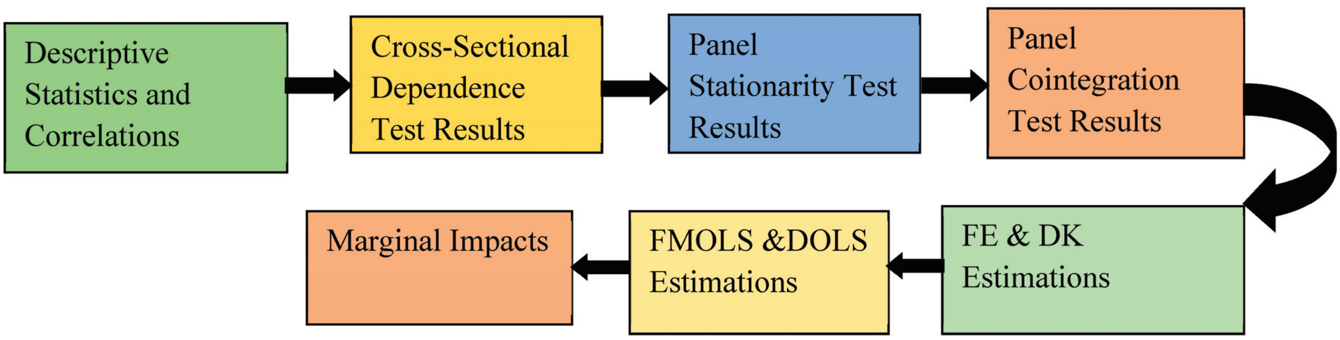

Figure 2. The methodological framework of the study.

4. Results and Discussion

4.1. Preliminary Analysis

Table 2 shows the descriptive statistics and correlation matrix of the variables used for estimations in this study. The standard deviation represents the dispersion from the mean value of each variable. Population variables have the highest standard deviation among the variables. The correlation coefficients in Table 2′s lower panel reveal the correlation analysis between the dependent variable (CO2 emissions) and other variables. Except for the natural resources variable, the independent variables are positively associated with the dependent variable.

Table 2. Descriptive statistics and correlations.

Variable	CO2	EFP	GDP	ENG	NRE	PRI	SEC	TER	POP	TRD
Mean	26,776.04	35,502,934	1807.785	0.401	9.564	92.696	41.779	17.721	22,481,021	54.076
Minimum	160	1,014,855	164.337	0.003	0.001	21.708	5.221	0.332	822,423	4.104
Maximum	447,980	1.98×10^8	10,199.48	5.734	58.65	149.307	109.444	86.714	1.91×10^8	175.798
Std. Dev.	69,641.86	46,758,195	1836.281	1.009	9.038	25.376	25.74	21.63	29,072,716	30.126
CO2	1.000									
EFP	0.555	1.000								
GDP	0.555	0.155	1.000							
ENG	0.968	0.611	0.542	1.000						
NRE	−0.039	0.273	−0.526	−0.051	1.000					
PRI	0.251	0.003	0.39	0.205	−0.1	1.000				
SEC	0.632	0.252	0.771	0.587	−0.337	0.675	1.000			
TER	0.412	0.303	0.597	0.407	−0.194	0.502	0.737	1.000		
POP	0.565	0.573	−0.309	0.6	0.435	−0.133	−0.067	−0.095	1.000	
TRD	0.186	0.063	0.652	0.182	−0.441	0.391	0.531	0.487	−0.392	1.000

Notes: CO2 = carbon emissions, EFP = ecological footprint, GDP = real GDP per capita, ENG = energy consumption, NRE = natural resources, PRI = gross primary school enrollments, SEC = gross secondary school enrollments, TER = gross tertial education enrollments, POP = population, TRD = trade openness.

The CSD findings are shown in Table 3. The results of the tests indicate that the null hypothesis of no CSD is rejected at a 1% significant level for the panels. As a result, CSD exists among the panel countries, suggesting that any shock in one of the sample countries can spread to the others.

Table 3. Cross-sectional dependence test results.

Test	Breusch–Pagan LM	Pesaran Scaled LM	Bias-Corrected Scaled LM	Pesaran CD
	2008.3820 ***	50.6095 ***	50.0354 ***	0.5065 ***

Notes: *** denotes statistical significance at the 1% level.

Table 4 displays the panel unit root test results. The findings show that the null hypothesis of the presence of unit roots in the variables at different levels cannot be rejected, implying that the panel contains unit roots. Although some variables are stationary at levels using CADF, CIPS demonstrates that they are not. As a result, we conclude that such variables are not stationary at level.

Table 4. Panel stationarity test results.

Variables	CIPS		CADF	
	Level	Difference	Level	Difference
CO2	5.983	−15.210 ***	−1.529 *	−12.293 ***
EFP	4.978	−17.843 ***	−4.298 ***	−12.998 ***
GDP	5.421	−10.377 ***	−0.013	−8.134 ***
ENG	5.663	−14.885 ***	−1.711 **	−10.919 ***
NRE	−3.43553 **	−16.080 ***	−1.137	−12.634 ***
PRI	−1.589 *	−6.647 ***	−1.274	−5.208 ***
SEC	2.883	−5.006 ***	2.185	−5.007 ***
TER	3.141	−7.181 ***	2.453	−5.119 ***
POP	10.048	−20.557 ***	−13.65 ***	−11.030 ***
TRD	−2.13001 **	−15.453 ***	−0.010	−10.785 ***

Notes: ***, ** and * indicate statistical significance at 1%, 5% and 10%, respectively, and a rejection of the null hypothesis of unit root. CO2 = carbon emissions, EFP = ecological footprint, GDP = real GDP per capita, ENG = energy consumption, NRE = natural resources, PRI = gross primary school enrollments, SEC = gross secondary school enrollments, TER = gross tertial education enrollments, POP = population, TRD = trade openness.

We utilize the Westerlung cointegration test in Table 5. We conduct cointegration tests for different models based on the educational variable included in each of them. The test statistics confirm cointegration among the variables in each model at different significance levels. Therefore, we conclude that cointegration exists among the variables of the study. Since we have confirmed cointegration among the variables, we estimate the long-run relationships.

Table 5. Panel cointegration test results.

Model	Result
Model with Primary education	−2.854 ***
Model with Secondary education	−2.376 ***
Model With Tertiary education	−1.985 **

Notes: *** and ** indicates statistical significance at the 1% and 5% level of significance.

4.2. Estimation Results

Table 6 shows the estimated impact of economic growth, energy consumption, natural resources, and education on Africa's environmental pollution. Models 1–2 include the primary education variable, Models 3–4 contain the secondary education variable, and Models 5–6 have the tertiary education variable. Models 7–8, 9–10 and 11–12 incorporate interaction terms for the primary, secondary, and tertiary education variables. The results are generally similar.

Table 6. FE and DK estimations.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Variables	**FE**	**DK**	**FE**	**DK**	**FE**	**DK**	**FE**	**DK**	**FE**	**DK**	**FE**	**DK**
GDP	0.193 ***	0.193 ***	0.145 ***	0.145 **	0.252 ***	0.252 ***	0.191 ***	0.191 ***	0.180 ***	0.180 ***	0.253 ***	0.253 ***
	(0.050)	(0.054)	(0.054)	(0.066)	(0.059)	(0.048)	(0.053)	(0.058)	(0.062)	(0.049)	(0.064)	(0.049)
GDP^2	0.001	0.001	0.011	0.011	0.001	0.001	0.001	0.001	0.018	0.018	0.001	0.001
	(0.019)	(0.011)	(0.018)	(0.020)	(0.018)	(0.015)	(0.019)	(0.011)	(0.019)	(0.024)	(0.020)	(0.018)
ENG	0.461 ***	0.461 ***	0.349 ***	0.349 ***	0.273 ***	0.273 ***	0.461 ***	0.461 ***	0.343 ***	0.343 ***	0.274 ***	0.274 ***
	(0.029)	(0.054)	(0.031)	(0.048)	(0.032)	(0.040)	(0.029)	(0.054)	(0.031)	(0.046)	(0.035)	(0.047)
NRE	−0.052 ***	−0.052 ***	−0.027 *	−0.027 **	−0.020	−0.020	−0.053 ***	−0.053 ***	−0.025 *	−0.025 *	−0.020	−0.020
	(0.015)	(0.017)	(0.015)	(0.012)	(0.015)	(0.012)	(0.015)	(0.017)	(0.015)	(0.013)	(0.015)	(0.012)
PRI	0.128 ***	0.128 **					0.133 **	0.133 *				
	(0.046)	(0.055)					(0.060)	(0.067)				
SEC			0.148 ***	0.148 ***					0.120 ***	0.120 ***		
			(0.037)	(0.021)					(0.045)	(0.038)		
TER					0.093 ***	0.093 ***					0.093 ***	0.093 ***
					(0.022)	(0.013)					(0.025)	(0.015)
POP	0.978 ***	0.978 ***	0.996 ***	0.996 ***	1.095 ***	1.095 ***	0.979 ***	0.979 ***	1.009 ***	1.009 ***	1.095 ***	1.095 ***
	(0.065)	(0.090)	(0.081)	(0.050)	(0.073)	(0.037)	(0.065)	(0.090)	(0.082)	(0.050)	(0.074)	(0.035)
TRD	0.195 ***	0.195 ***	0.231 ***	0.231 ***	0.188 ***	0.188 ***	0.195 ***	0.195 ***	0.234 ***	0.234 ***	0.189 ***	0.189 ***
	(0.032)	(0.048)	(0.032)	(0.027)	(0.033)	(0.031)	(0.032)	(0.047)	(0.032)	(0.027)	(0.034)	(0.032)
ENG×PRI							0.003	0.003				
							(0.027)	(0.012)				
ENG×SEC									−0.016	−0.016		
									(0.014)	(0.012)		
ENG×TER											−0.001	−0.001
											(0.009)	(0.008)
Constant	−8.881 ***	−8.881 ***	−9.190 ***	−9.190 ***	−11.335 ***	−11.335 ***	−8.895 ***	−8.895 ***	−9.583 ***	−9.583 ***	−11.348 ***	−11.348 ***
	(1.038)	(1.663)	(1.295)	(0.990)	(1.304)	(0.829)	(1.044)	(1.646)	(1.341)	(0.823)	(1.323)	(0.753)
Observations	810	810	566	566	568	568	810	810	566	566	568	568
No of Countries	31		31		31		31		31		31	
Mean VIF	6.40		7.78		7.05		6.20		7.39		7.93	
Heterosk-edasticity	37.48 [000]		27.88 [000]		39.20 [000]		37.13 [000]		28.74 [000]		35.60 [000]	
Serial Correlation	66.846 [000]		52.398 [000]		65.466 [000]		60.555 [000]		52.122 [000]		65.454 [000]	

Notes: ***, ** and * indicate statistical significance at 1%, 5% and 10%, respectively. Standard errors in parenthesis. Probability values are in the bracket.

The results show that economic growth is positive and statistically significant in all our estimations. Our findings are consistent with those of previous studies. The findings indicate that Africa may have neglected environmental preservation to achieve economic growth. The present economic growth may be unsustainable because of the African economy's dependence on fossil fuels. According to the findings, a slowdown in economic development might positively impact the environment. On the contrary, this strategy is not viable since policy intervention must consider harmful effects on environmental quality via economic growth. It is probable that due to the continent's sustained economic growth trend, environmental pollution may become a problem. This argument becomes apparent when analyzing the effects of the squared term of economic growth. The squared terms of economic growth coefficients are insignificant in our estimations. These findings imply that the EKC hypothesis is not feasible in Africa. They also support the view that the EKC does not appear by chance and underline the need for Africa-tailored policies that counteract the negative environmental impacts of economic growth with education.

The positive nexus between CO2 emissions and the energy consumption coefficient is positive and statistically significant, suggesting that energy consumption significantly aggravates environmental pollution in Africa. These findings are in line with those of Ehigiamusoe [4] and Zafar [60]; however, they contradict those of others who have discovered that using renewable energy reduces CO2 emissions [59,74]. This result can be ascribed to Africa's growing reliance on fossil fuel energy. In Africa, fossil fuel consumption accounts for more than 90% of overall energy consumption. Increased fossil fuel use results in higher CO2 release [100]. Furthermore, Africa's rapid industrialization and transportation network growth have boosted energy consumption, resulting in negative environmental externalities such as increasing CO2 emissions. As African economies rise, so does the need for fossil fuels for commercial, residential, and industrial usage, resulting in rising greenhouse gas (GHG) emissions.

The negative relationship between natural resources and CO2 emissions illustrates that increasing natural resource usage decreases pollution in Africa. These findings agree with those of Danish et al. [14], Balsalobre-Lorente et al. [101], Khan [15], Zhang et al. [16] and many others but differ from the findings of [102]. These findings imply that natural resource utilization helps improve Africa's environmental quality. Additionally, the findings confirm that countries with abundant natural resources have a higher environmental quality standard than those with a scarcity of natural resources [16].

Surprisingly, primary, secondary and tertiary education levels positively affect CO2 emissions, implying that they adversely influence environmental pollution in Africa. These findings corroborate those of Ahmed et al. [73], Katircioglu et al. [65] and Zafar et al. [60], and Zafar et al. [103]. They discovered that education contributes to environmental pollution. However, this discovery contradicts previous research indicating that education lowers environmental pollution [5,21,59,72]. According to the findings, a higher level of education facilitates access to energy-intensive technology. These findings could be explained by the fact that education programs in Africa lack specialized content on environmental sustainability. Without energy-saving training and targeted environmental awareness initiatives, education will likely foster a more resource-intensive, affluent lifestyle, contributing to environmental pollution [73]. These findings show that education cannot help lessen environmental pollution without an environmentally sustainable curriculum. A comprehensive set of environmental rules is essential to derive any value from education. Otherwise, education will increase people's purchasing power, energy usage, and usage of unsustainable natural resources, resulting in environmental pollution. Incorporating environmental content into education, raising media awareness, and providing energy efficiency training are all possible policy options for boosting the environmental benefits of education [103].

The findings also show that the interaction term coefficients between energy consumption and education variables are not statistically significant. However, just because the coefficients of the interaction terms are insignificant does not imply that the variables do not interact [74]. The reason is that the interaction terms are not interpreted as unconditional effects. Thus, we need to calculate the marginal impacts [99]. Section 4.4 examines the marginal impacts of energy consumption at different educational levels.

The population coefficient shows significantly positive relationships with CO2 emissions in all our models, suggesting that the population causes serious environmental pollution in Africa. The findings concur with those of Hanif et al. [48], Ohlan [104] and Wang et al. [105]. With the end of colonialism in Africa came a striking expansion of social services across the continent, notably in healthcare and education. Due to this increase, infant mortality significantly decreased, and population growth quickly increased [106]. Africa is the fastest-growing continent, with the highest population growth rate. The population of Sub-Saharan Africa is anticipated to double by 2050 [107]. Similarly, the empirical findings also indicate that trade openness increases environmental pollution. The findings align with Ali et al. [13], Abid [38] and Pata and Caglar [70]. These findings might be because, during an earlier stage of development, the primary objective of African policymakers was to achieve growth, even at the expense of the environment. As a result, low-cost, polluting technologies were introduced into African nations to promote output, and the technical impact of trade openness deteriorated environmental quality in the process [108].

4.3. Robustness Checks

To determine how sensitive the results are to various estimation strategies and methods, we performed a number of robustness checks. First, we used the FMOLS and DOLS methodologies to assess the robustness of our estimation results. The results in Table 7 are similar to those in Table 6. The coefficients have comparable signs, sizes, and significance. The findings confirm that our estimations are robust. Second, the robustness checks involve using ecological footprints as an alternative proxy for environmental pollution. The results are shown in Table 8. The results are similar to our earlier results in Table 6 except for some variables. The findings show that energy consumption and natural resource use increase environmental pollution, while trade openness exerts negative relationships with environmental pollution. Education variables have mixed impacts. Primary education is significantly positive, implying that primary education contributes to environmental degradation. On the other hand, the secondary education variable is significantly negative, indicating that secondary education reduces environmental degradation. In contrast, tertiary education has no significant impact on environmental pollution in Africa. Moreover, the findings indicate that the moderating role of education and energy consumption exacerbates environmental pollution.

Table 7. FMOLS and DOLS estimations.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Variables	**FMOLS**	**DOLS**	**FMOLS**	**DOLS**	**FMOLS**	**DOLS**	**FMOLS**	**DOLS**	**FMOLS**	**DOLS**	**FMOLS**	**DOLS**
GDP	0.176 **	0.275 ***	−0.004	−0.053	0.250 **	0.190	0.186 **	0.300 ***	0.047	0.511 ***	0.308 ***	0.165
	(0.077)	(0.074)	(0.084)	(0.094)	(0.098)	(0.138)	(0.080)	(0.079)	(0.098)	(0.196)	(0.109)	(0.150)
GDP^2	0.016	−0.033	0.015	−0.075*	0.007	−0.048	0.019	−0.035	0.023	−0.263 **	0.029	−0.011
	(0.030)	(0.035)	(0.029)	(0.040)	(0.030)	(0.060)	(0.029)	(0.036)	(0.030)	(0.109)	(0.034)	(0.072)
ENG	0.471 ***	0.316 ***	0.410 ***	0.237 ***	0.240 ***	0.283 ***	0.462 ***	0.311 ***	0.396	0.168 ***	0.265 ***	0.249 ***
	(0.044)	(0.040)	(0.047)	(0.044)	(0.055)	(0.073)	(0.043)	(0.040)	(0.048)	(0.056)	(0.060)	(0.079)
NRE	−0.063 ***	−0.038 **	−0.004	−0.025	−0.019	−0.001	−0.060 ***	−0.033 *	−0.003	−0.030	−0.021	−0.004
	(0.022)	(0.019)	(0.021)	(0.020)	(0.023)	(0.025)	(0.022)	(0.020)	(0.021)	(0.025)	(0.023)	(0.026)
PRI	0.152 **	0.152 **					0.160*	0.054				
	(0.070)	(0.070)					(0.089)	(0.091)				
SEC			0.110 *	0.196 ***					0.073 ***	0.022		
			(0.062)	(0.050)					(0.073)	(0.080)		
TER					0.106 ***	0.106 **					0.082 *	0.092 *
					(0.038)	(0.045)					(0.042)	(0.048)
POP	0.991 ***	1.116 ***	1.115 ***	1.464 ***	1.118 ***	1.054 ***	0.990 ***	1.130 ***	1.136 ***	1.120 *	1.141 ***	1.130 ***
	(0.103)	(0.094)	(0.137)	(0.130)	(0.128)	(0.186)	(0.102)	(0.097)	(0.137)	(0.616)	(0.132)	(0.204)
TRD	0.231 ***	0.116 ***	0.233 ***	0.080 *	0.237 ***	0.116 *	0.227 ***	0.122 ***	0.232 ***	0.061	0.258 ***	0.106 *
	(0.049)	(0.041)	(0.052)	(0.044)	(0.054)	(0.059)	(0.048)	(0.042)	(0.052)	(0.060)	(0.056)	(0.061)
ENG×PRI							0.012	0.054				
							(0.040)	(0.042)				
ENG×SEC									0.019	0.053		
									(0.021)	(0.043)		
ENG×TER											0.018	0.001
											(0.015)	(0.018)

Notes: ***, ** and * indicate statistical significance at 1%, 5% and 10%, respectively. Standard errors in parenthesis.

Table 8. FE and DK estimations using ecological footprints as a proxy for a robustness check.

	(2)	(3)	(7)	(8)	(2)	(3)	(2)	(3)	(2)	(3)	(2)	(3)
Variables	**FE**	**DK**	**FE**	**DK**	**FE**	**DK**	**FE**	**DK**	**FEM**	**DK**	**FE**	**DK**
GDP	0.307 ***	0.307 ***	0.377 ***	0.377 ***	0.385 ***	0.385 ***	0.259 ***	0.259 ***	0.343 ***	0.343 ***	0.254 ***	0.254 ***
	(0.028)	(0.026)	(0.033)	(0.031)	(0.037)	(0.053)	(0.029)	(0.042)	(0.038)	(0.033)	(0.038)	(0.033)
GDP^2	0.129 ***	0.129 ***	0.099 ***	0.099 ***	0.111 ***	0.111 ***	0.130 ***	0.130 ***	0.092 ***	0.092 ***	0.066 ***	0.066 ***
	(0.011)	(0.004)	(0.011)	(0.007)	(0.012)	(0.009)	(0.011)	(0.005)	(0.012)	(0.009)	(0.012)	(0.012)
ENG	0.036 **	0.036**	0.025	0.025	0.001	0.001	0.031 *	0.031 ***	0.030	0.030 **	−0.072 ***	−0.072 ***
	(0.016)	(0.014)	(0.019)	(0.016)	(0.020)	(0.027)	(0.016)	(0.010)	(0.019)	(0.014)	(0.021)	(0.025)
NRE	0.057 ***	0.057 ***	0.056 ***	0.056 ***	0.057 ***	0.057 ***	0.051 ***	0.051 ***	0.055 ***	0.055 ***	0.058 ***	0.058 ***
	(0.008)	(0.011)	(0.009)	(0.014)	(0.009)	(0.017)	(0.008)	(0.010)	(0.009)	(0.014)	(0.009)	(0.018)
PRI	0.120 ***	0.120 ***					0.234 ***	0.234 **				
	(0.025)	(0.041)					(0.033)	(0.095)				
SEC			−0.096 ***	−0.096 **					−0.070**	−0.070 *		
			(0.023)	(0.037)					(0.027)	(0.038)		
TER					−0.011	−0.011					0.044 ***	0.044 **
					(0.014)	(0.018)					(0.015)	(0.020)
POP	0.748 ***	0.748 ***	1.042 ***	1.042 ***	0.928 ***	0.928 ***	0.756 ***	0.756 ***	1.029 ***	1.029 ***	0.905 ***	0.905 ***
	(0.036)	(0.049)	(0.050)	(0.033)	(0.046)	(0.033)	(0.035)	(0.041)	(0.050)	(0.033)	(0.043)	(0.030)
TRD	−0.073 ***	−0.073 ***	−0.077 ***	−0.077 ***	−0.106 ***	−0.106 ***	−0.080 ***	−0.080 ***	−0.079 ***	−0.079 ***	−0.143 ***	−0.143 ***
	(0.017)	(0.009)	(0.020)	(0.020)	(0.021)	(0.021)	(0.017)	(0.007)	(0.020)	(0.022)	(0.020)	(0.024)
ENG×PRI							0.078 ***	0.078 **				
							(0.014)	(0.037)				
ENG×SEC									0.015 *	0.015 ***		
									(0.009)	(0.005)		
ENG×TER											0.046 ***	0.046 ***
											(0.005)	(0.004)
Constant	1.986 ***	1.986 **	−2.322 ***	−2.322 ***	−0.838	−0.838	1.679 ***	1.679 ***	−1.945 **	−1.945 ***	0.300	0.300
	(0.572)	(0.789)	(0.790)	(0.645)	(0.822)	(0.798)	(0.565)	(0.562)	(0.817)	(0.667)	(0.777)	(0.632)
Observations	810	810	566	566	568	568	810	810	566	566	568	568
Number of Countries	31		31		31		31		31		31	
Mean VIF	7.26		8.85		7.99		6.20		7.39		7.93	
Heterosk-edasticity	39.37 [0.000]		22.26 [0.000]		23.22 [0.000]		34.25 [000]		15.02 [000]		16.09 [0.000]	
Serial Correlation	21.557 [0.000]		6.050 [0.0201]		9.343 [0.0048]		21.523 [000]		5.931 [0.0213]		9.810 [0.0048]	

Notes: ***, ** and * indicate statistical significance at 1%, 5% and 10%, respectively. Standard errors in parenthesis. Probability values are in the brackets.

4.4. Marginal Impacts

Table 9 shows the results of the marginal impacts. Following that, we discuss the marginal impact of energy usage on environmental pollution at the minimum, mean and maximum levels of education. Our findings show that the marginal impacts of energy consumption at various levels of education (primary, secondary and tertiary) positively impact environmental pollution. The results support Osuntuyi and Lean [67], who revealed that education had direct and moderating effects on environmental pollution. According to the findings, higher school enrollments intensify the negative consequences of energy consumption in Africa. Again, these findings can be attributed to the absence of environmental awareness content in African countries' curricula. When the magnitudes of the impacts are compared, primary schooling has the most negative marginal impacts on energy consumption. The amplitude of the impacts decreases with secondary and tertiary education variables. These findings show that low-educated individuals lack an understanding of environmental quality and consume more non-renewable energy, contributing to environmental damage. In comparison, those with better education and income would purchase energy-saving technology that is less harmful to the natural environment [19].

Table 9. Marginal impacts of energy consumption (at different levels of education).

		Minimum	**Mean**	**Maximum**
ENG×PRI	$\partial CO2_{it}/\partial ENG_{it}$	0.471 ***	0.476 ***	0.478 ***
		(0.077)	(0.091)	(0.097)
ENG×SEC	$\partial CO2_{it}/\partial ENG_{it}$	0.316 ***	0.287 ***	0.268 ***
		(0.034)	(0.032)	(0.039)
ENG×TER	$\partial CO2_{it}/\partial ENG_{it}$	0.274 ***	0.273 ***	0.272 ***
		(0.053)	(0.039)	(0.037)

Note: *** indicates statistical significance at a 1% level. Figures in parenthesis are standard errors calculated based on Brambor [99]. The marginal impacts are based on the results of DK estimation.

5. Conclusions and Policy Implications

The impact of pollution on the environment is undoubtedly alarming. Over time, the world's environment has degraded substantially. Several variables have been identified in the literature as impacting environmental pollution. However, the literature on the impacts of education levels on environmental pollution is limited. As a result, from 1990 to 2017, this study investigated the moderating impacts of education levels in the energy–growth–environment nexus in Africa. We employed fixed effect estimation and Driscoll–Kraay standard errors and computed the marginal impacts of education. For a robustness check, we used the FMOLS estimator and DOLS estimator. We also utilized the ecological footprint as an additional proxy for environmental pollution. The paper's empirical findings yield several intriguing inferences with significant policy implications.

The findings indicate that pollution rises as the economy grows. However, the findings show that the squared terms of economic growth coefficients are insignificant, suggesting that the EKC is invalid. The results also demonstrate that energy consumption significantly increases environmental pollution in Africa. On the other hand, natural resources were found to reduce environmental pollution. Education levels at the primary, secondary and tertiary levels have been shown to have adverse effects on environmental pollution. Additionally, the findings reveal no statistical significance for the interaction term coefficients between energy consumption and the education variables. The results also divulge that the marginal effects of energy consumption at different levels of education contribute to environmental damage. According to the findings, higher school enrollments exacerbate the negative impacts of energy consumption in Africa. In all of our models, the population coefficient has a significantly positive relationship with CO2 emissions, suggesting that the population causes serious environmental pollution. Similarly, the empirical findings show that trade openness contributes to environmental damage in Africa.

Based on a shred of empirical evidence, this study highlights several policy implications for environmental sustainability. The invalidity of the EKC hypothesis demonstrates that economic growth is not a remedy for Africa's environmental pollution. Thus, effective measures are required to reduce environmental pollution significantly and promptly. The massive use of fossil fuels to generate economic growth has aggravated African environmental pollution. Therefore, Africa should decrease its dependency on fossil fuels while increasing its use of renewable energy sources.

Furthermore, governments in Africa must develop legislation to educate the populace about natural resource exploitation to prevent deforestation and land degradation, which will mitigate sustainability problems. Increasing awareness and leveraging governmental regulatory pressures may be a way to address environmental sustainability issues. Additionally, decision-makers should implement measures to balance the demand and supply of resources that will eventually contribute to preserving the environment's quality. The negative consequences of education on Africa's environment show that education alone will not result in a more ecologically conscious attitude or better environmental quality. School curricula must be transformed to foster environmental knowledge, competence, and mindset to combat environmental pollution. Hence, environmental education must be incorporated into the African education curriculum, necessitating interactive teaching and learning approaches that encourage and empower people to alter their environmental behavior and take action for sustainable development. Incorporating environmental sustainability knowledge and practices into African countries' education curricula can promote the sustainable use of energy and reduce environmental concerns in Africa.

Additionally, education is a crucial tool for implementing sustainable development in Africa. It offers an essential framework for integrating apparent social, economic, and environmental conflicts into a coherent idea and the goal of sustainable well-being for all. This extends beyond the fact that education is listed as a single sustainable development goal, necessitating a more profound comprehension of education's function as a cross-cutting implementation strategy to boost accomplishments across many other goals in Africa. A more comprehensive knowledge of environmental education creates a stronger mechanism for promoting environmental sustainability. Therefore, achieving a sustainable development agenda in Africa depends on people having appropriate environmental knowledge and adopting proactive attitudes toward resolving environmental issues throughout their lifetimes.

The findings that population growth promotes environmental deterioration highlight the importance of increasing environmental awareness programs, encouraging people to adopt eco-friendly lifestyles, and rigorously monitoring the impacts of population growth on environmental sustainability. Furthermore, African authorities should use international trade to preserve environmental quality. Because small-scale industry players may be unable to produce endogenous clean production methods, trade openness might be leveraged to import cleaner technologies for those firms. With this approach, players at different industry levels will have enough time to establish their production methods and capitalize on the benefits of imported technology during that period.

In addition, this study's outcomes show that some variables' environmental impacts vary depending on the environmental indicator used. This could be because CO2 emissions only account for a portion of environmental damage, whereas ecological footprint provides a more comprehensive environmental sustainability assessment. As a result, Africa should implement comprehensive environmental policies that consider not just carbon emissions but also ecological footprint components such as built-up land, cropland, carbon absorption land, fishing grounds, forest area and grazing land.

This study, like so many others, has limitations. One potential drawback of the study is that we employ data from several institutions, which may have measurement errors. Furthermore, the study's empirical approach uses the DK, FMOLS, and DOLS estimators. Different panel data techniques may provide different outcomes. As a result, future studies using data from an extended period and new methods could be conducted to verify the validity of the findings of this study. Moreover, because some data were unavailable for an extended period, no country-specific analysis was carried out. Given this constraint, future research should concentrate on time-series analysis at the national level. Exploring the relationship between these variables within each country will be necessary to understand the relationship fully and will be critical for directing sustainable development policy. Additionally, total energy was used in the study. Future research could look at the relationship using disaggregated data. Finally, future studies should use the per capita version of carbon emissions and energy consumption rather than the absolute figures used in the current study.

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Article

Analyzing the Influence of Philanthropy on Eco-Efficiency in 108 Countries

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Abstract: This paper analyzes philanthropy's influence on countries' eco-efficiency. The hypothesis to be verified is that philanthropy can favour the eco-efficiency. A data panel was built with statistical information from 2009 to 2018. Two methods were applied. First, a Data Envelopment Analysis model output oriented was estimated to identify the situation of overall efficiency in countries. We consider the relationship between Gross Domestic Product per capita and carbon dioxide per capita as our desirable and undesirable products, respectively. The second estimated method was a Stochastic Frontier, through which it was possible to assess the impact of philanthropy on eco-efficiency (rank of overall efficiency from DEA). Assessing the average eco-efficiency of countries around the world, it is possible to state that the results are worrying, since they reveal a fall in the average eco-efficiency of the countries over the years. Moreover, according to the second econometric model, the philanthropy index positively impacts on eco-efficiency. These empirical results fill a gap in the literature on donations' effect on countries' eco-efficiency. They allow policymakers to see how philanthropy can be one more tool to help countries improve their eco-efficiency. However, there is a warning that some attention is needed (control and regulation) for the best use of donations.

Keywords: eco-efficiency; philanthropy; DEA; Stochastic Frontier

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1. Introduction

Many people and institutions worldwide spend time and/or money on the environment. Moreover, in times of crisis, philanthropy becomes more prominent. Philanthropy is not exclusive to public or private institutions (for profit or not). Any person can contribute (even if on a small scale) to a better world. Furthermore, philanthropy is not static, and its good use can benefit society. This article intends to bring to the debate the importance of philanthropy for the eco-efficiency of the world's countries while extolling the need for public policies for the good management of funds.

Philanthropy is defined as great generosity towards other human beings [1]. According to data from the Charities Aid Foundation (CAF), it is possible to see that worldwide, 2.5 billion people have helped a stranger. In addition, almost 1 in 5 adults are globally volunteers [2]. Philanthropy can be practised in several ways, one of the main (and simplest) being the donation of money.

The "eco-efficiency", in turn, is achieved by the delivery of competitively priced goods and services that satisfy human needs and contribute to the quality of life while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the Earth's estimated carrying capacity [3].

This paper aims to analyze philanthropy's influence on countries' eco-efficiency. A gap in the literature inspired us to achieve this objective. Indeed, researchers have not yet answered the following question: How do philanthropic factors impact the eco-efficiency of countries? The hypothesis to be verified is that philanthropy collaborates to improve countries eco-efficiency. Therefore, a data panel was built to fulfil the objective and collaborate to answer the question. In this paper, 108 countries of the world are considered. However, due to a limitation of statistical data, our analysis is confined to the period from 2009 until 2018.

Two empirical methods were used in this research. First, the Data Envelopment Analysis (DEA) model with constant returns to scale allows us to identify the current eco-efficiency situation in each country. As proposed by Picazo-Tadeo et al. [4], the carbon dioxide emissions per capita (CO_2) (undesirable product), and Gross Domestic Product per capita, based on purchasing power parity (GDP) (desirable product), will be used to obtain our eco-efficiency measure. Moreover, in this paper we used a Stochastic Frontier estimation introduced by Aigner et al. [5], and extended by Greene [6,7], through which it is possible to assess the impact of philanthropy on eco-efficiency (rank of overall efficiency from DEA). In this study, the composition of the philanthropy indicator considered giving money, giving time, and helping a stranger.

Globally, countries try to find a balance between economic growth and CO_2 emissions. Figure 1 shows the historical trade-off between GDP (a proxy of economic growth) and CO_2 emissions, based on data from the World Bank.

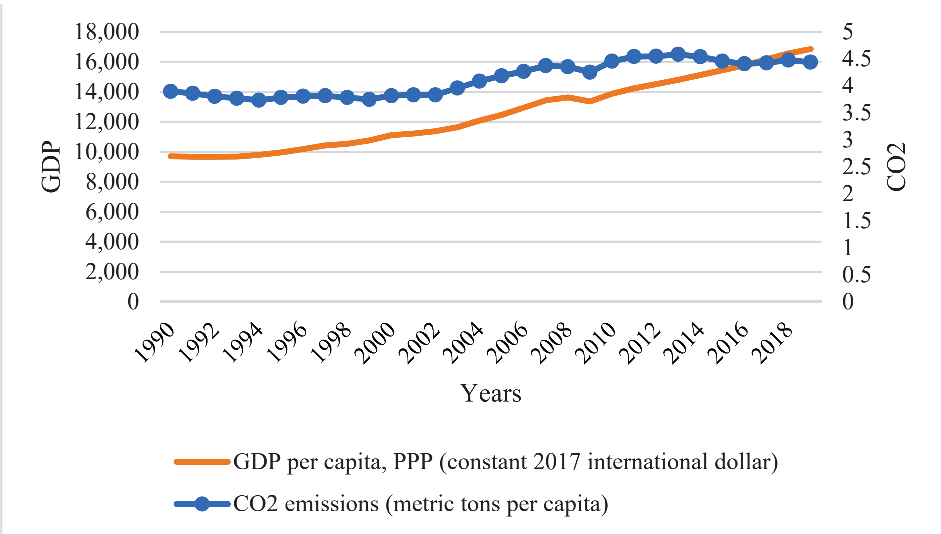

Figure 1. GDP and CO_2. (Author's elaboration.)

The paper's organisation adopts the following sequence: Section 2 presents the literature review; Section 3 is dedicated to the methodological aspects (empirical approach and methods) that guide this research; Section 4 is devoted to econometric results; in Section 5, the discussion and public proposals are made. Finally, in Section 6, we show the conclusions.

2. Literature Review

2.1. Eco-Efficiency

Eco-efficiency is a key concept encompassing economic and environmental aspects to promote more efficient use of resources and lower emissions [8]. Eco-efficiency has been proposed to transform unsustainable development into sustainable development [9,10]. The definition of eco-efficiency has its roots in the business world [10]. However, currently, eco-efficiency can be sought by different agents, people, families, public or private institutions, sectors of the economy and even countries. Countries seek the optimum point across their economic development, controlling the consumption of natural goods, and minimizing the pollution they generate. However, this is not always an easy task, with viewpoints not even consensual in the literature [11].

Eco-efficiency assessment was initially approached using simple indicators, such as GDP over CO_2 at the macro-level [4]. It is possible to find examples in the literature that describe the general definition of eco-efficiency as a ratio between an environmental element and a production value [12]. Some authors show that environmental intensity metrics are widely used in eco-efficiency studies. A typical example is CO_2. This variable was used by Rodríguez-García et al. [13] and indicated that a decrease in the CO_2 ratio over sales implies a lower environmental intensity or an improvement in its eco-efficiency; at the macro level, this eco-efficiency assessment ratio would consider GDP and CO_2 as variables.

An important role that the concept of eco-efficiency can play is if used to support policymakers' decisions, aiming at long-term sustainable development [14]. Therefore, analyzing patterns can be an important contribution to studying eco-efficiency in countries. In a way, it is possible to identify, in the most eco-efficient countries (or cities), patterns, policies, and strategies that made them stand out as more eco-efficient. Furthermore, in this sense, measuring the eco-efficiency of products, services, and design can be an important tool to assist in decision-making [8].

The literature is rich in research that presents eco-efficiency as an output of more sustainable production [13]. There are examples in literature that have studied cities [15], regions of a country [10,16], or groups of countries [13,14,17,18]. Several approaches were applied in these studies, with DEA being one of the most common [16–18].

The eco-efficiency of countries and/or economic sectors has already been evaluated using DEA techniques [19] and combined with regressions [8,18]. For example, Castilho et al. [18] considered CO_2 emissions as input and GDP as output to assess the impact of the tourism sector on eco-efficiency in Latin American and Caribbean countries. Their results indicated that tourism arrivals decrease these countries' eco-efficiency in the short and long term [18].

Moutinho et al. [19] studied the eco-efficiency of 26 European countries from 2001 to 2012. The technical eco-efficiency rankings were identified using the DEA-variable returns-to-scale and DEA-constant returns-to-scale models. Their results indicated that the share of renewable and non-renewable energy sources was important in explaining the differences in emissions. Furthermore, they suggested a significant change in European countries' economic and environmental efficiency trends and pointed out their large disparities [19].

Xiao et al. [15] applied a two-stage network DEA framework, which is proposed to measure eco-efficiency and sectoral efficiency. The authors' results reveal that the average eco-efficiency of China's resource-based cities shows a promising increase between 2007 and 2015. Belucio et al. [8], on the other hand, studied the sector of building rehabilitation in Southern European scenarios and proposed a multi-methodological analysis (combining LCA, DEA and regression) to obtain more eco-efficient results.

De Araújo et al. [16] evaluated eco-efficiency and its determinants in 41 Brazilian municipalities with DEA and Tobit regression between 2014 and 2016. The authors show which reference municipalities (those with the greatest eco-efficiency) support public policymakers (local, national and international).

Yu et al. [20] studied the impact of the pollution information transparency index on eco-efficiency using a new panel dataset covering 109 key environmental protection cities in China from 2008 to 2015 with significant eco-efficiency temporalities; they conclude that the links between the different regions must be strengthened so that eco-efficiency can be promoted in a coordinated way, improving industrial agglomeration, and optimising the allocation of resources [20].

Analyzing the eco-efficiency of countries may not be intuitive. Moreover, several efforts in the literature have shown the different reasons to explore the topic [8,15,16,18–20]. Eco-efficiency can be influenced by characteristics such as the composition of a country's economic activity [14] and environmental factors. Therefore, investigating the eco-efficiency of countries is important for societies in general. Since the environment and economy are related, both must be considered together to analyze eco-efficiency.

2.2. Philanthropy and the Environment

The biggest international charity/philanthropy actions that have taken place recently have been triggered by the emergence of the world COVID-19 pandemic and the Russian War against Ukraine. Philanthropists/charities reacted quickly to the request for help from governments and international organisations in the case of COVID-19 [21] and there are several reports of donations of vaccines, and supplies, medical equipment, to fight the disease. In the case of the war, still in the winter of 2022, many cases of donations to Ukraine are found.

Several types of charity/philanthropy are related to the environment in the literature. For example, Tesselaar et al. [22] show the relationship between natural disasters (floods), government aid and insurance in European countries. Sadrnia et al. [23] show that networks of charities to repurpose a variety of home appliances to reduce municipal solid waste (which enters the environment) and help low-income families are possible. In recent decades, people, institutions, and countries that work to preserve the environment have begun to receive donations for this purpose. Authors also consider that each person can contribute to the growth of initiatives for a less carbon-intensive economy [24].

Philanthropy is not a practice exclusive to the West and is present and growing in many places [21]. However, the various forms of philanthropy have little prominence in economic science research. Nevertheless, Michelson [25] recalls that in science and technology policy, it is important to recognise philanthropies' role in establishing research directions. Furthermore, philanthropy is central to environmental movements [26].

For institutions from different economic sectors, philanthropy plays a crucial role through corporate social responsibility [27–29]. Donations to important causes improve institutions' image and generate more brand engagement. However, there are several cases where companies "omit" to mention their environmental malpractice [30] and make these donations is commonly known as greenwashing.

Lu and Zhu [29] show important aspects of the relationship between philanthropy and corporate taxes. Some companies aim to make more profits and use philanthropy to deduct taxes.

Ames [26] shows that individual donations and grants from foundations have sustained organisations, people, and programs in the independent sector that, although small, have contributed significantly to shaping environmental issues and setting directions for public policy. Currently, the influence of donations continues to impact public policies. For example, Farrell [31] shows that in the case of the USA, the development of the influence of private sector philanthropy is one of the agents that most affect policy, but the author also relates philanthropy to misinformation about climate change [32].

When well directed, the vast volumes of money from philanthropy circulating through economies can be a starting point for the fight against climate change. Nevertheless, Beer [32], who studies the Chilean case of the preservation of Chilean Patagonia, shows how philanthropy plays a more prominent role in funding biodiversity protection. This case also suggests that funding is no longer sufficient for some donors. Environmental philanthropists increasingly seek to get their hands on the state apparatus itself, leveraging their money and influence to demand structural changes in the political framework [32].

Fuentenebro [21] brings an essential question to the debate on the importance of philanthropy in the world: why has philanthropy that has existed for decades not worked to solve structural problems? A possible answer (and in line with [32]) may be how those who hold positions of public policy decision-making and managers of philanthropic institutions have worked. Pope Francis' concerns in the *Laudato Si'* encyclical remain unresolved and demonstrate the weakness of international policy in creating a normative system that includes inviolable limits and ensures the protection of ecosystems [33]. Philanthropy can be a way to collaborate to reduce climate change but it requires more joint efforts and cannot be performed as isolated actions.

Agenda 2030 Sustainable Development Goals [34] shed light on important global environmental topics. Corporate and individual philanthropy can contribute to fulfilling these goals. However, public policies, regulations and philanthropy/charity control tools must be in place so that donations do not become a "trap". In this sense, countries must create/update legislation and controls to ensure that donations reach the proper destination.

In line with the control mechanisms, the implementation of systems that facilitate procedures for raising funds should be encouraged by the State. The institutions that receive the funds must have well-designed programs to fulfil their core business, eliminating gaps in their operations and collaborating for the environmental, socioeconomic, and personal development of those who benefit from philanthropy.

3. Methodology

The methodology section will be divided into three subsections (Figure 2 summarizes the methodology). The first subsection will show the selected data and statistical characteristics. In the second subsection, the DEA model with constant returns to scale is the first method applied to identify the overall efficiency of countries (i.e., the eco-efficiency). Finally, in the last subsection, a panel analysis with Stochastic Frontier estimation will be applied to find the impact of philanthropy on the abovementioned eco-efficiency index built by the DEA.

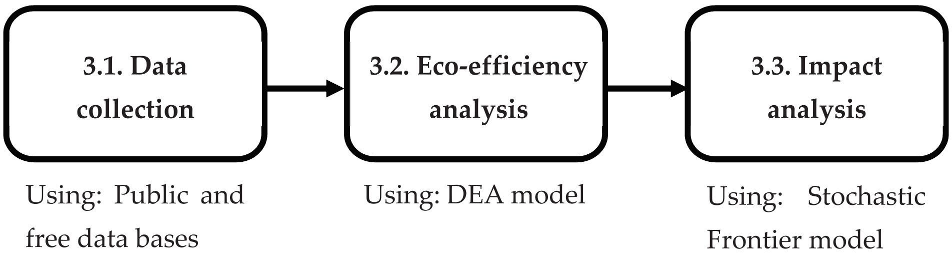

Figure 2. DEA and Stochastic Frontier estimation. (Author's elaboration.)

3.1. Statistical Data

Statistical data are essential for suggesting robust public policies. In this paper, all data were obtained from public and free databases. Thus, other researchers can replicate studies of this nature. Furthermore, we built a data panel with the variables normalised through per capita values. An advantage of using this normalisation is that it can remove distortion produced by population variations [35]. Next, in Table 1, we present some details about the characteristics of the data.

Table 1. Variables.

Variables	Acronyms	Units	Databases
GDP per capita based on purchasing power parity	GDP	Constant (2017) international dollar	World Bank ǀ World Development Indicators
CO_2 emissions per capita	CO_2	metric tons	
Giving money	MON	%	CAF—World Giving Index
Giving time	TIME	%	
Helping a stranger	STRAN	%	

The period was limited due to several variables: the indicators of philanthropy of the World Giving Index began in 2009, and the CO_2 emissions data covers the period up to 2018, impeding the econometric analysis from being extended. Nevertheless, this period is important for many countries worldwide as it marks the beginning of the economic recovery after the 2008 financial crisis [36]. It was possible to select 108 countries worldwide (Afghanistan, Albania, Argentina, Armenia, Australia, Austria, Azerbaijan, Bangladesh, Belarus, Belgium, Benin, Bolivia, Bosnia and Herzegovina, Botswana, Brazil, Bulgaria, Burkina Faso, Cambodia, Cameroon, Canada, Chad, Chile, China, Colombia, Congo (Brazzaville), Costa Rica, Croatia, Cyprus, Czech Republic, Democratic Republic of the Congo (Kinshasa), Denmark, Dominican Republic, Ecuador, Egypt, El Salvador, Estonia, Finland, France, Georgia, Germany, Ghana, Greece, Guatemala, Guinea, Haiti, Honduras, Hungary, India, Indonesia, Iraq, Ireland, Israel, Italy, Jordan, Kazakhstan, Kenya, Kyrgyzstan, Latvia, Lebanon, Lithuania, Luxembourg, Madagascar, Malawi, Mali, Malta, Mauritania, Mexico, Mongolia, Montenegro, Morocco, Nepal, Netherlands, New Zealand, Nicaragua, Niger, Nigeria, Pakistan, Panama, Paraguay, Peru, Philippines, Poland, Portugal, Republic of Moldova, Romania, Russian Federation, Rwanda, Saudi Arabia, Senegal, Serbia, Slovakia, Slovenia, South Africa, Spain, Sweden, Tajikistan, Thailand, Tunisia, Turkmenistan, Uganda, Ukraine, United Kingdom, United Republic of Tanzania, USA, Uruguay, Uzbekistan, Zambia, and Zimbabwe). The criterion for selecting the countries for this analysis was that there was no break in the data structure. Table 2 presents the descriptive statistics of the dataset. The exact number of observations confirms the balanced panel data.

Table 2. Descriptive statistics.

Variables	Observations	Mean	Standard Deviation	Minimum	Maximum
GDP per capita	1080	9.3574	1.1049	6.7282	11.6404
CO_2 emissions per capita	1080	0.7092	1.4697	−3.6441	3.0827
Giving money	1080	28.8482	18.0739	2.0000	87.0000
Giving time	1080	20.3833	10.8174	2.0000	61.0000
Helping a stranger	1080	47.3861	12.2994	13.0000	81.0000

3.2. Data Envelopment Analysis—DEA

The DEA developed in 1978 by Charnes, Cooper, and Rhodes (CCR) [37] was selected for eco-efficiency analysis. This model assumes constant returns to scale (CRS). In the CCR model, each Decision-Making Unit (DMU) k (k = 1, . . . , n) is a country that used p inputs x_{ik}, (i = 1, . . . , p) to produce d outputs y_{jk} (j = 1, . . . , d). In this study, CO_2 emissions per capita is our input parameter, i.e., undesirable product. GDP per capita is our output parameter, i.e., desirable product. Thus, each DMU represents the economic and environmental situation of the country (N) in the year (T). A linear programming formulation is presented in the model (1) [37]:

$$
\begin{gathered}
Max\ Eco\ efficiency_0 = \sum_{j=1}^{d} m_j y_{j0} \\
\text{Subject to,} \\
\sum_{i=1}^{p} v_i x_{i0} = 1 \\
\sum_{j=1}^{d} m_j y_{jk} - \sum_{i=1}^{p} v_i x_{ik} \leq 0,\ \ k = 1,\ 2,\ 3, \ldots, n \\
v_i,\ m_j \geq 0\ ,\ \ i = 1,\ \ldots,\ p;\ j = 1,\ \ldots,\ d.
\end{gathered}
\tag{1}
$$

where $Eco\ efficiency_0 \in [0,1]$ is the efficiency score for DMU_0 (the DMU under analysis); y_{j0} and x_{i0} are the inputs and outputs of DMU_0; and v_i are the weights of the inputs i and m_j are the weights of the outputs j.

Belucio et al. [8] indicate that this formulation is called the envelopment model. It computes the weights for the inputs and the outputs that maximise the efficiency of DMU_0. Those weights are not subjectively set but reflect the benevolent perspective of evaluating the DMU under the most favourable weights maximising its eco-efficiency. If it is possible to choose weights such that $Eco\ efficiency_0$ = 1, then DMU_0 is efficient. Otherwise, $Eco\ efficiency_0$ < 1 indicates an inefficient DMU (the lower, the worse) [8].

3.3. The Panel Data Analysis with a Stochastic Frontier Estimation

After building the eco-efficiency variable through the DEA model we will estimate how philanthropy can impact it. To this end, firstly we will build the philanthropy index (PHI) by using the following equation (simple arithmetic average):

$$\text{PHI} = \frac{\text{MON} + \text{TIME} + \text{STRAN}}{3} \tag{2}$$

where, MON, TIME and STRAN indicate some dimensions of philanthropy, namely "Giving money", "Giving time" and "Helping a stranger", respectively. The behaviour of the PHI index will be presented in due course. Secondly, we apply the panel analysis with a Stochastic Frontier estimation [5–7] that takes into account the fixed effects, composed of the following equations:

$$\text{ECO}_{it} = \alpha_0 + \alpha_1 ln\text{GDP}_{it-n} + \alpha_2 ln\text{CO2}_{it-n} + \alpha_3 trend + v_{it} + u_{it} \tag{3}$$

$$\sigma^2_{ui} = \exp(\beta_1 \text{PHI}_{it-n} + z_{it}) \tag{4}$$

In Equation (3), v_{it} represents residuals and u_{it} captures the inefficiency, namely the distance from the frontier of each country. This case represents the frontier equation that builds the frontier with the best country performances in terms of eco-efficiency, given the GDP and CO_2 emissions levels. Equation (4), where z_{it} is the residual, is called the inefficiency equation, because it estimates with an exponential function which factor can influence the distance of a country from the frontier of the best performances (technical efficiency); a negative coefficient means that philanthropy reduces this distance.

The use of lagged variables has twofold value: it considers both the potential endogeneity concerning the reverse relationships and the potential timing of the relationships considered. The main idea is that philanthropy can influence how economic and technological factors impact eco-efficiency. Given the same technologies and economic factors, philanthropy offers all operators, individually and collectively, more propensity for the actions and choices more environmentally sustainable.

4. Results

First, we recall that the objectives of the study is to provide an overview of the relationship between philanthropy and eco-efficiency. For this reason, we have chosen not to illustrate specific country cases throughout the section.

We present a map built with the PHI index for the year 2018 (Figure 3). The results show scale between 0 to 100%. However, only eight countries in the sample (Australia, Canada, Indonesia, Ireland, Netherlands, New Zealand, United Kingdom, and the United States of America) have a PHI index between 50% and 58.3%. They suggest that all countries (and their populations) have a great opportunity to grow and positively impact the eco-efficiency of the planet.

When we disaggregate the economies according to their income level we see that countries have new behaviour patterns (details in Table 3). The classification was performed using data from the World Bank [38]. The indicator shows that economies' income level is divided into four categories: (i) low-income economies equate to those with a Gross National Income (GNI) per capita of 1085 USD or less in the year 2021; (ii) lower-middle-income economies are those between 1086 and 4255 USD; (iii) upper-middle-income economies are those between 4256 and 13,205 USD; and (iv) high-income economies are those of 13,205 USD or more [38]. Throughout the section, the same criteria for classifying countries according to their income will be maintained.

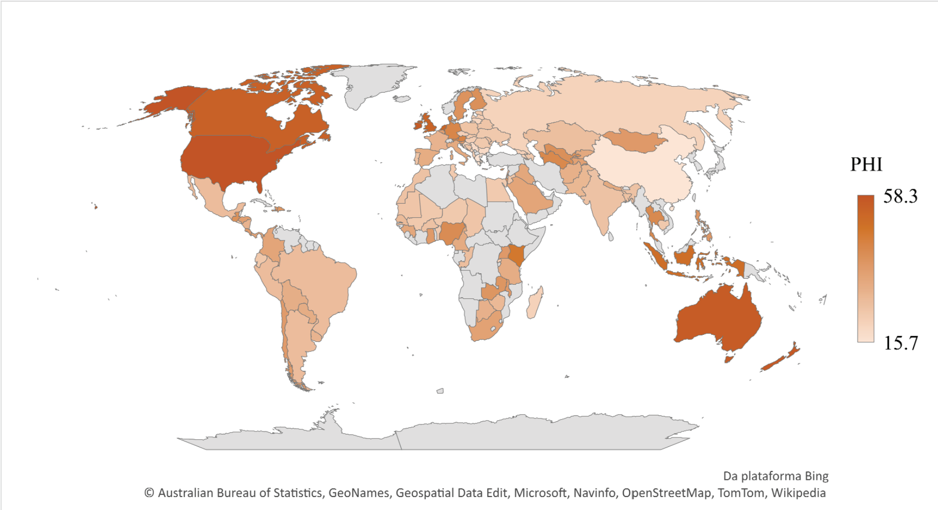

Figure 3. 2018 PHI index. (Author's elaboration).

Table 3. 2018 PHI ranking grouped by country income.

	Low	Lower-Middle	Upper-Middle	High
1st	Zambia	Indonesia	Turkmenistan	United States of America
2nd	Malawi	Kenya	Thailand	New Zealand
3rd	Uganda	Nigeria	Guatemala	Australia
4th	Guinea	Uzbekistan	Dominican Republic	Ireland
5th	Afghanistan	Haiti	Costa Rica	Canada
6th	Burkina Faso	Philippines	South Africa	United Kingdom
7th	Chad	Mongolia	Colombia	Netherlands
8th	Mali	Ghana	Iraq	Malta
9th	Niger	Honduras	Paraguay	Austria
10th	Madagascar	Tajikistan	Botswana	Denmark
11th	Rwanda	Kyrgyzstan	Argentina	Germany
12th	Democratic Republic of the Congo (Kinshasa)	Nepal	Brazil	Cyprus
13th		Cameroon	Mexico	Finland
14th		United Republic of Tanzania	Peru	Luxembourg
15th		Bolivia	Kazakhstan	Sweden
16th		Lebanon	Republic of Moldova	Israel
17th		Nicaragua	Belarus	Chile
18th		Pakistan	Bosnia and Herzegovina	Slovenia
19th		Zimbabwe	Jordan	Belgium
20th		Senegal	Ecuador	Panama
21st		Congo (Brazzaville)	Azerbaijan	Saudi Arabia
22nd		Bangladesh	Georgia	Italy
23rd		India	Armenia	Spain
24th		Morocco	Russian Federation	France
25th		Mauritania	Montenegro	Uruguay
26th		El Salvador	Bulgaria	Poland
27th		Cambodia	Serbia	Portugal
28th		Ukraine	China	Estonia
29th		Egypt		Slovakia
30th		Tunisia		Romania
31st		Benin		Hungary
32nd				Latvia
33rd				Czech Republic
34th				Croatia
35th				Lithuania
36th				Greece

High-income countries are expected to do more philanthropic actions since Maslow's base-of-pyramid problems (basic physiological and safety needs) are not a concern. Seven of the eight countries with a philanthropy index above 50% belong to the high-income category. This result demonstrates the ability of rich countries to help those most in need. The five countries with the worst philanthropy index are Lithuania 20%, Bulgaria 19%, Serbia 18.7%, Greece 16.3% and China 15.7%. These countries have GNI per capita which places them in the "upper-middle" and "high" income categories. There are possible problems of income inequality in populations, which may affect a country's ability to do philanthropy. In addition, the cultural factor exerts an important influence on the decision to donate.

Next, after checking the correlation between CO_2 and GDP, it is possible to affirm (at a 5% statistical significance) that the variables are relationship positive, which means the parameters maintain an isotonic relationship [39] and can be used on the proposed DEA model. Details about the correlation matrix are shown in the Appendix A (Table A1). In this test, a positive correlation shows that the variables have symmetrical behaviour, i.e., both increase and decrease simultaneously. This result suggests the existence of common factors in the increase or decrease of GDP and CO_2. Moreover, the result of this test showing the correlation between variables should not be read as an impact between variables. Instead, it should be considered an indicator of their behaviour in pairs (symmetric, asymmetric, or neutral).

The DEA model was estimated considering the constant returns to scale. We show the eco-efficiency ranking (Figure 4) for the year 2018. The ranking DEA was obtained through the CRS. The Gross Domestic Product per capita was considered a desirable product. On the other hand, carbon dioxide per capita was considered an undesirable product. The results show a scale from 0 to 1.

Figure 4. 2018 eco-efficiency ranking. (Author's elaboration.)

Next, average DEA results are shown in Figure 5. We found results that show countries' average eco-efficiency regressed between 2009 and 2018. In addition, we also present the average results by income category, as classified by the World Bank [38]. Countries classified as low-income had the highest average eco-efficiency and were the ones that dropped the most in the indicator when analyzing the first and last years of the sample. If we go to the other extreme, the average of high-income countries also showed a drop, but the smallest drop among the different income categories of countries.

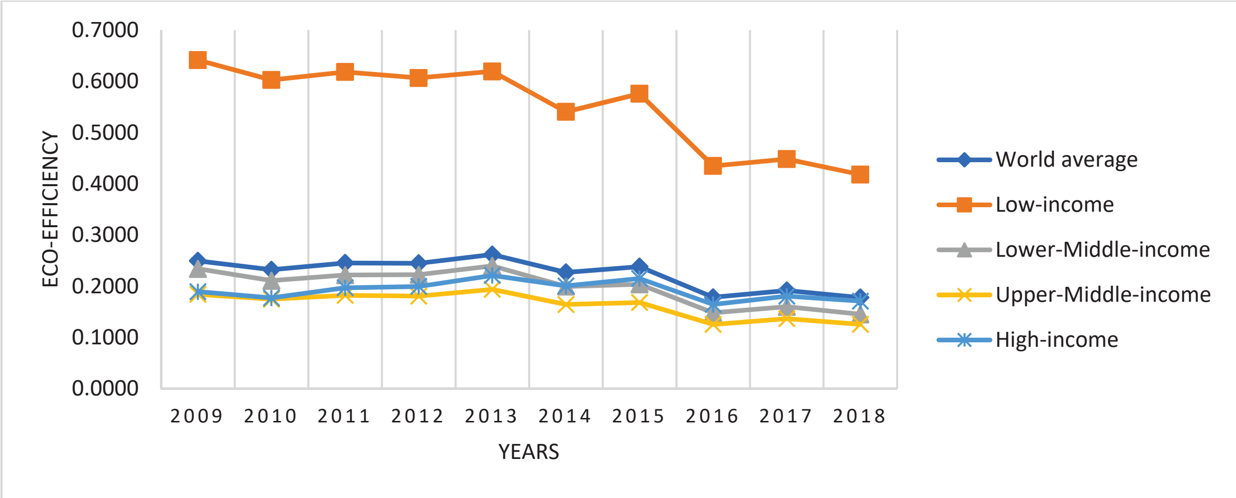

Figure 5. Eco-efficiency per year. (Author's elaboration.)

In Table A2 (see Appendix A), we show the ranking of countries' classification by year and eco-efficiency. We also show the eco-efficiency average by country, the standard deviation, and the coefficient of variation. We can indicate that we have null, tiny, or small correlations when evaluating the coefficient of variation. For example, Pakistan was the only country with a moderate variation coefficient. Finally, through the mean Variance Inflation Factor (VIF) statistic (see Appendix A Table A3), it is possible to affirm that there is no multicollinearity in the DEA model. Thus, the estimated DEA model is robust, with an average VIF value of 1.00.

In Table 4, we again disaggregate eco-efficiency ranking by classifying economies according to their income level (low, lower-middle, upper-middle, and high). Again, a new a configuration of countries occupies the top positions regarding eco-efficiency when sorted by income category.

Table 4. 2018 eco-efficiency ranking grouped by country income.

	Low	Lower-Middle	Upper-Middle	High
1st	Democratic Republic of the Congo (Kinshasa)	United Republic of Tanzania	Costa Rica	Sweden
2nd	Mali	Kenya	Paraguay	Malta
3rd	Rwanda	Cameroon	Colombia	Panama
4th	Chad	Haiti	Guatemala	Uruguay
5th	Malawi	Ghana	Peru	Ireland
6th	Uganda	Nepal	Dominican Republic	France
7th	Madagascar	Bangladesh	Brazil	Denmark
8th	Niger	El Salvador	Albania	Lithuania
9th	Afghanistan	Nigeria	Armenia	United Kingdom
10th	Guinea	Nicaragua	Argentina	Italy
11th	Burkina Faso	Congo (Brazzaville)	Georgia	Austria
12th	Zambia	Philippines	Mexico	Latvia
13th		Cambodia	Montenegro	Romania
14th		Honduras	Ecuador	Luxembourg
15th		Mauritania	Thailand	Spain
16th		Senegal	Botswana	Portugal
17th		Indonesia	Azerbaijan	Croatia
18th		Pakistan	Jordan	Hungary
19th		Benin	Republic of Moldova	New Zealand
20th		Egypt	Bulgaria	Cyprus
21st		Bolivia	Belarus	Netherlands
22nd		Tajikistan	Serbia	Belgium

Table 4. *Cont.*

	Low	Lower-Middle	Upper-Middle	High
23rd		Tunisia	Russian Federation	Germany
24th		Morocco	Bosnia and Herzegovina	Finland
25th		Zimbabwe	Kazakhstan	Israel
26th		Lebanon	Iraq	Slovenia
27th		India	China	Chile
28th		Ukraine	South Africa	Slovakia
29th		Kyrgyzstan		Greece
30th		Uzbekistan		Czech Republic
31st		Mongolia		United States of America
32nd				Poland
33rd				Australia
34th				Canada
35th				Saudi Arabia
36th				Estonia

In Table 5 we show the eco-efficiency ranking for 2018 per geographical area to underline the relevance of the particular territorial characteristics. The countries in the general rank were grouped according to the continent. The region where the countries are inserted and their border neighbours can influence the management of wealth and the environment. All regions have the potential to stand out; in some cases, however, the mechanisms of corruption do not allow a good distribution of income aligned with measures to combat environmental degradation to evolve.

Table 5. Eco-efficiency ranking by continent in 2018.

	Africa	Asia	Europe	North America	Oceania	South America
1st	Democratic Republic of the Congo (Kinshasa)	Afghanistan	Sweden	Panama	New Zealand	Uruguay
2nd	Mali	Nepal	Malta	Costa Rica	Australia	Paraguay
3rd	Rwanda	Bangladesh	Ireland	Haiti		Colombia
4th	Chad	Armenia	France	El Salvador		Peru
5th	Malawi	Cyprus	Denmark	Guatemala		Brazil
6th	Uganda	Philippines	Lithuania	Dominican Republic		Argentina
7th	United Republic of Tanzania	Cambodia	United Kingdom	Nicaragua		Chile
8th	Madagascar	Israel	Italy	Honduras		Ecuador
9th	Niger	Georgia	Austria	Mexico		Bolivia
10th	Kenya	Indonesia	Latvia	United States of America		
11th	Cameroon	Thailand	Romania	Canada		
12th	Guinea	Pakistan	Luxembourg			
13th	Burkina Faso	Azerbaijan	Spain			
14th	Ghana	Tajikistan	Portugal			
15th	Zambia	Jordan	Albania			
16th	Nigeria	Lebanon	Croatia			
17th	Congo (Brazzaville)	India	Hungary			
18th	Mauritania	Saudi	Netherlands			
19th	Senegal	Kyrgyzstan	Belgium			
20th	Botswana	Kazakhstan	Germany			
21st	Benin	Iraq	Finland			
22nd	Egypt	China	Slovenia			
23rd	Tunisia	Uzbekistan	Slovakia			
24th	Morocco	Mongolia	Montenegro			
25th	Zimbabwe	Turkmenistan	Greece			
26th	South Africa		Czech Republic			
27th			Republic of Moldova			
28th			Poland			
29th			Bulgaria			
30th			Belarus			
31st			Ukraine			
32nd			Estonia			
33rd			Serbia			
34th			Russian Federation			
35th			Bosnia and Herzegovina			

Next, we show the results of the Stochastic Frontier estimation (Table 6). The coefficients (Coef.) of LnGDP and LnCO2 are positive and negative, respectively. As both are statistically significant, this indicates how each variable impacts the eco-efficiency indicator for 1, 2, and 3 lags. Furthermore, 1 to 3 lags are considered in estimation to take into account the potential endogeneity/simultaneity. In all estimations a temporal trend was used. Finally, the PHI variable reveals a negative coefficient (statistically significant) to 1, 2, and 3 lags, i.e., it means that philanthropy reduces the distance of a country from the frontier of the highest performances, in other terms philanthropy impacts positively on the process of improving eco-efficiency.

Table 6. Stochastic Frontier results.

Dependent Variable: ECO		1 Lag		2 Lags		3 Lags	
		Coef.	P > |z|	Coef.	P > |z|	Coef.	P > |z|
Frontier							
	LnGDP	0.723	0.000	0.472	0.000	0.319	0.051
	LnCO2	−0.483	0.000	−0.263	0.000	−0.122	0.017
Years		−0.039	0.000	−0.042	0.000	−0.045	0.000
Usigma							
	PHI	−0.030	0.009	−0.040	0.072	−0.158	0.000
	Constant	−4.491	0.000	−4.962	0.000	−2.982	0.003
Vsigma							
	unef	−0.012	0.750	−0.014	0.599	0.008	0.593
	Constant	−7.024	0.000	−6.436	0.000	−5.832	0.000
	E(Sigma_u)	0.066		0.051		0.025	
	E(sigma_v)	0.031		0.043		0.056	
	Trend	YES		YES		YES	
	Observations	972		864		756	
	Log likelihood	1297.028		1167.306		1030.296	
	Prob>chi2	0.000		0.000		0.075	
	Wald chi2	5.10e+07		3.80e+07		5.19	

Note: "Ln" denotes "natural logarithm"; "unef" (female unemployment) by World Bank | World Development Indicators is the explanatory variable for the idiosyncratic error variance function.

Based on the results found in the Stochastic Frontier model, it can be stated that it is appropriate to motivate philanthropy to leverage the eco-efficiency of countries. Thus, the results show that philanthropy collaborates to reduce the inefficiency of the countries

The results show that philanthropy collaborates to reduce the inefficiency of the countries, and it can be considered the main finding of our study. In this study, the composition of the philanthropy indicator considered giving money, giving time, and helping a stranger. However, we warn that some attention is needed (control and regulation) to ensure that donations/philanthropic actions that reach their intended and good destination.

5. Discussion and Policy Implications

Based on the results obtained with the DEA model, we can say that, on average, the eco-efficiency situation in the world has worsened since 2009. The possible explanation for this phenomenon is that after the shock caused by the financial crisis (due to sub-prime mortgages, etc.), countries reduced their concern for the environment in pursuit of economic growth, ultimately increasing greenhouse gas emissions. This explanation corroborates [36], which shows that countries tend to prioritise economic recovery and loosen environmental regulation in times of crisis. In this sense, the current crises (pandemic crisis caused by the COVID-19 virus and the crisis of the Russia-Ukraine war) should generate public policies attentive to post-crisis measures, as there is a tendency to seek economic recovery by loosening environmental regulations [36]. As in the European case, an increase in coal consumption is expected, due to the lack of gas that results from the war. There are indications that many countries in the world speak in favor of the environment but are willing to implement short-term measures that harm it.

Our data cover dozens of countries on all continents. There are many with different policies regarding the preservation of the environment and the search for high eco-efficiency. Even those who align with pro-environmental policies by signing international treaties do not always comply with them (as in the case of the United States of America, for example, which reversed several pro-environment policies after the election of President Trump). Furthermore, some countries that make up the sample are among the world's poorest. The low GDP is the result of weak and underdeveloped economic activity. The lack of industrialisation, the low sectorial diversification of the economy, and corruption can help explain the low eco-efficiency. The optimum point of pollution and growth is easily exceeded by developed countries that seek rapid recovery and/or more growth. In developing countries, the optimal point is rarely reached, and the most common result is a low level of CO_2 emissions and little (or no) economic growth, which worsens the poverty situation of these nations.

The world's countries must cooperate in dealing with the problem of decarbonisation, and measures that facilitate the transfer of technology to reduce emissions must be encouraged. High-income countries can also finance part of the sustainable development of other nations. These measures are commonly known as "green growth". Althouse et al. [40] show that, in theory, green growth policies can result in a virtuous shift to high-value-added sectors. Another policy proposal could be the end of tax havens combined with policies that allow the richest to donate their taxes to countries or institutions that preserve the environment directly. Some countries allow individuals and companies to allocate part of their taxes directly to institutions.

Donations of money or, in some cases, skilled labour can promote an increase in global eco-efficiency. However, world organisations first choose to make loans to support economic recovery; typically, these loans increase the public debt, drive away foreign investors, and make the country ineligible for new future programs/loans. In this way, donations become a viable option for the first step towards economic recovery, which can boost important sectors of the recipient economy. Regarding philanthropic factors in societies, donating money (transferring from the rich to the poor) can help in some ways, but it does not solve the problems of eco-inefficiency and corruption. Therefore, programs must be supported by robust measures that guarantee the correct application of funds. Control mechanisms are needed for countries to find the best solutions according to their national and regional characteristics. Furthermore, Duquette [41] makes an important observation about a problem associated with philanthropy, as it can increase the extent of inequality between places over time. Therefore, public donation policies must be well-targeted, filling gaps and ending corruption in this economic sector; philanthropic programs should last for the strictly necessary time, building personal and institutional capacity so as not to create a long term dependency, but generating opportunities to improve eco-efficiency on a sustainable basis.

The elaboration of regulations for national and international charity/philanthropy and the elaboration of methods of evaluation and control of the destination of donations are fundamental to avoid the creation of lobbies that influence a specific sector and/or country through donations. In addition, these control measures tend to contribute to the correct destination of the fruits of philanthropic actions.

Donation of time to charitable causes can be relevant in environmental and economic aspects. Therefore, the volume of philanthropic activities in the poorest countries should be encouraged through more international programs and policies that facilitate this type of action. However, the security factor of host countries can be a barrier to these initiatives and requires the attention of policymakers. Another important point to be considered regarding the donation of time in philanthropic activities should be the final activity of the donor. Well-structured programs are needed, so that philanthropic activity does not revert to a negative impact in the longer term. The correct selection of people is essential, considering that to carry out an activity, many stakeholders must be consulted. In some case, a development activity may cause displacement and an associated negative environmental impact. In this way, the donor's exit strategy should be planned from the start so that the overall gains outweigh any loss of impetus and possible residual negative impact. An example of a policy that can favour philanthropy's impact on countries' eco-efficiency is to align charity with institutions focused on social enterprise and small businesses. This type of charity investment, rated as positive by the literature, can if well implemented make a difference for many people with support for education, combating poverty, and promoting gender equality, and access to clean energy, among others.

6. Final Considerations

The aim of this paper (to analyze the influence of philanthropy on eco-efficiency) has been accomplished. It was possible to build a panel of data from 108 countries worldwide. The period covered by the analyses started in 2009 and lasted until 2018. Two econometric methods were used in this research, a DEA model with constant returns to scale to find the rank of overall efficiency (our eco-efficiency parameter) and a Stochastic Frontier to verify the influence of philanthropy on eco-efficiency.

The results of the DEA model were estimated considering CO_2 emissions per capita (undesirable product) and GDP in purchasing power parity per capita (desirable product). They show that the world's average eco-efficiency situation has worsened in the analyzed period.

Based on Stochastic Frontier, we find that philanthropy reduces the distance of a country from the frontier of the most performing countries. This result suggests that public policies encouraging money donations can reinforce other measures to improve the eco-efficiency of the countries.

Well-targeted public policies can contribute to a more eco-efficient world. Furthermore, it is essential to assess the situation of less efficient countries to establish assertive measures for sustainable (economic and environmental) development. The search for standards in the most (or less) eco-efficient countries can help public policymakers to design better solutions for society. Philanthropy can be a way to help combat the decline in global eco-efficiency. However, this path alone has only a small positive impact, so philanthropy must be combined with other actions to maximise results.

Regulatory and control mechanisms for the correct distribution of charity/philanthropic funding should be encouraged to reduce corruption, especially in the most vulnerable countries.

In this research, some barriers and limitations were not overcome. Therefore, it is suggested that the theme be revisited in the future to try to resolve the following limitations: the period and the number of countries that it was possible to include in the analysis; the need to consider the direct and indirect effects of the health crisis caused by COVID-19 virus, and more recently the Russia-Ukraine war on eco-efficiency.

Furthermore, it would be interesting to deepen additional investigations by working with individual or neighboring countries or groups of countries (e.g., Latin Americans, Europeans, Africans, Asians, OECD, MENA, BRICS, and others). The selection of countries could also be made in line with research priorities of leading institutions active in promoting eco-efficiency. It is possible to analyze countries according to globalisation or industrialisation or environmental factors. Another suggestion for future research will be to verify the existence of a pattern in the sample of the most eco-efficient/inefficient countries and assess the speed and time required to move from inefficiency to efficiency.

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Appendix A

Table A1. Spearman correlation matrix.

	LnGDP	**LnCO2**
LnGDP	1.0000	
LnCO2	0.9170 **	1.0000

Note: Ln denote natural logarithm; "**" denotes statistical significance at a 5% level.

Table A2. Countries' eco-efficiency by year.

Rank	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Country	Mean	SD	CV
1st	Democratic Republic of the Congo (Kinshasa)	Mali	Mali	Mali	Mali	Mali	Mali	Democratic Republic of the Congo (Kinshasa)	Democratic Republic of the Congo (Kinshasa)	Democratic Republic of the Congo (Kinshasa)	Afghanistan	0.2582	0.0421	0.1632
2nd	Mali	Democratic Republic of the Congo (Kinshasa)	Chad	Democratic Republic of the Congo (Kinshasa)	Chad	Chad	Democratic Republic of the Congo (Kinshasa)	Mali	Mali	Mali	Albania	0.2196	0.0348	0.1586
3rd	Rwanda	Rwanda	Rwanda	Chad	Rwanda	Rwanda	Chad	Chad	Chad	Rwanda	Argentina	0.1821	0.0282	0.1549
4th	Madagascar	Chad	Democratic Republic of the Congo (Kinshasa)	Rwanda	Democratic Republic of the Congo (Kinshasa)	Malawi	Rwanda	Rwanda	Rwanda	Chad	Armenia	0.1938	0.0195	0.1004
5th	Chad	Malawi	Malawi	Malawi	Malawi	Democratic Republic of the Congo (Kinshasa)	Malawi	Malawi	Malawi	Malawi	Australia	0.0915	0.0106	0.1163
6th	Nepal	Madagascar	Uganda	Uganda	Uganda	Uganda	Uganda	Uganda	Uganda	Sweden	Austria	0.2244	0.0274	0.1220
7th	Uganda	Zambia	Madagascar	Nepal	Paraguay	Paraguay	Nepal	Malta	Sweden	Uganda	Azerbaijan	0.1468	0.0278	0.1897
8th	Malawi	Nepal	Zambia	Paraguay	Nepal	Sweden	Sweden	Sweden	Malta	Malta	Bangladesh	0.2736	0.0434	0.1587
9th	Zambia	Uganda	Nepal	Kenya	Madagascar	Nepal	Paraguay	Niger	Uruguay	Panama	Belarus	0.0953	0.0136	0.1423
10th	Niger	Paraguay	Paraguay	Madagascar	Zambia	Madagascar	Costa Rica	Madagascar	Costa Rica	United Republic of Tanzania	Belgium	0.1833	0.0224	0.1222
11th	Haiti	United Republic of Tanzania	Burkina Faso	Zambia	Kenya	Uruguay	Uruguay	Costa Rica	Panama	Costa Rica	Benin	0.1670	0.0372	0.2231
12th	United Republic of Tanzania	Burkina Faso	Niger	Haiti	Sweden	Kenya	Niger	Uruguay	United Republic of Tanzania	Madagascar	Bolivia	0.1388	0.0231	0.1662
13th	Paraguay	Niger	United Republic of Tanzania	Costa Rica	Niger	Costa Rica	Madagascar	United Republic of Tanzania	Niger	Uruguay	Bosnia and Herzegovina	0.0640	0.0088	0.1373
14th	Burkina Faso	Kenya	Kenya	Burkina Faso	Costa Rica	Burkina Faso	Zambia	Paraguay	Madagascar	Niger	Botswana	0.1951	0.0592	0.3033
15th	Kenya	Haiti	Costa Rica	Sweden	Haiti	Zambia	Malta	Panama	Paraguay	Kenya	Brazil	0.2237	0.0398	0.1777
16th	Costa Rica	Costa Rica	Sweden	Niger	Burkina Faso	Niger	Kenya	Burkina Faso	Kenya	Ireland	Bulgaria	0.1019	0.0113	0.1105
17th	Sweden	Uruguay	Haiti	United Republic of Tanzania	Guinea	United Republic of Tanzania	Panama	Kenya	Cameroon	Paraguay	Burkina Faso	0.3664	0.0853	0.2329

Table A2. *Cont.*

Rank	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Country	Mean	SD	CV
18th	Nigeria	Sweden	Guatemala	Cameroon	Uruguay	Guinea	United Republic of Tanzania	Zambia	Afghanistan	Cameroon	Cambodia	0.2384	0.0665	0.2790
19th	Bangladesh	Guatemala	Uruguay	Guatemala	United Republic of Tanzania	Haiti	Burkina Faso	Cameroon	Ireland	Afghanistan	Cameroon	0.2951	0.0459	0.1556
20th	Ghana	Nigeria	Panama	Panama	Cameroon	Cameroon	Cameroon	Afghanistan	Guinea	Haiti	Canada	0.0962	0.0123	0.1276
21st	Guinea	Panama	Ghana	Guinea	Panama	Panama	Haiti	Nepal	Ghana	Guinea	Chad	0.7768	0.1549	0.1995
22nd	Guatemala	Bangladesh	France	Nigeria	Guatemala	France	Guinea	Ghana	Haiti	Burkina Faso	Chile	0.1696	0.0251	0.1483
23rd	Panama	Botswana	Bangladesh	Colombia	Cambodia	Afghanistan	France	Haiti	Burkina Faso	France	China	0.0524	0.0038	0.0721
24th	Afghanistan	Ghana	Cameroon	France	Mauritania	Ghana	Nigeria	Guinea	Denmark	Denmark	Colombia	0.2691	0.0357	0.1328
25th	Mauritania	Colombia	Colombia	Bangladesh	Bangladesh	Guatemala	Ireland	France	France	Ghana	Congo (Brazzaville)	0.1841	0.0348	0.1888
26th	Colombia	Mauritania	Nigeria	Uruguay	France	Bangladesh	Denmark	Nigeria	Colombia	Colombia	Costa Rica	0.3683	0.0441	0.1197
27th	Uruguay	Cambodia	Cambodia	Cambodia	Nigeria	Nigeria	Afghanistan	Ireland	Nepal	Nepal	Croatia	0.1910	0.0215	0.1128
28th	France	France	Mauritania	Ghana	Ghana	Denmark	Ghana	Denmark	Nigeria	Bangladesh	Cyprus	0.1871	0.0240	0.1285
29th	Cambodia	Guinea	Guinea	Mauritania	Afghanistan	Colombia	Colombia	Bangladesh	Lithuania	Lithuania	Czech Republic	0.1132	0.0113	0.0997
30th	Brazil	Tajikistan	Tajikistan	Denmark	Colombia	Lithuania	Lithuania	Lithuania	El Salvador	United Kingdom	Democratic Republic of the Congo (Kinshasa)	0.8937	0.1495	0.1672
31st	Tajikistan	Brazil	Botswana	El Salvador	El Salvador	Mauritania	Bangladesh	Colombia	Bangladesh	El Salvador	Denmark	0.2477	0.0301	0.1214
32nd	Albania	Cameroon	Brazil	Albania	Lithuania	Cambodia	Guatemala	United Kingdom	Zambia	Zambia	Dominican Republic	0.2112	0.0219	0.1035
33rd	Cameroon	Georgia	El Salvador	Philippines	Denmark	Ireland	Congo (Brazzaville)	Latvia	United Kingdom	Italy	Ecuador	0.1540	0.0207	0.1343
34th	Philippines	El Salvador	Philippines	Tajikistan	Nicaragua	El Salvador	El Salvador	Mauritania	Guatemala	Austria	Egypt	0.1398	0.0196	0.1404
35th	El Salvador	Albania	Ireland	Austria	Tajikistan	Italy	United Kingdom	Guatemala	Latvia	Nigeria	El Salvador	0.2385	0.0300	0.1259
36th	Austria	Philippines	Lithuania	Lithuania	Peru	Austria	Italy	Italy	Italy	Guatemala	Estonia	0.0756	0.0076	0.1010
37th	Peru	Portugal	Denmark	Brazil	Italy	Nicaragua	Austria	Luxembourg	Dominican Republic	Latvia	Finland	0.1644	0.0195	0.1186
38th	Botswana	Afghanistan	Portugal	Peru	Ireland	Latvia	Latvia	El Salvador	Luxembourg	Peru	France	0.2821	0.0315	0.1116
39th	Latvia	Peru	Austria	Ireland	Albania	Spain	Mauritania	Austria	Peru	Dominican Republic	Georgia	0.1857	0.0401	0.2159

Table A2. *Cont.*

Rank	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Country	Mean	SD	CV
40th	Italy	Spain	Italy	Portugal	Austria	Dominican Republic	Luxembourg	Spain	Austria	Romania	Germany	0.1759	0.0188	0.1068
41st	Lithuania	Italy	Peru	Italy	Spain	Portugal	Peru	Albania	Romania	Luxembourg	Ghana	0.2827	0.0299	0.1057
42nd	Georgia	Austria	Albania	Nicaragua	Portugal	Malta	Spain	Romania	Nicaragua	Spain	Greece	0.1394	0.0159	0.1140
43rd	Spain	Armenia	Spain	Latvia	Philippines	United Kingdom	Albania	Dominican Republic	Spain	Brazil	Guatemala	0.2770	0.0600	0.2166
44th	Portugal	Ireland	Dominican Republic	Spain	Latvia	Peru	Dominican Republic	Nicaragua	Congo (Brazzaville)	Nicaragua	Guinea	0.2938	0.0459	0.1564
45th	Ireland	Dominican Republic	Georgia	Afghanistan	Brazil	Philippines	Nicaragua	Peru	Brazil	Portugal	Haiti	0.3498	0.0879	0.2513
46th	Nicaragua	Nicaragua	United Kingdom	Dominican Republic	Dominican Republic	Congo (Brazzaville)	Philippines	Congo (Brazzaville)	Armenia	Albania	Honduras	0.1621	0.0168	0.1033
47th	Dominican Republic	Lithuania	Nicaragua	Botswana	Malta	Romania	Romania	Portugal	Albania	Croatia	Hungary	0.1888	0.0249	0.1320
48th	Armenia	Denmark	Latvia	Georgia	Botswana	Hungary	Portugal	Brazil	Portugal	Armenia	India	0.1048	0.0108	0.1034
49th	Denmark	Argentina	Argentina	Croatia	Congo (Brazzaville)	Albania	Brazil	Armenia	Croatia	Hungary	Indonesia	0.1624	0.0207	0.1273
50th	Montenegro	United Kingdom	Armenia	United Kingdom	Romania	Brazil	Cambodia	Philippines	Philippines	New Zealand	Iraq	0.0704	0.0101	0.1436
51st	United Kingdom	Cyprus	Cyprus	Cyprus	Hungary	Luxembourg	Hungary	Croatia	Hungary	Cyprus	Ireland	0.2490	0.0284	0.1140
52nd	Argentina	Azerbaijan	Belgium	Benin	United Kingdom	Croatia	Armenia	New Zealand	Belgium	Congo (Brazzaville)	Israel	0.1430	0.0135	0.0944
53rd	Netherlands	Croatia	Netherlands	Hungary	Cyprus	Belgium	Croatia	Hungary	New Zealand	Netherlands	Italy	0.2243	0.0252	0.1123
54th	Romania	Romania	New Zealand	Belgium	Croatia	Netherlands	Cyprus	Belgium	Cyprus	Philippines	Jordan	0.1237	0.0195	0.1574
55th	Chile	Malta	Croatia	Argentina	Benin	Armenia	New Zealand	Cyprus	Finland	Belgium	Kazakhstan	0.0569	0.0065	0.1140
56th	Croatia	New Zealand	Germany	Netherlands	Luxembourg	New Zealand	Belgium	Cambodia	Netherlands	Germany	Kenya	0.3670	0.0680	0.1852
57th	Benin	Chile	Malta	New Zealand	Armenia	Cyprus	Finland	Netherlands	Germany	Cambodia	Kyrgyzstan	0.0976	0.0175	0.1799
58th	Cyprus	Latvia	Hungary	Germany	Argentina	Chile	Netherlands	Germany	Honduras	Finland	Latvia	0.2160	0.0255	0.1180
59th	Senegal	Hungary	Benin	Malta	Belgium	Argentina	Germany	Indonesia	Argentina	Argentina	Lebanon	0.1360	0.0286	0.2100
60th	New Zealand	Netherlands	Luxembourg	Armenia	Georgia	Germany	Argentina	Finland	Mauritania	Israel	Lithuania	0.2374	0.0280	0.1177
61st	Malta	Senegal	Pakistan	Romania	New Zealand	Benin	Chile	Montenegro	Cambodia	Georgia	Luxembourg	0.1940	0.0178	0.0916

Table A2. *Cont.*

Rank	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Country	Mean	SD	CV
62nd	Belgium	Pakistan	Chile	Congo (Brazzaville)	Netherlands	Georgia	Indonesia	Argentina	Montenegro	Slovenia	Madagascar	0.4456	0.1334	0.2995
63rd	Hungary	Germany	Romania	Luxembourg	Pakistan	Tajikistan	Tajikistan	Honduras	Indonesia	Honduras	Malawi	0.5956	0.1079	0.1811
64th	Germany	Luxembourg	Honduras	Pakistan	Indonesia	Finland	Slovenia	Botswana	Slovenia	Mauritania	Mali	0.8972	0.1472	0.1640
65th	Luxembourg	Honduras	Senegal	Chile	Germany	Pakistan	Pakistan	Chile	Georgia	Chile	Malta	0.2595	0.0707	0.2727
66th	Azerbaijan	Belgium	Ecuador	Finland	Chile	Slovenia	Benin	Slovenia	Mexico	Mexico	Mauritania	0.2428	0.0622	0.2561
67th	Honduras	Benin	Afghanistan	Senegal	Finland	Indonesia	Georgia	Slovakia	Chile	Senegal	Mexico	0.1525	0.0168	0.1102
68th	Indonesia	Indonesia	Congo (Brazzaville)	Ecuador	Honduras	Botswana	Slovakia	Mexico	Ecuador	Indonesia	Mongolia	0.0533	0.0068	0.1271
69th	Pakistan	Lebanon	Lebanon	Honduras	Senegal	Mexico	Mexico	Georgia	Senegal	Slovakia	Montenegro	0.1577	0.0241	0.1528
70th	Ecuador	Ecuador	Finland	Indonesia	Montenegro	Montenegro	Botswana	Israel	Israel	Montenegro	Morocco	0.1244	0.0173	0.1388
71st	Bolivia	Congo (Brazzaville)	Azerbaijan	Mexico	Ecuador	Honduras	Honduras	Pakistan	Slovakia	Ecuador	Nepal	0.4271	0.1443	0.3379
72nd	Finland	Bolivia	Indonesia	Montenegro	Mexico	Slovakia	Montenegro	Ecuador	Botswana	Thailand	Netherlands	0.1821	0.0218	0.1195
73rd	Slovenia	Egypt	Slovenia	Slovakia	Slovenia	Israel	Israel	Senegal	Pakistan	Botswana	New Zealand	0.1839	0.0183	0.0995
74th	Greece	Mexico	Mexico	Slovenia	Lebanon	Senegal	Ecuador	Greece	Thailand	Pakistan	Nicaragua	0.2125	0.0296	0.1393
75th	Mexico	Slovenia	Egypt	Bolivia	Israel	Ecuador	Senegal	Tajikistan	Benin	Greece	Niger	0.3869	0.0735	0.1900
76th	Egypt	Greece	Bolivia	Lebanon	Azerbaijan	Greece	Greece	Benin	Greece	Benin	Nigeria	0.2799	0.0489	0.1748
77th	Tunisia	Thailand	Montenegro	Azerbaijan	Slovakia	Azerbaijan	Azerbaijan	Thailand	Zimbabwe	Egypt	Pakistan	0.1639	0.0290	0.1767
78th	Lebanon	Jordan	Thailand	Egypt	Egypt	Egypt	Egypt	Egypt	Tajikistan	Azerbaijan	Panama	0.3177	0.0261	0.0823
79th	Thailand	Montenegro	Slovakia	Thailand	Bolivia	Lebanon	Thailand	Azerbaijan	Egypt	Bolivia	Paraguay	0.4097	0.0926	0.2260
80th	Jordan	Finland	Tunisia	Tunisia	Tunisia	Thailand	Bolivia	Bolivia	Azerbaijan	Tajikistan	Peru	0.2201	0.0296	0.1345
81st	Morocco	Tunisia	Jordan	Greece	Greece	Bolivia	Tunisia	Tunisia	Bolivia	Tunisia	Philippines	0.2152	0.0390	0.1810
82nd	Slovakia	Slovakia	Greece	Israel	Thailand	Tunisia	Lebanon	Zimbabwe	United States of America	Czech Republic	Poland	0.1080	0.0119	0.1101
83rd	Israel	Morocco	Israel	Morocco	Republic of Moldova	Morocco	Morocco	Morocco	Tunisia	United States of America	Portugal	0.2127	0.0314	0.1475
84th	Congo (Brazzaville)	Israel	Morocco	Jordan	Morocco	Republic of Moldova	Czech Republic	United States of America	Czech Republic	Jordan	Republic of Moldova	0.1127	0.0160	0.1416
85th	Zimbabwe	Kyrgyzstan	United States of America	United States of America	Jordan	Czech Republic	United States of America	Lebanon	Morocco	Morocco	Romania	0.1953	0.0188	0.0962
86th	Kyrgyzstan	Zimbabwe	Czech Republic	Zimbabwe	United States of America	Jordan	Jordan	Jordan	Republic of Moldova	Zimbabwe	Russian Federation	0.0739	0.0097	0.1317

Table A2. *Cont.*

Rank	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Country	Mean	SD	CV
87th	United States of America	India	Kyrgyzstan	Czech Republic	Czech Republic	Zimbabwe	Republic of Moldova	Czech Republic	Jordan	Republic of Moldova	Rwanda	0.7833	0.1496	0.1910
88th	Czech Republic	United States of America	India	Poland	Zimbabwe	United States of America	Poland	Republic of Moldova	Lebanon	Lebanon	Saudi Arabia	0.0925	0.0137	0.1479
89th	India	Czech Republic	Zimbabwe	Republic of Moldova	Bulgaria	Poland	Zimbabwe	Poland	Poland	Poland	Senegal	0.1591	0.0242	0.1523
90th	Republic of Moldova	Republic of Moldova	Republic of Moldova	India	Poland	Bulgaria	India	India	India	Bulgaria	Serbia	0.0779	0.0103	0.1323
91st	Bulgaria	Poland	Poland	Belarus	India	India	Belarus	Bulgaria	Bulgaria	India	Slovakia	0.1459	0.0169	0.1161
92nd	Poland	Bulgaria	Belarus	Bulgaria	Belarus	Belarus	Bulgaria	Canada	Kyrgyzstan	Australia	Slovenia	0.1553	0.0158	0.1017
93rd	Saudi Arabia	Canada	Saudi Arabia	Canada	Canada	Australia	Canada	Kyrgyzstan	Canada	Canada	South Africa	0.0518	0.0070	0.1344
94th	Canada	Saudi Arabia	Canada	Saudi Arabia	Saudi Arabia	Canada	Australia	Belarus	Belarus	Saudi Arabia	Spain	0.2148	0.0252	0.1175
95th	Belarus	Belarus	Bulgaria	Australia	Australia	Kyrgyzstan	Kyrgyzstan	Australia	Australia	Belarus	Sweden	0.3762	0.0373	0.0991
96th	Australia	Australia	Australia	Kyrgyzstan	Kyrgyzstan	Serbia	Saudi Arabia	Saudi Arabia	Ukraine	Ukraine	Tajikistan	0.2000	0.0673	0.3365
97th	Iraq	Serbia	Russian Federation	Serbia	Serbia	Saudi Arabia	Estonia	Estonia	Saudi Arabia	Kyrgyzstan	Thailand	0.1378	0.0152	0.1106
98th	Estonia	Iraq	Iraq	Estonia	Russian Federation	Ukraine	Ukraine	Ukraine	Estonia	Estonia	Tunisia	0.1320	0.0211	0.1600
99th	Serbia	Russian Federation	Serbia	Russian Federation	Ukraine	Russian Federation	Serbia	Serbia	Serbia	Serbia	Turkmenistan	0.0301	0.0026	0.0869
100th	Russian Federation	Ukraine	Estonia	Iraq	Iraq	Estonia	Russian Federation	Russian Federation	Russian Federation	Russian Federation	Uganda	0.5163	0.1053	0.2040
101st	Ukraine	Bosnia and Herzegovina	Ukraine	Ukraine	Estonia	Bosnia and Herzegovina	Iraq	Iraq	Iraq	Bosnia and Herzegovina	Ukraine	0.0756	0.0067	0.0881
102nd	Bosnia and Herzegovina	Estonia	Bosnia and Herzegovina	Bosnia and Herzegovina	Bosnia and Herzegovina	Kazakhstan	Bosnia and Herzegovina	Bosnia and Herzegovina	Bosnia and Herzegovina	Kazakhstan United Kingdom	0.2143	0.0164	0.0766	
103rd	Kazakhstan	Kazakhstan	South Africa	Kazakhstan	Mongolia	Iraq	Kazakhstan	Kazakhstan	Kazakhstan	Iraq	United Republic of Tanzania	0.3750	0.0667	0.1778
104th	South Africa	South Africa	Mongolia	South Africa	South Africa	Mongolia	Mongolia	China	China	China	United States of America	0.1149	0.0120	0.1043
105th	Mongolia	Mongolia	Kazakhstan	Mongolia	Kazakhstan	Uzbekistan	Uzbekistan	Uzbekistan	Uzbekistan	Uzbekistan	Uruguay	0.3357	0.0383	0.1141
106th	China	China	China	China	China	China	China	Mongolia	Mongolia	Mongolia	Uzbekistan	0.0487	0.0075	0.1533

Table A2. *Cont.*

Rank	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Country	Mean	SD	CV
107th	Uzbekistan	Uzbekistan	Uzbekistan	Uzbekistan	Uzbekistan	South Africa	South Africa	South Africa	South Africa	South Africa	Zambia	0.3942	0.1332	0.3379
108th	Turkmenistan	Turkmenistan	Turkmenistan	Turkmenistan	Turkmenistan	Turkmenistan	Turkmenistan	Turkmenistan	Turkmenistan	Turkmenistan	Zimbabwe	0.1153	0.0107	0.0927

Note: "SD" denote standard deviation; "CV" denote coefficient of variation.

Table A3. VIF statistic.

Variable	VIF	1/VIF
LnCO2	1.00	1.0000
Mean VIF	1.00	

Note: LnGDP values were used as dependent variables in VIF statistics of DEA analysis.

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Article

Quantifying the Competitiveness of Cultural Industry and Its Impacts on Chinese Economic Growth

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Abstract: One potential way to promote China's economic growth is to develop a cultural industry and enhance its competitiveness. To confirm this hypothesis, this study first utilizes the five-element diamond model, principal component analysis, and factor analysis to evaluate the competitiveness of the cultural industry in the 31 Chinese provinces during the period 2013–2019. The results reveal that the competitiveness of cultural industry in the eastern region is the strongest, followed in descending order by the central, northeastern, and western regions of China. Then, the panel regression is employed to explore the impact of the cultural industry's competitiveness index on economic growth. The results indicate that the cultural industry's competitiveness is positively associated with China's economic growth. We also conduct another panel regression analysis by examining the impact of cultural industry factors on China's economic growth to gain insight into the influence of the cultural industry components on growth. In this analysis, our results indicate that cultural industry factors, including fixed asset investment and labor, significantly play an important role in Chinese growth. This study also finds that total patent applications, the total profit of cultural enterprises, and government expenditure positively impact economic growth, but the evidence is weak. Thus, these three variables could be considered potential future driver factors. The empirical findings offer insights into strategies that the national government could implement to strengthen the cultural industry's competitiveness as China's new powerful driver of economic development. Compared with previous empirical studies, this research deepens the competitive cultural analysis, increases the number of observations, and lengthens the period studied.

Keywords: Chinese economic growth; competitiveness index; cultural industry; panel regression models

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1. Introduction

Under the integration of culture and science and technology backgrounds in the digital era, the cultural and creative industries foster income generation, exports, and employment, and have become major drivers of the economic prosperity of many countries worldwide [1]. The United Nations [2] considers the creative economy as "a significant sector and a meaningful contributor to national gross domestic product." In 2019, China's culture and related industries generated an added value of 4501.6 billion-yuan, accounting for 4.54% of GDP, which indicates that the cultural industry, as an emerging industry with broad prospects, is a new driving force for economic growth. The fifth plenary session of the 17th Central Committee of the Communist Party of China proposed promoting the cultural industry to become a pillar industry of the national economy. Furthermore, in the report of the Nineteenth National Congress of the Communist Party of China, General Secretary Xi Jinping emphasized that it is necessary to advance the development of the cultural industry, improve the cultural management system, and build a mechanism that integrates social and economic benefits. The cultural industry creates the possibility for optimizing industrial structure, reconstructing regional economic patterns, and accelerating the transformation of the economic development mode.

The achievements of China's cultural industry in recent years are mainly reflected in the diverse cultural goods, cultural serviceability, reformation of the cultural system, internal cultural exploration, and external cultural communication. Li [3] pointed out that the cultural and creative industries will provide a new path for the sustainable and healthy development of the economy and society, and get the economic transformation from "Made in China" to "Created in China" realized. The latest 14th five-year plan expounded the tasks of developing advanced socialist culture and enhancing the country's cultural soft power. The strengthening of China's cultural soft power will dedicate to the Two Centenary Goals and the Chinese Dream of the great rejuvenation of the Chinese nation [4]. The core issue of the development of the cultural industry is to improve its competitiveness [5]. The competitiveness of the cultural industry is an essential part of a country's international competitiveness, which refers to the ability of a country or a regional cultural enterprise's products and services to develop and occupy the market in world and obtain profits. The cultural and creative industries demonstrate a country's economic growth and have become a critical strategy for enhancing the core competitiveness of the national economies [6]. Therefore, a comprehensive understanding of the interaction between the cultural industry's competitiveness and economic growth is crucial. The present study aims to identify the competitiveness of the cultural industry and its impact on economic growth by using a combination of quantitative and qualitative methods. Based on Porter's five-factor diamond model, this paper constructs an evaluation index system of the cultural industry and uses principal component analysis and factor analysis to evaluate the competitiveness of the cultural industry in 31 provinces of China from 2013 to 2019. Subsequently, the panel regression models are adopted to analyze the influence of the competitiveness index and relevant factors on economic growth.

Domestic and international experts and scholars have obtained some good research outcomes on the issues of the cultural industry's competitiveness and the relationship between the cultural industry and economic growth [7–10]. They advocated some indexes to evaluate the competitiveness of the cultural industry and analyze its characteristics. However, there is a certain subjectivity, one-sidedness, and superficiality in the selection of indicators for evaluating the competitiveness of the cultural industry. Moreover, there is little data to support the conclusion that the cultural industry's competitiveness positively affects economic growth. This paper selects the evaluation indicators of the cultural industry's competitiveness with a systematic, dynamic, and operable principle. By quantifying the qualitative data to obtain the cultural industry's competitiveness index and putting it into regression analysis, the relationship between the cultural industry's competitiveness and economic growth can be fully explained and understood. This analysis can be used by decision-makers in crafting policies around the cultural industry to give full play to its leading role in the overall economic environment and coordinate the development of various regions in China.

2. Literature Review

In recent years, research on the development of the cultural industry has mainly focused on policy and management, the influence of new technologies, workforce size, and the competitiveness of the cultural industry from the perspective of countries, regions, and enterprises. Many studies have shown that in Asian countries, such as Singapore, Japan, the Republic of Korea, and China, the policies on the cultural industry and creative industry are key to their national development and attach importance to the role of national cultural characteristics and the creativity of cultural production [11–14]. The specialization of the cultural industry is inseparable from the support of technology and talents. For example, Bujor and Avsilcai [15] explored the contribution of technology to the creative industries at the European Union level and pointed out that creative tech (IT and Software and Computer Services) can continually help them to develop and to cope with market demands.

Nathan et al. [16] compared creative economies in the United States of America and the United Kingdom by using the creative trident framework and found that the UK creative economy is larger in workforce shares, while the US creative workers are more evenly dispersed across all industries. Moreover, the cultural industry's competitiveness can affect various sectors of the economy and create shared-value benefits is no longer debatable. Michael Porter's diamond model is the most widely used among the evaluation models of the cultural industry's competitiveness. Harabi [17] used Porter's diamond model to explain the economic performance of four creative industries (book publishing, music sound recording, film production, and software industries) in five Arab countries (Morocco, Tunisia, Egypt, Jordan, and Lebanon). Chen et al. [18] applied the six-element diamond model to study the competitiveness of the cultural and creative industries in China and put forward suggestive thinking on improving the competitiveness of the 18 provinces and cities along the "Belt and Road". The competitiveness of the sub-industries of the cultural industry also attracts the attention of scholars. For instance, Einarsson [19] described the competitive position of the music industry as music being a part of the cultural and creative industries in Iceland by adopting Porter's five forces model.

The cultural industry is expanding and reforming alongside the digital economy, which is more flexible with the downward economic pressures. Based on the understanding of the cultural industry's commercial and ideological value, scholars and researchers have achieved certain results on the relationship between it and economic growth. Montalto, et al. [20] presented an econometric model that revealed the positive impact of the cultural and creative industries on the GDP per inhabitant, and the share of cultural employment in total employment on cultural consumption expenditure. Piergiovanni et al. [21] explored the impact of a series of factors, including creativity, intellectual property rights activities, new business formation, and the provision of amenities, on economic growth for 103 Italian provinces. Findings showed an increase in the number of firms active in the creative industries, net entry, a greater provision of leisure amenities, and the share of legal immigrants have a positive effect on regional economic growth. Daubaraitė and Startienė [22] discussed the impact of creative industries on the Lithuanian national economy by creating jobs, contributing to GDP, and enlarging exports. Correa-Quezada et al. [23] evaluated the impact of employment in creative industries on the regional and national economic growth of Ecuador. The main findings showed a significant influence of creative employment on regional production and development. In addition, domestic scholars not only further verified the promotion of economic growth by the cultural industry but also underlined the importance of investment scale, human capital, and innovation. Lu [24] found a significant positive correlation between China's cultural industry investment and economic growth by using cointegration analysis, error correction model, Granger causality test, and vector autoregression (VAR) model. Wang and Gu [25] stated that the development of the cultural industry has significantly promoted the economic growth of the Yangtze River Delta region, and the stock of human capital and the scale of capital inflow will affect the growth effect of the cultural industry. Li and Liu [26] noticed that the cultural industry has a relatively significant impact on economic growth, especially the driving role of the tertiary industry, and emphasized the significance of cultural industry innovation to economic growth. The research on the relationship between cultural industry and economic growth has gradually attracted the attention of scholars. However, the competitiveness of a country or an industry is a complex concept that cannot be measured directly and requires extensive efforts for data collection [27,28]. As far as we are aware, there has not been a study that relates competitiveness of cultural industry and economic growth for China. Furthermore, the competitiveness of cultural industry has not been established yet, thus, this study aims to fill in this gap by building cultural industry competitiveness index (CI) using principal component analysis and factor analysis. Then, CI and other control variables are included in the panel regression analysis, which provides a more comprehensive and accurate method than using only a few indicators representing the cultural industry for investigating the impact of the cultural industry as a whole on economic growth. Moreover, the relevant factors of cultural industry are included in the second round of the panel regression analysis, which will benefit grasping the role of various factors in the economies and point out the further direction of cultural industry development and industrial structure adjustment.

3. Data

The data are retrieved from the National Bureau of Statistics of China [29], CNKI database [30], China statistical yearbooks of culture and related industries [31], China statistical yearbooks of cultural relics and tourism [32], China statistical yearbooks of the tertiary industry [33], China statistical yearbooks of science and technology [34], and provincial statistical yearbooks [35].

The research sample consists of China's 31 provinces: Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Hunan, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang. The period of the analysis covers 7 years, from 2013 to 2019. According to Porter's five-element diamond model, the evaluation framework of China's cultural industry's competitiveness is constructed. Table 1 shows the index system, which contains 5 first-level indicators, 11 second-level indicators, and 15 third-level indicators.

Table 1. China's cultural and related industry competitiveness evaluation index.

First Level Indicator	Second Level Indicator	Third Level Indicator	Unit	Source
Factor Conditions	Capital element	X_1: Fixed Asset Investment in Culture, Sports and Entertainment Industry	100 million yuan	The tertiary industry
	Labor element	X_2: Labor in Cultural Enterprises	person	Culture and related industries
	Cultural elements	X_3: Number of Collections in Museums	piece/set	Culture and related industries
		X_4: Total Collections in Public Libraries	10,000 copies	Culture and related industries
Demand Conditions	Industrial structure	X_5: Proportion of Tertiary Industry in Gross Regional Product	%	Culture and related industries
	Consumer behavior	X_6: Per Capita Consumption and Expenditure on Culture and Recreation of Nationwide Households	yuan	Culture and related industries
Firm Strategy, Structure and Rivalry	Operations and management	X_7: Number of Cultural Enterprises	number	Culture and related industries
		X_8: Users of Cable Radios and TVs	10,000 households	Culture and related industries
		X_9: Total Assets of Cultural Market Operating Institutions	1000 yuan	Cultural relics and tourism

Table 1. *Cont.*

First Level Indicator	Second Level Indicator	Third Level Indicator	Unit	Source
Firm Strategy, Structure and Rivalry	Innovation capacity	X_{10}: Total Patent Applications Granted on Culture and Related Industries	piece	Culture and related industries
	Profitability	X_{11}: Total Revenue of Cultural Enterprises	10,000 yuan	Culture and related industries
		X_{12}: Total Profit of Cultural Enterprises	10,000 yuan	Culture and related industries
Government Action, Opportunity and Advantage	Fiscal expenditure	X_{13}: Expenditure for Culture, Sport and Media of Regional Government Revenue	100 million yuan	Culture and related industries
Related and Supporting Industries	Tourism	X_{14}: Earnings from International Tourism	USD Million	Culture and related industries
	Information service industry	X_{15}: Number of Regional Internet Broadband Users	10,000 households	The tertiary industry

Notes: X_2, X_{11}, and X_{12} represent the sum of data related to cultural industrial enterprises, cultural wholesale and retail trades enterprises, and cultural services enterprises above the designated size, respectively. The data sources are the China statistical yearbooks, and the names are listed in the table.

Furthermore, the data in panel regression analysis consist of gross domestic product (GDP) growth rate, competitiveness index of cultural industry, total investment in fixed assets, number of employed persons, and the R&D expenditure input intensity. The list of variables used in this study is displayed in Table 2.

Table 2. The list of panel regression variables.

Variables	Description	Unit	Source
GDP	The year-over-year change in a region's economic output	%	CNKI
CI	The competitiveness level of cultural industry in various regions	number	own calculation
Inv	The purchase of newly produced fixed capital	100 million yuan	National Bureau of Statistics of China
EP	The number of people engaged in productive activities in an economy	10,000 persons	China provincial statistical yearbooks
RDE	R&D expenditure as a percentage of gross domestic product	%	China statistical yearbooks of science and technology

4. Research Methodology

4.1. The Competitiveness Index Calculation Method

4.1.1. Porter's Diamond Model

Porter [36] proposed the diamond model as an analytical framework for building and enhancing the competitive advantage in particular industries. Porter suggested that factor conditions, demand conditions, related and supporting industries, and firm strategy, structure, and rivalry as a system constitute diamonds of national advantage. Moreover, the role of the government and chance also have exogenous influences on the playing field that each nation establishes and operates for its industries (Figure 1). Under the combined action of these determinants, the development of the industries' competitiveness can be effectively promoted. According to Porter's diamond model, the cultural industry competitiveness evaluation system is constructed, and principal component analysis and factor analysis are used to calculate the cultural industry competitiveness index (CI) in this study.

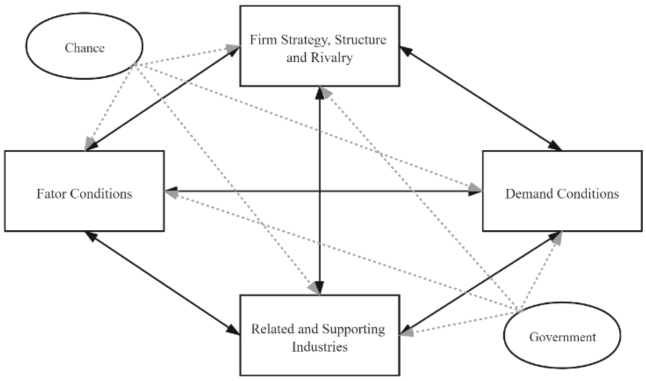

Figure 1. The Porter's Diamond Model.

4.1.2. Principal Component Analysis

Principal component analysis is a common statistical method of dimensionality reduction, which transforms numerous variables into several new comprehensive variables and minimizes the loss of information at the same time. Generally, these new variables result from linear weighted combinations of the original variables, known as principal components. The principal components are not related to each other and account for much of the variance among the initial variables. The principal components are ordered according to the amount of variation in the original variables they explain. Therefore, the variance of the first principal component is the largest and contains the most information. The variance of the second principal component is less than that of the first, and the covariance between the second principal component and the first principal component is 0, which means that these two components are completely uncorrelated. Subsequent components can also be constructed in this way. This paper uses principal component analysis to reduce the dimension of the data space studied, and principal components are extracted for subsequent CI calculation.

4.1.3. Factor Analysis

Factor analysis is a statistical technique used to reduce the number of variables and to identify underlying representative factors, which can detect structure in relationships between relevant variables [37]. There are four basic steps for calculating the CI: assessing the suitability of the data used, determining factor extraction, rotational method, and constructing factor scores and the CI. Firstly, the Kaiser–Meyer–Olkin (KMO) Measure of Sampling Adequacy and Bartlett's Test of Sphericity are common methods to detect whether the data are suitable for factor analysis. A KMO index close to 1.0 is considered ideal, while an index below 0.5 is not acceptable. The p-value of Bartlett's Test of Sphericity that corresponds to the test statistic is less than some significance level (like = 0.05), which indicates that the data are suitable for factor analysis. Secondly, the method of principal component analysis is used to calculate the cumulative percentage of variance and factor load. According to the criteria of cumulative percentage of variance >85% and the characteristic root >1, factor extraction is determined. Thirdly, the factor rotation method is used to produce more interpretable and concise factors, which provides a solution for the naming and meaning of factors. The varimax rotation maximizes the sum of the variances of the factor-squared loadings and produces uncorrelated factor structures [38]. Finally, the factor score coefficient matrix is obtained by regression algorithm, which is used to calculate the score of each factor, and the CI is obtained by taking the variance contribution rate of each factor after the rotation as the weight [18]. The factor score equation can be presented as:

$$FS_{kt} = \sum_{p=1}^{n} a_{pt}x_{pt} \quad (1)$$

where FS_{kt} is the kth factor score in year t, a_{pt} is the factor score coefficient in year t, x_{pt} is the pth initial variable in year t, and n is the number of initial variables.

The equation of the CI is presented as:

$$CI_{it} = \sum b_{kt}FS_{kt} \quad (2)$$

where CI_{it} is the competitiveness index of province i in year t, b_{kt} is the contribution rate of the variance of the kth factor in year t, and FS_{kt} is the score of the kth factor in year t.

4.2. Panel Regression Models

This paper investigates the impact of the cultural industry's competitiveness and relevant factors on China's economic growth. The following two panel regression models are employed:

Model 1:

$$\ln GDP_{it} = \theta_0 + \theta_1 \ln CI_{it} + \theta_2 \ln Inv_{it} + \theta_3 \ln EP_{it} + \theta_4 \ln RDE_{it} + \varepsilon_{it} \quad (3)$$

where GDP_{it} is the gross domestic product growth rate of province i in year t, CI_{it} is the competitiveness index of cultural industry of province i in year t, Inv_{it} is total investment in fixed assets of province i in year t, EP_{it} is the number of employed persons of province i in year t, RDE_{it} is R&D expenditure input intensity of province i in year t, θ_0 is the intercept, θ_1, θ_2, θ_3, θ_4 are the coefficients, and ε_{it} is the error term.

Model 2:

$$\begin{aligned}\ln GDP_{it} = \beta_0 + \beta_1 \ln X_{1it} + \beta_2 \ln X_{2it} + \beta_3 \ln X_{3it} + \beta_4 \ln X_{4it} + \beta_5 \ln X_{5it} + \beta_6 \ln X_{6it} + \beta_7 \ln X_{7it} \\ + \beta_8 \ln X_{8it} + \beta_9 \ln X_{9it} + \beta_{10} \ln X_{10it} + \beta_{11} \ln X_{11it} + \beta_{12} \ln X_{12it} + \beta_{13} \ln X_{13it} + \varepsilon_{it}\end{aligned} \quad (4)$$

where X_{1it}, X_{2it}, ..., X_{13it} are the relevant factors of the cultural industry of province i in year t. β_1, β_2, ..., β_{13} are the coefficients corresponding to 13 indicators X_1, X_2, ..., X_{13}. β_0 is the intercept, and ε_{it} is the error term. The observations of panel data analysis involve two dimensions: a cross-sectional dimension and a time series dimension [39]. Consequently, panel data contain more information, more variability, and more efficiency to better analyze the relationship between the cultural industry's competitiveness and economic growth. In Model 1, this paper's most concerned independent variable is the cultural industry competitiveness index (CI), which is obtained through principal component analysis and factor analysis. The selection of other independent variables is based on the endogenous growth theory. After analyzing how CI affects China's economic growth, there are still some deficiencies in investigating the impact of a certain indicator of cultural industry on economic growth. Therefore, the first 13 indicators in the cultural industry index system as independent variables are selected in Model 2 to discuss this issue. These 13 indicators represent the cultural industry's relevant factors, including X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9, X_{10}, X_{11}, X_{12}, and X_{13}. As X_{14} and X_{15} represent related and supporting industrial factors, they are not considered here. The negative values in X_{12} are replaced by 1, and their logarithm is taken.

Before setting and estimating the panel data regression model, evaluating the stationarity of the variables involved is necessary. Methods of Levin, Lin, and Chu [40] and the Augmented Dickey-Fuller [41] are used to test the null hypothesis that a unit root is present in the variables. In the panel regression analysis, F-test, Breusch-Pagan Lagrange Multiplier test, and Hausman test are used to make the selection among pooled regression model, fixed effects model, or random effects model [42–44].

5. Empirical Research

5.1. The Evaluation of the Competitiveness of China's Cultural Industry

5.1.1. Data Pre-Processing

The Kaiser–Meyer–Olkin (KMO) and Bartlett's tests are used to observe the correlation between selected variables from 2013 to 2019. The KMO values for the years from 2013 to 2019 are 0.807, 0.796, 0.833, 0.765, 0.792, 0.807 and 0.728, respectively. Moreover, Table 3 shows that all *p*-values of Bartlett's sphericity test are less than 0.05 for 2013–2019, indicating that the null hypothesis is rejected. This means that the selected data are suitable for factor analysis.

Table 3. KMO and Bartlett test results.

		2013	2014	2015	2016	2017	2018	2019
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0.807	0.796	0.833	0.765	0.792	0.807	0.728
Bartlett's Test of Sphericity	Approx. Chi-Square	722.965	724.527	748.146	726.322	727.374	707.013	746.092
	p-Value	0.000	0.000	0.000	0.000	0.000	0.000	0.000

5.1.2. Principal Component Analysis

We perform principal component analysis to calculate a composite competitiveness index (CI) based on the selected indicators related to China's cultural and related industry (X_1–X_{15}). The results are reported in Table 4, and we find that the first three components are the main components according to the standard of the characteristic root greater than 1. Moreover, the cumulative contribution rates from 2013 to 2019 have reached 87.463%, 87.162%, 89.398%, 88.386%, 89.293%, 87.902%, and 85.694%, respectively, indicating the three principal components can express most of the relevant information of the original 15 variables. This paper records the labels of the three principal components as F1, F2, and F3.

Table 4. Total variance explained before and after rotation.

	Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
		Total	Variance%	Cumulative %	Total	Variance%	Cumulative %	Total	Variance%	Cumulative %
2013	1	9.883	65.884	65.884	9.883	65.884	65.884	6.880	45.868	45.868
	2	1.976	13.171	79.054	1.976	13.171	79.054	3.869	25.793	71.661
	3	1.261	8.409	87.463	1.261	8.409	87.463	2.370	15.801	87.463
2014	1	9.846	65.643	65.643	9.846	65.643	65.643	7.016	46.774	46.774
	2	2.062	13.749	79.391	2.062	13.749	79.391	3.522	23.478	70.253
	3	1.166	7.770	87.162	1.166	7.770	87.162	2.536	16.909	87.162
2015	1	9.746	64.973	64.973	9.746	64.973	64.973	7.484	49.896	49.896
	2	2.560	17.064	82.037	2.560	17.064	82.037	3.376	22.506	72.402
	3	1.104	7.361	89.398	1.104	7.361	89.398	2.549	16.996	89.398
2016	1	9.581	63.872	63.872	9.581	63.872	63.872	7.230	48.202	48.202
	2	2.514	16.759	80.631	2.514	16.759	80.631	3.043	20.289	68.492
	3	1.163	7.755	88.386	1.163	7.755	88.386	2.984	19.894	88.386
2017	1	9.592	63.949	63.949	9.592	63.949	63.949	7.529	50.191	50.191
	2	2.622	17.483	81.432	2.622	17.483	81.432	3.050	20.334	70.524
	3	1.179	7.861	89.293	1.179	7.861	89.293	2.815	18.769	89.293

Table 4. *Cont.*

	Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
		Total	Variance%	Cumulative %	Total	Variance%	Cumulative %	Total	Variance%	Cumulative %
2018	1	9.372	62.477	62.477	9.372	62.477	62.477	7.635	50.900	50.900
	2	2.563	17.089	79.566	2.563	17.089	79.566	2.800	18.665	69.566
	3	1.250	8.336	87.902	1.250	8.336	87.902	2.750	18.336	87.902
2019	1	9.158	61.056	61.056	9.158	61.056	61.056	7.555	50.368	50.368
	2	2.440	16.270	77.326	2.440	16.270	77.326	2.758	18.384	68.752
	3	1.255	8.368	85.694	1.255	8.368	85.694	2.541	16.942	85.694

5.1.3. Factor Analysis

The three principal components, F1, F2, and F3, obtained from principal component analysis can be used as the main factors in factor analysis to comprehensively evaluate the competitiveness of China's cultural industry. Moreover, the three principal components of a certain year correspond to the comprehensive evaluation score of that year. After factor analysis, the significance of the factor load of 15 variables in the component matrix is not obvious, and it cannot give a reasonable explanation for the relationship between the three factors and variables. Through the method of orthogonal rotation of the maximum variance, Table 5 shows that the rotated component matrix from 2013 to 2019 is obtained, which can make each factor have a high load only corresponding to a few variables, and each variable has a high load only on a few factors. The main factor F1 has a larger load value on the core of the cultural industry's competitiveness. The main factor F2 has a larger load value on the relevant resources of the cultural industry. The main factor F3 has a larger load value on the demand market of the cultural industry. Therefore, the naming of factors can be reasonably explained: F1 is the core competition factor, F2 is the resource competition factor and F3 is the demand competition factor.

Table 5. Rotated component matrix.

	Variable	Component			Variable	Component			Variable	Component		
		1	2	3		1	2	3		1	2	3
2013	X_2	0.926	0.281	0.101	X_{11}	0.825	0.409	0.319	X_3	0.033	0.823	0.319
	X_4	0.612	0.611	0.276	X_{12}	0.789	0.454	0.337	X_8	0.625	0.753	−0.115
	X_7	0.832	0.427	0.260	X_{14}	0.866	0.064	0.278	X_{13}	0.456	0.745	0.253
	X_9	0.848	0.172	0.189	X_{15}	0.769	0.575	−0.173	X_5	0.185	−0.067	0.903
	X_{10}	0.870	0.291	0.086	X_1	0.353	0.738	−0.309	X_6	0.280	0.255	0.873
2014	X_2	0.932	0.271	0.102	X_{11}	0.830	0.379	0.337	X_3	0.041	0.824	0.346
	X_4	0.632	0.583	0.288	X_{12}	0.810	0.393	0.359	X_8	0.676	0.707	−0.111
	X_7	0.861	0.408	0.209	X_{14}	0.875	0.019	0.281	X_{13}	0.589	0.652	0.251
	X_9	0.596	0.330	0.383	X_{15}	0.778	0.560	−0.167	X_5	0.158	−0.076	0.903
	X_{10}	0.945	0.171	0.117	X_1	0.367	0.733	−0.332	X_6	0.283	0.207	0.877
2015	X_2	0.948	0.177	0.174	X_{11}	0.836	0.402	0.302	X_5	0.027	0.928	−0.035
	X_4	0.740	0.287	0.438	X_{12}	0.808	0.451	0.279	X_6	0.260	0.900	0.174
	X_7	0.895	0.225	0.325	X_{13}	0.695	0.358	0.518	X_9	0.357	0.864	0.064
	X_8	0.778	−0.069	0.595	X_{14}	0.838	0.331	−0.074	X_1	0.519	−0.285	0.653
	X_{10}	0.950	0.167	0.072	X_{15}	0.847	−0.132	0.481	X_3	0.086	0.244	0.853

Table 5. *Cont.*

	Variable	Component 1	Component 2	Component 3	Variable	Component 1	Component 2	Component 3	Variable	Component 1	Component 2	Component 3
2016	X_2	0.943	0.146	0.239	X_{11}	0.831	0.360	0.358	X_5	0.022	0.944	−0.033
	X_4	0.725	0.292	0.465	X_{12}	0.824	0.354	0.318	X_6	0.269	0.876	0.164
	X_7	0.872	0.169	0.400	X_{13}	0.704	0.376	0.487	X_9	0.450	0.754	−0.041
	X_8	0.751	−0.083	0.618	X_{14}	0.838	0.314	−0.075	X_1	0.424	−0.280	0.735
	X_{10}	0.954	0.154	0.088	X_{15}	0.745	−0.149	0.610	X_3	0.053	0.238	0.864
2017	X_2	0.945	0.126	0.246	X_{11}	0.854	0.361	0.312	X_5	0.083	0.939	−0.106
	X_4	0.766	0.257	0.431	X_{12}	0.850	0.364	0.250	X_6	0.275	0.877	0.122
	X_7	0.870	0.138	0.410	X_{13}	0.743	0.456	0.388	X_9	0.619	0.688	0.006
	X_8	0.704	−0.094	0.658	X_{14}	0.862	0.253	−0.067	X_1	0.317	−0.371	0.771
	X_{10}	0.961	0.110	0.066	X_{15}	0.747	−0.182	0.587	X_3	0.037	0.314	0.826
2018	X_2	0.947	0.258	0.069	X_{10}	0.971	0.030	0.048	X_{15}	0.699	0.618	−0.207
	X_4	0.779	0.422	0.237	X_{11}	0.882	0.236	0.378	X_1	0.210	0.805	−0.345
	X_7	0.887	0.397	0.083	X_{12}	0.818	0.202	0.421	X_3	0.035	0.834	0.321
	X_8	0.706	0.648	−0.097	X_{13}	0.769	0.371	0.414	X_5	0.134	−0.118	0.927
	X_9	0.692	−0.025	0.469	X_{14}	0.872	0.004	0.204	X_6	0.274	0.062	0.890
2019	X_2	0.938	0.259	0.076	X_{10}	0.957	0.004	0.013	X_{15}	0.677	0.625	−0.226
	X_4	0.809	0.401	0.201	X_{11}	0.864	0.228	0.410	X_1	0.135	0.795	−0.268
	X_7	0.896	0.330	0.162	X_{12}	0.892	0.115	0.355	X_3	0.061	0.835	0.271
	X_8	0.701	0.635	−0.114	X_{13}	0.754	0.458	0.321	X_5	0.095	−0.128	0.925
	X_9	0.617	−0.002	0.440	X_{14}	0.854	0.044	0.184	X_6	0.318	0.069	0.883

Then, the factor score coefficients are substituted into Equation (1), and the scores of each main factor in 2013–2019 are obtained. Finally, taking the contribution rate of the variance of each factor as the weight, the comprehensive scores of the competitiveness of the cultural industry of 31 provinces in China from 2013 to 2019 are calculated by Equation (2), and the CI and rankings are shown in Table 6. In Table 6, it is clear that the comprehensive score reflects the competitiveness level of the cultural industry in 31 provinces of China from 2013 to 2019. If the score of a certain province is greater than 0, it indicates that its competitiveness level is above the national average level for that year.

Table 6. Competitiveness index and ranking of cultural industry of 31 provinces in China, 2013–2019.

Region		2013		2014		2015		2016		2017		2018		2019	
		Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Eastern China	Beijing	0.74	4	0.80	4	0.91	4	0.86	4	0.89	4	0.90	4	0.84	4
	Tianjin	−0.20	15	−0.17	15	−0.16	15	−0.16	15	−0.21	16	−0.23	16	−0.25	17
	Hebei	−0.16	14	−0.14	14	−0.15	14	−0.15	13	−0.15	13	−0.19	15	−0.14	13
	Shanghai	0.69	5	0.68	5	0.75	5	0.66	6	0.76	5	0.71	5	0.78	5
	Jiangsu	1.41	2	1.39	2	1.43	2	1.37	2	1.27	2	1.17	2	1.09	3
	Zhejiang	1.02	3	1.04	3	1.01	3	0.94	3	0.92	3	1.00	3	1.20	2
	Fujian	0.11	7	0.12	7	0.16	7	0.14	8	0.15	9	0.21	7	0.13	10
	Shandong	0.68	6	0.65	6	0.67	6	0.69	5	0.62	6	0.56	6	0.47	6
	Guangdong	2.10	1	2.10	1	2.07	1	2.11	1	2.22	1	2.31	1	2.32	1
	Hainan	−0.47	27	−0.54	28	−0.55	28	−0.56	28	−0.53	28	−0.53	28	−0.53	28
Central China	Shanxi	−0.38	23	−0.37	23	−0.36	21	−0.37	21	−0.40	23	−0.38	21	−0.38	21
	Anhui	−0.09	13	−0.06	12	−0.12	12	−0.10	12	−0.11	12	−0.10	13	−0.07	12
	Jiangxi	−0.27	17	−0.25	16	−0.22	16	−0.23	17	−0.24	17	−0.25	17	−0.23	16
	Henan	0.03	9	0.08	8	0.11	8	0.11	10	0.08	10	0.02	11	0.03	11
	Hubei	−0.03	12	−0.04	11	−0.06	11	−0.04	11	−0.02	11	0.12	10	0.19	8
	Hunan	0.03	9	0.07	10	0.11	8	0.19	7	0.18	7	0.16	9	0.14	9
Western China	Mongolia	−0.29	19	−0.34	21	−0.39	22	−0.39	22	−0.37	21	−0.41	23	−0.43	23
	Guangxi	−0.29	19	−0.28	19	−0.29	18	−0.30	19	−0.31	19	−0.33	20	−0.29	20
	Chongqing	−0.31	21	−0.31	20	−0.30	19	−0.31	20	−0.33	20	−0.26	18	−0.27	18
	Sichuan	0.10	8	0.08	8	0.03	10	0.12	9	0.17	8	0.21	7	0.21	7
	Guizhou	−0.43	25	−0.36	22	−0.42	25	−0.42	25	−0.42	24	−0.43	24	−0.42	22

Table 6. *Cont.*

Region		2013		2014		2015		2016		2017		2018		2019	
		Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Western China	Yunnan	−0.27	17	−0.27	17	−0.32	20	−0.29	18	−0.30	18	−0.29	19	−0.28	19
	Tibet	−0.60	30	−0.60	30	−0.61	31	−0.63	31	−0.63	31	−0.67	31	−0.65	31
	Shaanxi	−0.26	16	−0.27	17	−0.27	17	−0.16	15	−0.16	14	−0.14	14	−0.14	13
	Gansu	−0.47	27	−0.49	27	−0.47	27	−0.45	26	−0.47	26	−0.48	26	−0.49	27
	Qinghai	−0.62	31	−0.61	31	−0.60	30	−0.61	30	−0.61	29	−0.64	30	−0.62	30
	Ningxia	−0.58	29	−0.59	29	−0.59	29	−0.59	29	−0.61	29	−0.61	29	−0.61	29
	Xinjiang	−0.45	26	−0.44	26	−0.45	26	−0.46	27	−0.47	26	−0.50	27	−0.48	26
North-eastern China	Liaoning	0.02	11	−0.07	13	−0.13	13	−0.15	13	−0.16	14	−0.08	12	−0.22	15
	Jilin	−0.41	24	−0.42	25	−0.41	24	−0.41	24	−0.42	24	−0.43	24	−0.44	25
	Heilongjiang	−0.36	22	−0.38	24	−0.39	22	−0.39	22	−0.37	21	−0.40	22	−0.43	23

In China, there are great differences in the competitiveness level of the cultural industry in 31 provinces, which is basically in agreement with the conclusions of many studies on China's cultural industry competitiveness evaluation [45–47]. The top provinces in 2013–2019 are mostly located in eastern China, which indicates that economic development has laid the foundation for competitiveness in the cultural industry. The eastern region has considerable advantages in talent, capital, technology, and information and has a large market consumer group [48]. The cultural industry competitiveness of central and northeastern China's provinces is at a medium level and has great development potential. There are still quite a few problems in the development of the cultural industry in the central and northeastern regions, for example, an unreasonable input–output structure, weak cultural brand awareness, lack of regional development linkage, and lack of supporting competition and management mechanisms [49,50]. In recent years, the national policy has been inclined toward western China, and its economic strength has been greatly improved. However, compared with the eastern, central, and northeastern regions, the development potential of cultural industry in western China needs to be further developed. Hu and Ma [51] pointed out that cultivating characteristic culture, improving cultural industry infrastructure construction, and breaking ethnic and religious segregation are conducive to accelerating the development of cultural industry in the western region.

5.2. Analysis of the Impact of the Competitiveness Index of Cultural Industry on China's Economic Growth

5.2.1. Results of Panel Unit Roots Test

Table 7 reports the results of the panel unit roots test in the level variables. The null hypothesis of the Levin, Lin and Chu test and ADF tests are rejected at the 1% significance level for all variables. Therefore, all variables are stationary at the level. In addition, we also examine the correlation among the independent variables in the first analysis in order to multicollinearity problem. The result is reported in Table 8, and we observe that the independent variables are low correlated (less than 0.70). Hence, we could conclude that there is no multicollinearity in our model.

Table 7. Results of the unit-roots test (first analysis).

Variable	Method	
	Levin, Lin & Chu	ADF—Fisher Chi-Square
lnGDP	−99.8470 ***	95.3349 ***
lnCI	−23.8080 ***	129.591 ***
lnInv	−12.9577 ***	120.158 ***
lnEP	−13.3925 ***	74.4365 ***
lnRDE	−32.4257 ***	121.615 ***

Notes: H_0: Panels contain unit roots, *Ha:* Panels are stationary. *** denotes significance at 1% critical value.

Table 8. Results of the correlation (first analysis).

	lnCI	lnInv	lnEP	lnRDE
lnCI	1.0000			
lnInv	0.6628	1.0000		
lnEP	0.6993	0.6201	1.0000	
lnRDE	0.6489	0.4943	0.4472	1.0000

5.2.2. Model Comparison and Results

Table 9 shows the parameter estimates of the pooled regression, fixed effects model, and random effects model. In the current research, the F-test, BP-test, and Hausman test are used for selection between the pooled regression, fixed effects model, and random effects model. From Table 10, it can be seen that the fixed effects model is more suitable for this study.

Table 9. Estimates of the pooled regression, fixed effects model, and random effects model (first analysis).

	Pooled Regression	Fixed Effects	Random Effects
Constant	9.2499 *** (1.8809)	52.1326 ** (22.2890)	14.5776 *** (2.8251)
lnCI	0.9914 ** (0.4550)	8.1024 *** (2.2233)	1.2470 * (0.7095)
lnInv	−0.0029 (0.3851)	−2.7108 *** (0.5059)	−1.4232 *** (0.3900)
lnEP	−0.1141 (0.4154)	−2.3168 (3.1608)	0.9626 * (0.5006)
lnRDE	−1.2182 *** (0.3061)	1.2232 (1.0602)	−0.9593 ** (0.4643)
R-squared	0.0791	0.5649	0.0893
Adjusted R-squared	0.0617	0.4832	0.0721
Sum squared residuals	706.0317	333.5361	448.2363
Log-likelihood	−434.4039	−353.4138	–
Akaike info criterion	4.0685	3.5964	–

Notes: ***, **, * denote significance at 1%, 5%, 10% critical value, respectively. Standard errors are in parentheses. Time and country fixed effects are considered in this analysis.

Table 10. Specification Tests (first analysis).

Spec. Tests	Statistic	Tested	Selection
F-test	6.7753 ***	pooled regression/fixed effects	fixed effects
Breusch-Pagan	359.7893 ***	pooled regression/random effects	random effects
Hausman	36.1481 ***	random effects/fixed effects	fixed effects

Note: *** denotes significance at 1% critical value.

According to the fixed effects model in Table 9, the competitiveness index of the cultural industry (CI) contributed to economic growth significantly (p-value < 0.001). If the competitiveness index of the cultural industry (CI) increases by 1%, GDP will increase by 8.1024%, on average. When the cultural industry is more competitive, it will have a considerable impact on economic growth. However, it is found that the purchase of newly produced fixed capital (Inv) has a significant and negative impact on the Chinese economy. This implies that the purchase of newly produced fixed capital did not play an essential role in increasing growth levels in China during 2013–2019. It could have decreased growth. The possible reason for explaining this result is due to the low technology absorption capacity and the low level of human capital in China. This conclusion is corroborated by Curwin and Mahutga [52], who suggested that the penetration of FDI reduces economic growth in the short and long term in socialist countries. In recent years, the steady growth of China's economy is no longer driven mainly by investment but by the development of knowledge-intensive and high-tech industries to achieve sustainable economic growth. Zhang and Yao [53] discussed the reasons that fixed asset investment had not played an important role in explaining China's economic growth since the beginning of the 21st century.

In terms of the control variables, we find that the number of the labor force cannot help to increase GDP in China under the current situation as the demographic dividend gradually disappears. Chen [54] found that the workforce size has no significant effect on China's economic growth but suggested that the quality of the labor force is more important. Similarly, research and development is not found to have a significant influence on economic growth

5.3. Analysis of the Impact of Cultural Industry Factors on China's Economic Growth

In addition, to gain more information on the cultural industry 's impact on growth, 13 sub-competitiveness indexes of the cultural industry, presented in Table 1, are used to estimate their impacts on Chinese growth. This enables us to explore the key driver of China's economic growth.

5.3.1. Results of Panel Unit Roots Test (Second Analysis)

Again, the panel unit root tests of LLC and ADF and correlation tests are also used to examine the stationary and correlation among 13 sub-competitiveness indexes. The results of these tests are reported in Tables 11 and 12, respectively. The results show that all panel variables are stationary at the level, and there is weak correlation among the independent variables, as the correlations of all pairs are lower than 0.75.

Table 11. Test results for panel unit roots (second analysis).

Variable	**Method**		**Variable**	**Method**	
	Levin, Lin & Chu	**ADF—Fisher Chi-Square**		**Levin, Lin & Chu**	**ADF—Fisher Chi-Square**
lnX1	−54.3690 ***	93.8035 ***	lnX8	−608.241 ***	117.162 ***
lnX2	−13.1298 ***	100.978 ***	lnX9	−34.6636 ***	83.1386 **
lnX3	−36.5545 ***	98.4927 ***	lnX10	−108.700 ***	145.841 ***
lnX4	−30.8708 ***	128.742 ***	lnX11	−9.41097 ***	95.0712 ***
lnX5	−10.6520 ***	127.488 ***	lnX12	−26.3860 ***	133.158 ***
lnX6	−58.1632 ***	101.275 ***	lnX13	−13.7596 ***	100.708 ***
lnX7	−3.48069 ***	77.3883 *			

Notes: H_0: Panels contain unit roots, *Ha*: Panels are stationary. ***, **, * denote significance at 1%, 5%, 10% critical value, respectively.

5.3.2. Model Comparison and Results (Second Analysis)

The parameter estimates of the pooled regression, fixed effects model, and random effects model are shown in Table 13. The comparison method is the same as that of the previous panel regression. The results in Table 14 suggest that the fixed effects estimation is preferred and is used for the discussion. The robustness results of the fixed effects estimation is also confirmed in Table A1.

According to Table 13, the fixed effects model shows evidence that the estimated coefficients of Fixed Asset Investment in Culture (X_1), labor in Cultural Enterprises (X_2), Total Collections in Public Libraries (X_4), Proportion of Tertiary Industry in Gross Regional Product (X_5), Per Capita Consumption and Expenditure on Culture and Recreation of Nationwide Households (X_6), and Users of Cable Radios and TVs (X_8) are significant (p-value < 0.10).

Table 12. Results of the correlation (second analysis).

	$\ln X_1$	$\ln X_2$	$\ln X_3$	$\ln X_4$	$\ln X_5$	$\ln X_6$	$\ln X_7$	$\ln X_8$	$\ln X_9$	$\ln X_{10}$	$\ln X_{11}$	$\ln X_{12}$	$\ln X_{13}$
$\ln X_1$	1.000												
$\ln X_2$	0.684	1.000											
$\ln X_3$	0.657	0.613	1.000										
$\ln X_4$	0.577	0.705	0.678	1.000									
$\ln X_5$	0.665	0.617	0.659	0.597	1.000								
$\ln X_6$	0.707	0.624	0.578	0.659	0.558	1.000							
$\ln X_7$	0.553	0.718	0.688	0.484	0.727	0.485	1.000						
$\ln X_8$	0.665	0.591	0.556	0.647	0.507	0.578	0.565	1.000					
$\ln X_9$	−0.132	0.218	0.202	0.143	0.266	0.118	0.162	0.155					
$\ln X_{10}$	0.209	0.637	0.586	0.478	0.570	0.615	0.529	0.673	0.577	1.000			
$\ln X_{11}$	0.650	0.645	0.463	0.674	0.501	0.683	0.713	0.693	0.166	0.626	1.000		
$\ln X_{12}$	0.671	0.560	0.631	0.662	0.637	0.682	0.726	0.699	−0.077	0.467	0.693	1.000	
$\ln X_{13}$	0.460	0.786	0.670	0.627	0.639	0.739	0.558	0.745	0.472	0.694	0.566	0.623	1.000

Table 13. Results of the pooled regression, fixed effects model, and random effects model (second analysis).

	Pooled Regression	**Fixed Effects**	**Random Effects**
Constant	34.5857 *** (4.2046)	69.4778 *** (9.2848)	39.2223 *** (5.1680)
lnX1	−0.6355 *** (0.2022)	0.1633 *** (0.0452)	−0.4368 ** (0.1940)
lnX2	0.2817 (0.5378)	1.2162 * (0.7326)	1.8169 *** (0.5486)
lnX3	0.1448 (0.1512)	−0.1516 (0.2832)	0.0426 (0.2010)
lnX4	−1.0142 *** (0.3753)	−2.0475 ** (0.9835)	−0.9249 * (0.5214)
lnX5	−4.8332 *** (0.9052)	−6.9455 *** (1.4336)	−5.9944 *** (1.0606)
lnX6	−1.5476 *** (0.3657)	−1.8289 ** (0.7387)	−1.6780 *** (0.4801)
lnX7	0.5248 (0.5199)	−0.2798 (0.6546)	−0.3414 (0.5487)
lnX8	−1.0532 *** (0.3247)	−2.3706 *** (0.5443)	−1.3267 *** (0.3741)
lnX9	0.0358 (0.1471)	−0.0265 (0.1319)	−0.0317 (0.1213)
lnX10	0.1002 (0.1903)	0.0804 (0.2133)	0.0727 (0.1843)
lnX11	0.5227 (0.3291)	−0.3869 (0.4760)	−0.0558 (0.3665)
lnX12	0.0930 * (0.0526)	0.0426 (0.0429)	0.0902 * (0.0401)
lnX13	0.0028 (0.3367)	0.4323 (0.6071)	0.1449 (0.4421)

Table 13. *Cont.*

	Pooled Regression	Fixed Effects	Random Effects
R-squared	0.4966	0.7950	0.5556
Adjusted R-squared	0.4644	0.7441	0.5272
Sum squared residuals	385.9677	157.1525	210.6021
Log-likelihood	−370.3901	−272.8988	–
Akaike info criterion	3.5427	2.9207	–

Notes: ***, **, * denote significance at 1%, 5%, 10% critical value, respectively. Standard errors are in parentheses. Time and country fixed effects are considered in this analysis.

Table 14. Specification tests in the second-panel regression model (second analysis).

Spec. Test	Statistic	Tested	Selection
F-test	8.3963 ***	pooled regression/fixed effects	fixed effects
Breusch-Pagan	110.7982 ***	pooled regression/random effects	random effects
Hausman	41.8395 ***	random effects/fixed effects	fixed effects

Note: *** denotes significance at 1% critical value.

The results show that the labor of cultural enterprises is a driver of economic growth Indicating that an increase in investment and labor enhance growth in the long run. This should not be surprising. Research in growth theories, such as Solow growth [55] and endogenous growth theories [56], provides evidence that investment and labor are the most important long-term source of economic growth [57]. However, it seems that total cultural collections, tertiary industry, consumption and expenditure, and the number of cable radios and TVs users are not likely to boost Chinese economic growth.

According to the above results, the evolution of an industry cannot rely on only some factors, so improving industrial competitiveness and optimizing industrial structure is key to the development of China's cultural industry. Increasing fixed investment and labor in the cultural industry not only gives full play to the potential advantages of the cultural industry but also helps to promote China's economic growth.

Finally, when we consider other insignificant variables, we observe that Total Patent Applications Granted on Culture and Related Industries (X_{10}), Total Profit of Cultural Enterprises (X_{12}), and Expenditure for Culture, Sport, and Media of Regional Government Revenue (X_{13}) show weak evidence of positive impact on the Chinese economy. Despite their insignificant effect on growth, we may view them as a potential factor in the future.

6. Conclusions

The evaluation of the competitiveness of cultural industries and its impact on Chinese economic growth remains neglected in the literature. Although Fu, Song, and He [8] and Wu, Xu, and Chen [9] have attempted to evaluate cultural industry competitiveness in Tianjin and Guifeng, there is a certain subjectivity, one-sidedness, and superficiality in the selection of indicators for evaluating the competitiveness of the cultural industry. Additionally, their evaluation is limited at the provincial level. Moreover, there is little data to support the conclusion that the cultural industry's competitiveness positively affects economic growth. To fill this gap, this study selects the evaluation indicators of the cultural industry's competitiveness with a systematic, dynamic, and operable principle. The present study conducts a comprehensive evaluation of the competitiveness of cultural industries in 31 provinces in China using the period 2013–2019 and also adds another research value by investigating the influence of cultural industry competitiveness, as well as its relevant factors, on economic growth in China.

The following conclusions can be drawn from the present study based on the current empirical findings. Firstly, the main outcome of this research is additional evidence that suggests a new cultural industry's competitiveness index, which could be added to the cultural literature [58]. We find that provinces in eastern China, such as Guangdong, Jiangsu, Zhejiang, and Shanghai, are more competitive in the cultural industry, and 31 provinces have a large gap in the competitiveness level of the cultural industry. Secondly, the competitiveness of the cultural industry is found to be an important factor in China's economic growth, according to the fixed effects model. The result is consistent with the research of Ager and Brückner [58] and Bălan and Vasile [59], who revealed a positive impact of culture on the economic growth of the US and Romania, respectively. The second analysis of panel regression estimation shows that investment and labor in cultural industries are the key drivers of Chinese GDP growth. This implies that the investment and labor of the cultural industry are not only the key to enhancing its competitiveness but also play an influential role in economic growth. This result is in line with Solow growth [55] and endogenous growth theories [56].

However, the development of the cultural industry in China continues to have problems, such as insufficient capital investment, lack of professional talents, weak innovation ability, and imperfect management mechanisms. It is particularly urgent to accelerate industrial restructuring and upgrading. To transform the development mode of the cultural industry and cultivate its core competitiveness, an open, competitive, and orderly cultural market system needs to be established. It is necessary to give full play to the government's public service functions to promote the prosperity of the cultural market and improve the legalization of the management of the cultural market.

The recommendations for promoting the development of China's cultural industry are put forward from four aspects: investment and trade, technology, creativity, and talent. Firstly, enhancing the effectiveness and guidance of financial and cultural investment can attract overseas capital and other social capital into the cultural industry. China should also actively explore the international cultural market and participate in the competition to adapt to the changes in cultural consumption in the market economy. Secondly, information technology promotes the diversification of cultural product dissemination methods and the intellectualization of cultural management. To achieve the goal of the high-quality development of the cultural industry, China should improve technological innovation capabilities and expand the supply of cultural products and services. Thirdly, enhancing the innovation and competitiveness of cultural products can be possible by developing cultural and creative products with Chinese style, promoting the creative transformation of Chinese traditional culture, and thus functioning the cultural industry's social and economic benefits. Finally, talents are the leading force for the transformation of cultural resources into cultural productivity; that is, the construction of cultural industry is essentially the construction of knowledge and high-value-added human resources products. Therefore, China should recognize the importance and urgency of cultivating artistic and managerial talents in the cultural industry. Local governments and higher education sectors should formulate talent training layout plans for the cultural industry and actively connect industrial resources to integrate learning and research with further access to the level of production and applications.

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Appendix A

To confirm the robustness results of our study, we perform the joint test for normality on error, Modified Wald test for Heteroscedasticity, and Wooldridge Autocorrelation test. Our results are reported in Table A1 and we confirm that there are no problems of heteroscedasticity, autocorrelation, and non-normality error in our estimation results of fixed effects models in Tables 9 and 13. In addition, we show that country and time fixed effects has a lower AIC when compared to time fixed effects and country fixed effects.

Table A1. Robustness check of fixed effects models.

Robustness Check	First Analysis	Second Analysis
Fixed effects (time)	AIC = 3.6930	AIC = 3.1254
Fixed effects (country)	AIC = 3.8490	AIC = 3.0192
Joint test for Normality on error term	χ^2 = 2.9324	χ^2 = 1.6423
Modified Wald test for Heteroscedasticity	χ^2 = 3.0024	χ^2 = 3.3001
Wooldridge Autocorrelation test	F = 2.3849	F = 1.9384

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Article

Improving Energy Efficiency in China Based on Qualitative Comparative Analysis

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Abstract: Currently, in China, the influence of energy efficiency problems on economic and social development is increasingly prominent. The factors influencing energy efficiency and improving them have become the focus of academics. In this study, the effects of allocation on technical progress, industrial structure, energy consumption structure, and economic levels of energy efficiency are discussed based on a sample of 30 provinces in China using qualitative comparative analysis (QCA). The results show that three paths could simulate high energy efficiency. The first path is dominated by economic level and energy consumption structure, with the assistance of industrial structure. The second path is dominated by economic level and energy consumption structure, with the assistance of technical progress. The third path is dominated by technical progress and industrial structure, with the assistance of economic level. None of the proposed four factors were required for high energy efficiency. Path 1 and path 2 formed the second-order equivalent configuration. In most provinces, high energy efficiency is stimulated through the path dominated by technical progress and industrial structure, assisted by economic level.

Keywords: energy efficiency; industrial structure; energy consumption structure; fsQCA

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1. Introduction

Currently, the energy problem has attracted the wide attention of academics, media personnel, and the general public. The energy problem not only influences the national economy and strategic safety but is also related to the improvement of people's living standards and the ecological environment. It has become a highly concerning problem. According to the International Energy Agency (IEA), in 2009, China surpassed the US and became the largest energy consumer in the world. In recent years, energy demands have increased significantly owing to accelerating industrialisation and urbanisation. However, the energy supply structure in China is relatively isolated. The trade-off between supply and demand brings China into a dilemma of serious energy shortage. There are two major approaches to solving the energy shortage. One is to seek new renewable energy sources and alternative energy sources on the energy supply end, while the other is to take measures to improve energy utilisation. The development and use of technologies of new and alternative energies are not yet perfect and they cannot meet the needs of production and daily life. Therefore, increasing energy utilisation is the most effective method to solve energy shortages in the short run. Hu et al. (2005) [1] estimated the energy conservation efficiency of 17 countries in the Asia-Pacific Economic Cooperation (APEC) economic entity from 1991 to 2000. The results show that the energy-saving rate in China is the highest, but approximately 50% of the energy sources are wasted due to low energy efficiency [1]. Improving energy utilisation is not only conducive to solving energy shortages but also making considerable contributions to the reduction of environmental pollution. Therefore, it is imperative to solve the issue for China's strategic development by exploring effective paths to improve energy efficiency continuously.

Existing research has achieved many results from the two perspectives of energy efficiency measurement and influencing factors and has also made important breakthroughs in theory. However, since energy efficiency is a complex system affected by many factors, it will be of essential research value to examine the formation paths of high energy efficiency in each region from an overall perspective. QCA adopts a holistic perspective, pays attention to the complexity of antecedents, and combines the advantages of qualitative and quantitative methods in the research paradigm. It has become an important tool for the study of complex causal systems. Using the QCA method, we can effectively explore the synergistic linkage of multiple antecedent conditions, to better explore the relationship between energy efficiency and its influencing factors. Energy efficiency may be affected by a combination of factors, such as economic development level, technological progress, industrial structure, and energy consumption structure. Therefore, this study started from the perspective of configuration, and on the basis of acknowledging the complexity of causality, adopted the fsQCA method to construct a model of influencing factors of energy efficiency by taking 30 provinces, municipalities and autonomous regions in China as the research objects. This research explored new horizons for energy efficiency research, and also provided theoretical reference for further improving energy efficiency in various regions.

2. Literature Review and Model Construction

For studies on energy efficiency, academics mainly focus on two aspects, namely the measurement of energy and factors influencing energy efficiency.

2.1. Studies on Energy Efficiency and Measurement

Energy efficiency refers to the ability of the highest economic output under fixed energy consumption or the ability to reach the lowest energy consumption under the fixed economic output level. Didier and Cécile (1997) [2] proposed two interpretations of energy efficiency: (1) economically, energy efficiency is the ability to acquire more outputs with a lower energy input; (2) energy efficiency is to decrease energy consumption by technical progress and changing lifestyle [2]. Chinese scholars proposed some definitions of energy efficiency. Wei and Liao (2010) defined energy efficiency as contributions of energy consumption to maintain and facilitate sustainable economic, social, and environmental development [3]. Wang and Wu (2015) pointed out that the connotation of energy efficiency is to 'acquire the maximum economic output with the lowest energy input while minimizing the negative environmental externality' [4].

Studies on the measurement of energy efficiency started in the 1950s. Farrell (1957) [5] believed that comprehensive technical efficiency and allocation efficiency are two major aspects of energy efficiency. Comprehensive technical efficiency is mainly used to measure the highest output achieved under the existing input level during production. Allocation efficiency measures the minimum cost for a given output with considerations of price factors of energy input [5]. Follow-up studies on the measurement of energy efficiency are carried out based on this concept. Phylipsen et al. (1997) [6] expanded their study on the energy efficiency problem based on the energy efficiency index pyramid, which was established by the IEA in 1997. They also pointed out that traditional energy efficiency only focused on input and output, which did not take other elements into account, thus resulting in poor reasonability [6]. In recent years, Chinese scholars proposed some suggestions in studies on the measurement of energy efficiency. Wang (2001) [7] viewed energy demands for GDP increase per unit as the comprehensive energy efficiency index of a country and divided the energy efficiency of a department into economic and physical indexes. Specifically, the economic index is expressed by energy consumption per unit output and the physical index is generally expressed by thermal efficiency [7]. Limited by the low marketisation degree in China, it is relatively challenging to deduce the shadow price of energy elements. Hence, most researchers focus on the comprehensive technical efficiency of energy. For example, Wei and Liao (2010) [3] analysed seven types of energy efficiency measurement indexes thoroughly and discussed the theoretical basis, hypotheses, applicability, strengths and weakness, and relations of indexes. They further elaborated on the understanding and wrong applications of energy efficiency indexes [3]. Moreover, data envelopment analysis (DEA) has become a common method for researchers to calculate the comprehensive technical efficiency of energy sources. DEA calculates comprehensive technical efficiency of energy by constructing the production leading surface, during which production input and output elements have to be set. Wei and Shen (2008) [8], Wu and Wu (2009) [9], and Du (2015) [10] used material capital, labour, force and energy as inputs. Shi and Shen (2008) [11] used the gross domestic production (GDP) of energy using regions as the single expected output.

2.2. Factors Influencing Energy Efficiency

In recent years, China has achieved rapid economic and social development at the cost of increasing and continuous energy consumption. However, the total global energy is decreasing continuously, which proposes higher requirements for energy efficiency in China. At present, China has a lower energy utilisation level compared with some developed countries, which restricts China's sustainable economic and social development to some extent. Hence, recognising factors influencing energy efficiency, decreasing energy waste, achieving higher output with limited energy sources, and improving energy efficiency continuously are of critical importance to the economic and social development of China.

Industrial restructuring optimised energy allocation, improved energy efficiency, and decreased energy consumption in China. This has been widely accepted by most scholars [12]. Lu (1999) [13] believed that industrial structural changes promote improvements in energy efficiency and are very important to the development of the energy industry. Increasing the proportion of the tertiary industry and optimizing the energy structure of the secondary industry can significantly improve regional energy efficiency [14]. Shi and Zhang (2003) [15] pointed out that different industries lead to different energy species needed for production, thus bringing different degrees and directions of influences of industrial structural changes on energy efficiency. However, industrial structural changes can improve energy efficiency. Based on panel data of 285 prefecture-level or higher-level cities in China from 2003 to 2013, Yu (2017) [16] discussed the effects of industrial structural changes on the improvement of energy efficiency by using the Dubin model (SDM). The results show that improving industrial structural adjustment quality can facilitate significant improvements in energy efficiency [16].

With continuous scientific developments, technical progress becomes one of the important factors that improve energy efficiency.

Ye and Sun (2002) [17] found that technical progress and scientific and technological innovation are major factors that improve energy efficiency. Using advanced technologies can promote the improvement of energy efficiency, updating of industrial structure, and optimisation of energy allocation. Similarly, based on China's provincial panel data, Feng (2015) [18] constructed an empirical model to analyse the dynamic effect of energy efficiency and influencing factors from the endogenous perspective. He concluded that technical progress has a significant and positive impact on energy efficiency [18]. Li (2022) [19] empirically tested the promotion effect of technological progress on energy efficiency by using the panel data of 271 prefecture-level cities in China from 2014 to 2019. The study found that, in addition to the direct impact, technological progress also has a positive impact on regional energy efficiency indirectly through economic growth and industrial structure upgrading.

The effects of the energy consumption structure on energy efficiency are also relatively obvious. The distribution of energy structure and consumption ratio can directly and positively influence energy efficiency. Hang and Tu (2006) [20] pointed out that reducing the ratio of coal consumption in primary energy sources significantly improved energy efficiency. Guo et al. (2008) [21] pointed out that China's energy efficiency is closely related to changes in primary energy consumption structure and the improvement of energy efficiency is significantly influenced by energy consumption's structural optimisation and updating. Brodny J (2022) [22] used the Gini coefficient and Lorenz curves to analyse the energy consumption structure and energy efficiency of the industrial sector in the European Union with data from 1995 to 2019. The analysis results proved that the energy consumption structure can significantly affect energy efficiency.

Economic level is also an important factor that influences energy efficiency. Wu and Wang (2019) [23] carried out quantitative analysis of the relationship between China's energy consumption, energy efficiency, and business cycle from the perspective of periodic fluctuation. Considering the industrial level, a stable economy is conducive to improvements in energy efficiency [23]. When studying factors influencing energy intensity changes in China, Shi (2002) [24] proposed that the opening level and marketisation reform have significant effects on improving energy efficiency. Moreover, Shi (2002) [24] pointed out that driven by market reform, enterprises will pay more attention to improvements in technological innovation and production efficiency due to market mechanisms, thus improving energy production and utilisation. With the continuous growth of the marketisation level, energy may also flow to enterprises with higher development efficiency as an important production factor, thus improving the overall allocation efficiency of energy sources [24].

2.3. Research Model

Complicated factors influence regional energy efficiency and no widely accepted comprehensive analysis system has been reached. By studying factors influencing energy efficiency in China from 1979 to 2006, Chen and Xu (2008) [25] found that it is beneficial to improve the energy efficiency of China, especially technical progress if the state increases scientific research input, accelerates human capital formation, and uses foreign direct investment positively. Zhang (2011) [26] analysed factors influencing energy efficiency, such as economic structure, technical progress, energy investment level, and energy marketisation, by using the structural equation model (SEM). They concluded that the above factors have direct or indirect influences on the improvement of energy efficiency [26]. Based on the current status of regional energy efficiency in China, Liang et al. (2020) [27] believe that technical progress, industrial structure, energy structure, environmental regulation, energy prices, and foreign exchange are major factors influencing energy efficiency in China. Jiang and Ji (2011) [28] carried out an empirical study on energy efficiency by using the ridge regression method and pointed out that technical progress, industrial structure, energy consumption structure, and comprehensive economic level are major factors influencing regional energy efficiency. All four influencing factors cover various aspects of energy efficiency, and this has been approved by many scholars [29].

Based on relevant theoretical analyses and analyses on variable sets of factors influencing regional energy efficiency [28], influences of technical progress, industrial structure, energy consumption structure, and comprehensive economic level on energy efficiency were investigated with considerations to the coverage of the above factors. It aims to identify the most effective pathway to improve regional energy efficiency [28]. The model constructed is shown in Figure 1.

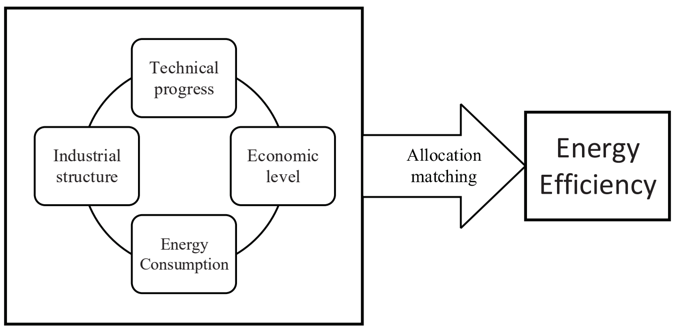

Figure 1. Influencing factors' model of energy efficiency.

3. Method

The social science field is currently plagued by complicated social phenomena which often involve many influencing factors. The formation of complicated events is a characteristic of multiple concurrence combinations. Therefore, the traditional quantitative analysis based on line causality cannot meet the needs of the current complicated studies. Therefore, the qualitative comparative analysis (QCA) was innovatively introduced as a major research method. As an emerging research paradigm, QCA can analyse multi-element, concurrence, and cause–effect asymmetric complicated social phenomena. It has been extensively applied to fields of management, sociology, information science, and disease transmission to name a few.

QCA was proposed by Charles C. Ragin at the end of the 19th century. QCA is based on the set theory and Boolean algebra. It surpasses the traditional case study method and realises trans-case analysis. It tries to investigate the causes of an event, the interaction of internal generation factors, and possible relational combinations systematically, aiming to explore internal correlations of antecedent conditions as well as causality between antecedent conditions and their combinations and consequences. Through empirical data and continuous theoretical dialogues, people's understanding of complicated causalities of events is deepened continuously [30].

In this study, QCA was chosen owing to the following reasons: (1) QCA applies to middle- and small-sized sample data analysis, and it requires a low sample size. In this study, 30 provinces, municipalities, and autonomous regions in 2020 in China were chosen as research samples and the sample size conforms to the requirements of the method. (2) Many factors influence the improvement of regional energy efficiency, and the realisation process is complicated. The QCA can determine the factor combination and core conditions of high regional energy efficiency by comparing the factor combination set relations. It can provide references for regions with different development characteristics to improve energy efficiency and thereby promote improvements in China's energy efficiency.

At present, QCA is mainly divided into csQCA (clear-set quantitative comparative analysis) and fsQCA (fuzzy-set quantitative comparative analysis). csQCA adopts the dichotomous variable method and divides variables according to 0|1. If a variable exists, it values 1; otherwise, it values 0. Nevertheless, many variables cannot be clearly determined whether they exist or not in the complicated reality. For instance, the technical progress of some provinces in this study is between existence and absence. This problem is solved by fsQCA. fsQCA calibrates the original data, which transfer to the 0~1 fuzzy membership fraction and transform the variable into a set. This solves the defect of csQCA in the mechanical division of variables. Therefore, fsQCA was chosen for data analysis.

The process of the fsQCA method consists of five parts: case selection, variable calibration, necessary condition analysis, configuration analysis and robustness test, as shown in Figure 2.

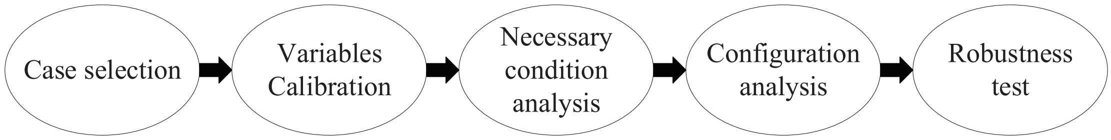

Figure 2. fsQCA method flow chart.

First, the QCA method is suitable for both large case samples and small case samples. Different from the requirements of traditional statistics on the number of cases, the QCA method pays more attention to the selection of cases. "Sufficient homogeneity of the case population and maximum heterogeneity within the case population" are the principles for selecting cases by the QCA method. Second, variable calibration is usually performed before analysis, converting the raw data into a fuzzy membership score between 0 and 1. Again, necessary condition analysis must be carried out. Necessary conditions are an important part of causality, and identifying necessary conditions plays an important role in analysing the causal relationship between variables. Finally, configuration analysis is performed. Through the configuration results, different paths to stimulate regional energy efficiency are obtained. Then, through a deeper qualitative analysis of the path, specific suggestions for improving energy efficiency in each region are summarized. Of course, robustness test should be performed before final path conclusions are determined.

4. Data and Variable Measurement

4.1. Data and Sample

Based on the availability of data, all sample data used in the analysis come from the Statistical Yearbook and China Energy Statistical Yearbook of 30 provinces (municipalities and autonomous regions) in 2020. Due to data missing from Tibet, it was excluded from the research samples.

4.2. Measurement and Calibration of Variables

4.2.1. Measurement of Variables

- Energy Efficiency

Studies on the measurement of energy efficiency are very mature. There are diversified measurement indexes. Among them, common and relative authoritative measuring indexes include energy consumption per unit GDP, energy consumption per unit added value, energy consumption per unit product, and terminal energy utilisation. With reference to the measurement method of energy efficiency proposed by [28], the energy efficiency of each sample province was calculated by using the following formula:

Energy efficiency = GDP (CNY 100 million)/energy consumption (10,000 tons of standard coal) (1)

- Technical Progress

Several methods are used to measure technical progress. As a type of intangible capital, technology is very difficult to be calculated and measured intuitively. For the convenience of this study, technical progress (development level) was expressed by the R&D expenditure of administrative regions in 2020 according to [31].

- Industrial Structure

As there are several measurement indexes of industrial structure, and the secondary and tertiary industries in China account for a high proportion of energy consumption, most scholars measured industrial structure by the proportion of the secondary and tertiary industries in GDP. Based on the above analysis, the proportion of secondary and tertiary industries was used to measure the industrial structures of the samples. With reference to [32], the industrial structural updating level of provinces was interpreted by introducing the industrial structural layer coefficient (upIns). The estimation formula is:

$$\mathrm{upIns} = \sum_{i=2}^{3} \mathrm{ci} \times \mathrm{i} \quad (2)$$

where upIns is the updating level of industrial structure and ci is the proportion of the ith industry. Next, 2 represents the secondary industry and 3 represents the tertiary industry.

- Energy Consumption Structure

In the energy consumption structure, a higher proportion of relatively clean energy is more beneficial to the updating of the energy consumption structure. Moreover, the increasing proportion of natural gas consumption has become an important means to promote energy consumption reform. Therefore, according to Xu and Wang(2018) [33], the proportion of natural gas consumption in total energy consumption was used to measure energy consumption structure.

- Economic Level

To measure regional economic level, Cao and Fan's (2016) opinion that 'the higher per capita GDP indicates the higher degree of economic development' was referred to. The per capita GDP of each sample region was chosen as the measuring index of regional economic level [34].

4.2.2. Calibration of Variables

The process where fsQCA transforms variables into a set is called the calibration of variables. Before calibration, the complete affiliated point, intersection point, and complete non-affiliated point have to be determined. According to Du and Jia (2017) [30], these three anchoring points were set as the maximum, mean, and minimum of variable data, respectively. The calibrated anchoring points in this study are listed in Table 1.

Table 1. Calibrated anchoring points of variables.

Set	Fuzzy-Set Calibration		
	Complete Affiliated Point	**Intersection Point**	**Complete Non-Affiliated Point**
Energy efficiency	3.02	1.91	1.11
Technical progress	979.28	525.86	161.23
Industrial structure	2.83	2.36	2.04
Energy consumption structure	11.62	5.9	4.05
Economic level	7.72	5.85	5.11

5. Fuzzy-Set Analysis

5.1. Necessary Analysis

A necessary condition can be viewed as a super-set of the results. It should be noted that if the necessary condition is included in the fsQCA analysis, it might be included in the logic residual term and thereby simplified. Hence, it is essential to analyse the necessary conditions before fsQCA analysis [35]. The analysis results of necessary conditions in this study are listed in Table 2.

Table 2. Results of analysis of essential conditions.

Configuration	Consistency	Coverage
technical progress	0.79	0.82
~technical progress	0.31	0.31
industrial structure	0.69	0.71
~industrial structure	0.40	0.41
energy consumption structure	0.66	0.70
~energy consumption structure	0.44	0.45
economic level	0.75	0.77
~economic level	0.34	0.35

The consistency of various condition variables is lower than 0.9, indicating that the condition variables are not necessary conditions to produce high energy efficiency.

5.2. fsQCA Analysis

fsQCA provides three types of solutions, namely parsimonious solution, intermediate solution, and complex solution [36]. Generally, the intermediate solution is superior to the other two solutions as it uses theoretical and practical logic residual terms and it does not simplify necessary conditions. Moreover, the central and contributing conditions of paths can be gained by comparing the intermediate and simplified solutions; the conditions that occur in the intermediate solution are only contributing conditions, while the conditions that occur in the intermediate solution and parsimonious solution together are centre conditions [36]. In this study, 30 provincial sample data were analysed by using fsQCA3.0. According to Du and Jia (2017) [30], the number for frequency was chosen as 1 and the consistency was higher than 0.8. Combining with PRI, consistency was higher than 0.75.

Based on the calculations, three paths stimulate high energy efficiency. It can be observed from Table 3 that the consistency values of the three paths are 0.97, 0.97, and 0.88, showing relatively high consistency [37].

Table 3. Paths of high energy efficiency.

Configuration	High Energy Efficiency Solution		
	L1	**L2**	**L3**
Technical progress		●	●
Industrial structure	●		●
Energy consumption structure	●	●	
Economic level	●	●	●
Consistency	0.97	0.97	0.88
Raw coverage	0.52	0.51	0.64
Unique coverage	0.04	0.16	0.09
Overall solution coverage		0.70	
Overall solution consistency		0.88	

Note: Relevant signs in the table are introduced as follows: with reference to expression modes of [37], ● represents the occurrence of condition variables [38]. Specifically, the big circle indicates core conditions, and the small circle indicates contributing conditions. The blank means that the condition variable is not important to the occurrence of results (either appearance or absence is acceptable).

This reflects that these three paths are sufficient conditions for high energy efficiency [37]. The overall coverage of the three paths is 0.70, indicating that these three paths explain 70% of causes of high energy efficiency and they have relatively strong explanation power. In the following text, each path will be independently analysed.

(1) Path dominated by economic level and energy consumption structure with the assistance of industrial structure

Path 1 indicates that high energy efficiency can be stimulated under any technological development level by optimising energy consumption structure and improving regional economic level with the assistance of industrial structural updating. At present, economic development in China is driven by energy consumption. Energy consumption is one of the major impetuses to economic growth. Moreover, economic level has a great influence on the energy consumption structure and the degree of influence tends to be reasonably continuous. With economic development, social demands for clean energy sources are increasing continuously. The energy consumption structure is optimised accordingly. Moreover, the industrial structure is closely related to the energy consumption structure. Due to the requirements of energy-saving and consumption reduction, the industrial structure is adjusted and optimised positively, and the tertiary industry is developed vigorously. All of these are conducive to the production of high energy efficiency.

Fan et al.(2012) [38] pointed out that improving the regional economic level was beneficial to shifting from resource-intensive industries to technical-intensive industries. The proportion of added value industry is increasing, while industrial structural updating drives optimisation of energy consumption structure. As a result, regional GDP is increased without increasing energy consumption, thus improving energy efficiency [38]. Li and Huo (2010) [39] pointed out that the influences of the economy on the energy consumption structure are very obvious in the short and long run. They emphasised trying to decrease the proportion of primary energy sources (coal), increase the proportion of clean energy consumption, and support the development and use of new energies under the premise of energy supply and safety. Meanwhile, accelerating optimisation, adjusting the industrial structure, and changing the economic growth model to an intensive type can increase energy utilisation better [39].

Under such a path, the major samples include Beijing City, Jiangsu Province, Shanghai City, Chongqing City, Guangdong Province, Zhejiang Province, and Hubei Province. All of these areas have high economic levels and the energy consumption structures in these regions have been optimising continuously in recent years. The proportion of coal in primary energy consumption is replaced by clean energy sources, such as natural gas. Furthermore, continuous optimisation and updating of the industrial structure are conducive to the increasing proportion of the tertiary industry of energy efficiency. Hence, these regions rank high among 30 samples in terms of energy efficiency.

Considering Jiangsu Province as an example, according to statistics, the energy consumption of Jiangsu Province in 2020 reached 326.7249 million tons of standard coals, which makes it top few in China. Stimulated by the numerous energy sources, in 2020, the economic strength of Jiangsu Province leapt high. The GDP of Jiangsu Province crossed over three 1000 billion-level steps and reached CNY 10,270 billion (equivalent to USD 14,390 billion) and the per capita GDP reached CNY 125,000 (equivalent to USD 17,524.9212), ranking top among all the samples. In 2020, Jiangsu Province accelerated industrial structural adjustment and the proportions of the added value of three industries were adjusted to 4.4:43.1:52.2. On one hand, Jiangsu Province formulated new heavy industrial development strategies which conform to future competition direction. It promoted transformation, upgrading, and high-quality development of steel, chemical, and coal power industries along the Yangtze River, while decreasing heavy industrial output and backward production capacity. These strategies were promoted together with industrial structure adjustment and layout optimisation. On the other hand, the Jiangsu provincial government introduced the *Opinions on Promoting Green Industrial Development* to implement the green development philosophy firmly, accelerate new–old kinetic energy transformation, and form coupling concurrence of the industrial chain. Jiangsu Province has preliminarily established the green low-carbon circulation system of high resource and energy utilisation and perfected the institutional mechanism of green industrial development gradually. Additionally, the focus is on the development of new energy industries and a group of new energies that lead the green industrial development. Jiangsu ranked the top in China in terms of new energy installation scale, such as offshore wind power and distributed photovoltaic devices. As a result, energy guarantees, such as power and natural gas, were further enhanced. The proportion of coal consumption decreased, while the proportion of other clean energy utilisation, such natural gas, increased significantly. According to data from the relevant statistical department, the energy consumption structure was continuously optimised due to rapid economic development. Driven by industrial structural transformation and updating, the energy consumption per unit GDP of Jiangsu Province decreased by 3.1% in 2020. The cumulative reduction during the '13th Five-year Plan' amounted to 20.6%. Hence, Jiangsu Province ranked first in China in terms of energy efficiency and submitted a qualified answer sheet for green development.

(2) Path dominated by economic level and energy consumption structure with the assistance of technical progress

Path 2 indicates that high energy efficiency can be stimulated under any regional industrial structure as long as there is a relatively high economic level and a relatively good energy consumption structure in the region, together driven by technical progress. The relatively high economic level lays a solid foundation for technological development. Improving economy and technologies facilitate optimisation and adjustment of the regional industrial structure together. Under the collaborative effect of economic level, technical progress, and industrial structure, relatively high energy efficiency is triggered. Qin et al. (2015) [40] pointed out that whether technical progress can improve energy efficiency by improving energy consumption structure is determined by the local economic level. Only when the economic level reaches a certain threshold can the region attract sufficient talents, build relatively perfect infrastructures, and purchase advanced equipment. Under such a scenario, the energy efficiency can be improved by optimising the energy consumption structure [40]. Zhou and Kong (2018) [41] pointed out that with the increasing national economic level, wealth accumulation, and high and new technological development, some new energy sources are developed and used gradually, thus making the energy consumption structure more balanced and optimised. The proportion of high-efficiency cleaning energy is increasing continuously, thus increasing energy efficiency [41].

The sample cities under this path mainly include Beijing City, Jiangsu Province, Shanghai City, Guangdong Province, Zhejiang Province, Shaanxi Province, and Hubei Province. These regions rank the highest in China in terms of economic level, while the proportion of clean energy consumption in these regions is higher than the national average. In recent years, they have optimised the energy consumption structure continuously and are thereby ranked high in terms of energy efficiency due to technical progress.

Considering Zhejiang Province as an example, in 2020, Zhejiang completed the '13th Five-year Plan' perfectly. It achieved decisive achievements to build a moderately and comprehensively prosperous society at a high level. The economic aggregates of Zhejiang Province amounted to 6000 billion and the GDP increased by 3.6% to CNY 6461.3 billion (equivalent to USD 950.74 billion) compared to that of the previous year. The annual average growth reached 6.5%. Zhejiang ranked first in terms of both economic aggregates and economic growth rates. The considerable economic strength lays solid foundations for the technological development of Zhejiang Province. Zhejiang Province has been enlisted as an innovative province and it maintained a stable position in the first gradient of innovation strength. In 2020, the R&D expenditure of Zhejiang Province reached CNY 185.99 billion (equivalent to USD 26.07 billion) and it was ranked fourth in China. The proportion of GDP increased from 2.3% in 2019 to 2.8%, a new historical high. The quantity of high-tech enterprises increased quickly, and the contribution rate of technological progress was relatively high. In 2020, Zhejiang Province won the annual State Science and Technology Award for 38 technical achievements and built a region-wide innovation system with global influence and national first-class and local characteristics. Technological innovation significantly supported high-quality development. Concerning the energy utilisation structure, Zhejiang Province is endeavouring to develop clean energy sources, promote new construction and reconstruction of natural gas distributed heat-power cogeneration, promote the construction of pilot projects positively, and increase the consumption of natural gas. Furthermore, Zhejiang Province continued to support the development and use of wind photoelectricity, develop offshore wind power generation greatly, and promote the construction of ground photovoltaic power stations to accelerate the approval and construction of nuclear power projects in the province. Under the collaborative efforts of multiple parties, clean energy in Zhejiang Province has been consumed completely and a series of innovative practices that facilitate 'carbon emission peak' have been carried out continuously. As clean energy replaces traditional coal, Zhejiang optimised and updated the energy consumption structure continuously. During the '13th Five-year Plan', Zhejiang supported 6.5% of GDP growth at the energy consumption growth rate of 2.5%, and it realised green, high-efficiency, and sustainable development. In 2020, Zhejiang Province ranked high in terms of energy efficiency due to the relatively high economic level, relatively good energy consumption structure, and technical innovation.

It is important to note that path 1 and path 2 form the second-order equivalent combination. In these two paths, economic level and energy consumption structure are viewed as the centre conditions, while technical progress is a contribution condition. This indicates that to stimulate high energy efficiency through these two paths, the key attention shall be paid to improving the economic level and energy consumption structure.

(3) Path dominated by technical progress and industrial structure with the assistance of economic level

Path 3 indicates that high energy efficiency can be achieved under any energy consumption structure as long as it can improve the economic level and technical progress and optimise the industrial structure. Improving the technical level can facilitate updating of regional industrial structure, which can further promote regional economic development. In this path, high technical progress and high industrial structure are viewed as centre conditions, indicating that priority shall be paid to the improvement of technical progress and industrial structural optimisation to improve energy efficiency through path 3. Wu et al. (2019) [42] believed that it can facilitate reform on the supply side of industrial structure effectively, encourage clean energy development, and continue to promote optimisation and updating of the industrial structure by facilitating inter-regional technological communication and improving technical level. Developing the industrial structural scale effect is conducive to improving the allocation efficiency of economic resources and thereby improving regional energy efficiency [42]. Zhou (2017) [43] carried out a Pearson test on the relationship between regional energy efficiency levels and influencing factors. The results show that regions can effectively improve energy efficiency by facilitating technical progress, optimising industrial structure, and improving the economic level [43].

The samples under this path include Beijing City, Shanghai City, Zhejiang Province, Guangdong Province, Jiangsu Province, Fujian Province, Anhui province, Hubei Province, and Hunan Province. These regions have relatively high economic levels, high technical development expenditures, and relatively reasonable industrial structural configurations. They are regions with good economic development.

Considering Guangdong Province as an example, from the perspective of technological innovation, Guangdong Province promoted innovation-driven development strategies greatly, deepened structural reform at the supply end, and accelerated the transformation and updating of the real economy in 2020. The total R&D expenditure of Guangdong Province in 2020 reached CNY 320 billion (equivalent to USD 44.86 billion), which accounted for 2.9% of regional GDP. Guangdong Province ranked first in terms of regional innovative comprehensive ability, the number of valid invention patents, and the number of PCT national patent applications. Technological innovation excited the continuous updating of industrial structure in Guangdong Province. According to statistics, the proportions of primary, secondary, and tertiary industries in Guangdong Province in 2020 were 4.3%, 39.2%, and 56.5%, respectively. The proportions of value-added of the manufacturing industry and high-tech manufacturing industry were increasing continuously and accounted for 56.1% and 31.1%, respectively. Industrial cooperation and competitiveness enhanced continuously. This indicates that the industrial structure of Guangdong Province was optimising and updating continuously. Concerning economic development, Guangdong is a big economic province in China, and it takes the leading role in China given several economic indexes, possessing obvious economic strengths. In 2020, Guangdong Province implemented the macro-control policy of the central government and the '1 + 1 + 9' work deployment thoroughly and promoted continuous steady healthy economic development throughout the province, bringing the comprehensive economic strength to a big step and increasing the quality benefits significantly. In 2020, the GDP of Guangdong Province exceeded CNY 11,000 billion (equivalent to USD 1542.1 billion). The annual growth rate of GDP was 6% during the '13th Five-year Plan'. Guangdong Province ranked first for 32 successive years in terms of economic aggregates. Further, the per capita GDP in Guangdong Province reached CNY 94,000 (equivalent to USD 13,175.04), which ranked first in China. Under the collaborative effect of technical progress, industrial structural updating, and economic level, Guangdong Province ranked first in terms of energy efficiency.

5.3. Robustness Test

The robustness of the examination and analysis results is an important step in QCA studies. According to Zhang and Du (2019) [36], a robustness test was carried out by adjusting the consistency threshold. With reference to the method of Ordanini et al. (2014) [44], the consistency threshold was increased by 0.05. In other words, the consistency threshold was 0.85 instead of 0.8 for secondary analysis. The analysis results are shown in Table 4.

Under this circumstance, the adjustment of parameters did not cause substantial changes in combination modes, consistency, and coverage, indicating that the analysis results are more robust [44].

Table 4. Robustness test.

Configurations	High Energy Efficiency	
	L1	**L2**
Technical progress		●
Industrial structure	●	
Energy consumption structure	●	●
Economic level	●	●
Consistency	0.97	0.97
Raw coverage	0.52	0.51
Unique coverage	0.04	0.03
Overall solution coverage	0.54	
Overall solution consistency	0.96	

Note: Relevant signs in the table are introduced as follows: ● represents the occurrence of condition variables. Specifically, the big circle indicates core conditions, and the small circle indicates contribution conditions. The blank means that the condition variable is not important to the occurrence of results (either appearance or absence is acceptable).

6. Conclusions, Discussion, and Limitations

6.1. Conclusions

As an important index that influences economic and social development, energy efficiency is widely considered by countries globally when they formulate energy policies and make economic decisions. As the largest developing country, China has relatively lower energy efficiency than developed countries. Moreover, the extensive energy consumption mode still exists, which brings pressure on environmental protection and restricts economic development. Hence, it is urgent to improve energy efficiency to develop the economy.

Based on the idea of configuration, the relations of energy efficiency with technical progress, industrial structure, energy consumption structure, and economic level under the combination and complicated causality mechanism were investigated by QCA. The following conclusions could be drawn:

(1) According to the analysis of the essential conditions, none of the four dependent variables is a necessary condition of the outcome variable (high energy efficiency). In other words, technical progress, industrial structure, energy consumption structure, and economic level are not bottlenecks of energy efficiency. Which means, no matter what situation the city or region is in, it can stimulate high energy efficiency through the rational allocation of the four conditions of technological progress, industrial structure, energy consumption structure and economic level.

(2) According to combination analysis, three paths are found to improve energy efficiency. The first path is dominated by economic level and energy consumption structure with the assistance of industrial structure. The second path is dominated by economic level and energy consumption structure with the assistance of technical progress. The third path is dominated by technical progress and industrial structure with the assistance of the economic level.

(3) Path 1 and path 2 form the second-order equivalent combination, indicating that technical progress and industrial structure are replaceable when energy consumption structure and economic level are relatively good.

(4) It can be understood from the coverage of the paths that L3 shows the highest coverage, indicating that it can stimulate high energy efficiency the highest.

6.2. Discussion and Implications

6.2.1. Theoretical Contributions

The theoretical contributions of this study are as follows:

(1) The causality relations based on essentiality are analysed through essential conditions. It was found that technical progress, industrial structure, energy consumption structure, and economic level are not essential conditions to stimulate high energy efficiency. This means although each province has a different degree of a single factor, this does not hinder the stimulation of high energy efficiency through different combination modes.
(2) This study organised and selected four key variables that influence energy efficiency and the three paths that stimulate high energy efficiency are recognised by QCA. This proves that these four key variables influence and mutually depend on energy efficiency rather than presenting a simple linear relationship. This result expanded studies on energy efficiency.

6.2.2. Management Enlightenment

This study gained the following enlightenment in management:

(1) Most regions achieve high energy efficiency mainly through technical progress and industrial structure, assisted by economic level. Therefore, attention should be paid to the important role of technical progress, industrial structure, and economic level. The perfect completion of the '13th Five-year Plan' further improved the economic development of different regions. All cities in China have improved their economic strength by following up the tide of age development, which provides capital support to technical progress. They all increased R&D expenditures continuously, and guided enterprises and scientific research institutes in technological R&D and innovation. Significant attention is paid to the promotion effect of technical progress in industrial structural optimisation. The industrial structure is updated by improving technological innovation levels continuously, thus making proportions of light and heavy industries increasingly more reasonable. The production technological level of the industrial department has increased and a development system with high value-added, high-energy efficiency, and energy conservation has been established.
(2) Path 1 and path 2 formed the second-order combination. This means that industrial structure and technical progress are replaceable when the economic level and energy consumption structure are relatively good. Central and western China shall introduce and reform advanced technologies continuously, strengthen technological communication among regions, and improve regional energy efficiency through technical progress. Coastal regions in eastern China shall emphasise optimisation and adjustment of industrial structure, continue to implement the strategy of 'shifting from a labour-intensive industry to service the economy', and transfer production actors from low-productivity sectors to those with high-productivity. On the one hand, the structural and production effects brought by the productivity transfer continue to promote economic development, and on the other hand, 'shifting from a labour-intensive industry to service the economy' decreases economic dependence on energy sources, thus improving energy efficiency.

6.3. Limitations

Essentially, this study has some shortcomings.

(1) This study mainly focuses on the analysis of the four key variables that influence energy efficiency. However, more factors influence energy efficiency. Follow-up studies can involve more condition variables to analyse the possible allocation effect of their combinations, aiming to increase the universality of this study.
(2) This study is a static case study without considering the important possible influences of time dimension on energy efficiency. In the future, panel data should be collected and dynamic QCA should be used to further verify the complicated causality between different influencing factors and energy efficiency.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142316103/s1.

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The Role of Intra-Industry Trade, Foreign Direct Investment, and Renewable Energy on Portuguese Carbon Dioxide Emissions

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Abstract: This paper revisited the link between intra-industry trade (IIT) between Portugal and Spain and Portuguese carbon dioxide (CO_2) emissions. The research also considers the effects of foreign direct investment (FDI) on CO_2 emissions, pondering the arguments of the pollution haven hypothesis and the halo hypothesis. As an econometric strategy, this investigation has applied panel data, namely a Pooled Mean Group of an Autoregressive Distributed Lag (ARDL) model and Panel Quantile Regression (PQR). The preliminary unit root tests indicated that IIT, Portuguese and Spanish renewable energy, and Portuguese FDI are integrated into the first differences and stationary with the second generation test (Pesaran methodology). In the next step, this study applied the multicollinearity test and cross-dependence between the variables. The variance inflation factor test demonstrated that FDI and IIT have no multicollinear problems. However, as expected, collinearity exists between Portuguese and Spanish renewable energy. Regarding the cross-sectional dependence test, this investigation concluded that the variables have a dependence between them. The cointegration test revealed that the variables are overall cointegrated. In the econometric results with the ARDL estimator, this investigation has found that IIT between Portugal and Spain is negatively correlated with Portuguese CO_2 emissions, showing that this type of trade encourages environmental improvements. However, the PQR demonstrates that there is an opposite relationship. According to this, Portuguese and Spanish renewable energy is negatively impacted by CO_2 emissions, revealing that renewable energy aims to decrease pollution. Finally, Portuguese FDI reduces CO_2 emissions, which is explained by product differentiation, innovation, and monopolistic competition.

Keywords: foreign direct investment; bilateral trade; panel ARDL model; panel quantile regression; carbon dioxide emissions

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1. Introduction

The effects of intra-industry trade (IIT), foreign direct investment (FDI), and renewable energy have been studied in international economics and energy economics issues. Indeed, the theoretical models of IIT emerged in the 1980s and 1990s to explain product differentiation (e.g., Krugman [1]; Lancaster [2]; Falvey and Kierzkowski [3]; and Shaked and Sutton [4]). However, empirical studies of horizontal and vertical IIT became notable in the literature with the investigation, for example, by Greenaway et al. [5]. In this line, the researchers used countries and industry characteristics to explain the determinants of IIT (e.g., Faustino and Leitão [6]; Leitão and Faustino [7]; Jambor and Leitão [8]; and Doanh and

Heo [9]). The determinants of IIT are explained by the gravity model, such as geographical distance, border, and economic dimension, or by industry explanatory variables, such as industrial concentration, product differentiation, scale economies, and FDI.

Another area of research concerns the issue of marginal IIT and structural adjustment issues in the labour market (e.g., Brülhart and Thorpe [10]; Thorpe and Leitão [11]; and Leitão et al. [12]). The empirical studies use wages, productivity, apparent consumption, and marginal IIT as independent variables in labour market adjustments. Moreover, they consider that the adjustment is smooth whenever the marginal IIT negatively correlates with changes in employment.

Recently, the empirical studies of Roy [13], Leitão and Balogh [14], Leitão [15], and Kazemzadeh et al. [16] showed that IIT and trade intensity could mitigate the damage to the environment, promote cleaner air quality and slow climate change. This assumption is explained by considering that IIT is associated with innovation and product differentiation. The internalisation process of multinational enterprises was developed based on the theories of international investments, namely organisations, localisation and internalisation theories and transaction costs (e.g., Dunning and Lundan [17]).

Considering the determinants of FDI, the empirical studies use the gravity model and organisation, localisation and internalisation advantages and characteristics, where the explanatory variables utilised are economic dimensions, the border, geographical distance, production costs, the exchange rate, or, more recently, the impact of corruption and democratisation on the FDI host country (e.g., Leitão [15]; and Egger and Pfaffermayr [18]). Furthermore, another issue of the investigation into FDI is the question of economic growth, i.e., the linkage between FDI and economic development (e.g., Alfaro et al. [19]; and Alfaro and Charlton [20]). Academics and scholars have investigated the relationship between FDI and the pollution haven hypothesis versus the pollution halo hypothesis (e.g., Cole et al. [21]; Singhania and Saini [22]; and Kisswani and Zaitouni [23]).

Although the literature has widely explored the relationship between IIT, FDI, renewable energy and CO_2 emissions, no investigations have explored the IIT between Portugal and Spain and the impact of FDI and renewable energy on Portuguese CO_2 emissions. In other words, existing gaps in the literature regarding these topics need to be filled and explored to understand this possible relationship in Portugal better. For this reason, the present research aims to fill the abovementioned gaps by analysing the impact of IIT between Portugal and Spain on Portuguese CO_2 emissions. It also considers investigating the effects of FDI on CO_2 emissions, pondering the arguments of the pollution haven hypothesis and the halo hypothesis.

Therefore, this investigation seeks to answer these questions: What is the impact of IIT between Portugal and Spain, FDI, and renewable energy on Portuguese CO_2 emissions? What is their directional relationship?

Thus, to fill these gaps and the main questions mentioned above, this investigation will conduct a macroeconomic analysis using a panel with data from Portugal from 2000 to 2018. A pooled mean group (PMG) of an autoregressive distributed lag (ARDL) model and panel quantile regression (PQR), as well as the Pairwise Dumitrescu–Hurlin panel causality test, will be used to carry out this empirical investigation.

This investigation is innovative for the literature by investigating the influence of the IIT between Portugal and Spain, FDI, and renewable energy on Portuguese CO_2 emissions. As mentioned above, the literature has not so far approached this topic. Moreover, ARDL, PQR models, and the Pairwise Dumitrescu–Hurlin panel causality test were used to carry out this empirical investigation.

Additionally, this study contributes to the literature in three ways. First, the relationship between IIT and climate change, air quality and the impact of IIT on CO_2 emissions are analysed both in theoretical and empirical terms of CO_2 emissions, which, as a rule, empirical studies tend to attribute a negative correlation, demonstrating that they allow a reduction in greenhouse effects and global warming. Second, we assess the relationship between FDI and polluting emissions. In this relationship, there are two different perspectives. On the one hand, empirical studies demonstrate that FDI positively impacts CO_2 emissions, which is explained by the pollution haven hypothesis. In other words, countries use FDI to circumvent stringent domestic environmental standards. This results in moving polluting activities to less environmentally regulated countries.

On the other hand, empirical studies indicate that FDI is associated with innovation factors, reducing greenhouse effects, and consequently improving climate change. In this case, it is explained by the pollution halo hypothesis, i.e., transnational enterprises transfer green technology via FDI to host countries. Therefore, we observe that the crucial objective of this research is to evaluate the effect of IIT and FDI on pollution and the environment. Moreover, this article considers the association of renewable energy with CO_2 emissions. Usually, empirical studies argue that renewable energy aims to decrease climate change and global warming (e.g., Usman et al. [24]; and Yu et al. [25]).

Finally, this investigation is important because its experimental findings contribute to the development of the existing literature and have significant implications for the policies of complex economies with diversified export products to reduce environmental degradation. Moreover, the results and explanations of this study will support policymakers and governments in developing consistent policies and initiatives that promote clean energy, reduce energy consumption, and achieve sustainable development.

The literature review and the empirical studies will emerge in the next section; Section 3 presents information on data collection, the hypotheses to be tested, and the economic model to apply. Subsequently, the empirical results appear in Section 4, and finally, we present the conclusions of this investigation in Section 5.

2. Literature Review and Empirical Studies

This part discusses the relevant empirical studies and theoretical models to study the linkages between IIT and pollution emissions and the nexus between FDI, renewable energy and CO_2 emissions.

2.1. Theoretical Framework

In the first stage, we present some preliminary issues to do with IIT. Understanding this type of trade in the world economy and its relationship with the environment is essential. In the second stage, we present two perspectives on the effects of FDI on CO_2 emissions (pollution haven hypothesis versus pollution halo hypothesis). Finally, we examine the link between renewable energy and pollution emissions.

In this context, IIT is explained by economies of scale, industrial concentration, and the differentiation in products. This type of trade predominates in the same sector or the same branch; see, for instance, Grubel and Lloyd [26] and Greenaway and Milner [27].

The theoretical models of the IIT (e.g., Krugman [1]; Lancaster [2]; Falvey and Kierzkowski [3]; and Shaked and Sutton [4]) are based on the assumptions of monopolistic competition, where geographical proximity, similarities or different factor endowments, and the respective consumer preferences are usually the explanatory variables. Therefore, this investigation will also refer to the connection between the IIT and environmental issues explained by monopolistic competition. However, before introducing the relationship between IIT and ecological issues, it is also important to mention that there is a set of empirical studies that assess the determinants of the IIT through the gravity model, i.e., using the characteristics of the countries or through the characteristics of the industries (e.g., Hasim et al. [28]; Vidya and Prabheesh [29]; and Jošić and Žmuk [30]).

2.2. The Relationship between IIT and Air Pollution

When a literature review is carried out on the relationship between IIT and climate change, it is observed that there are more theoretical than empirical models on this link. Thus, it can be inferred that empirical studies should emerge in the literature. Indeed, this type of research makes it possible to assess whether a given country or a set of sectors of a given economy is associated with the theory of comparative advantages, where inter-industry trade predominates. Consequently, higher pollution levels are expected. On the contrary, innovation and using more sustainable practices translate into IIT, where it is possible to improve the environment. However, there seems to be a convergence between theoretical models and empirical studies. Indeed, most studies conclude that the IIT allows for an improvement in the environment.

There is a set of theoretical and empirical models (e.g., Roy [13]; Leitão and Balogh [14]; Leitão [15]; Kazemzadeh et al. [16]; Copeland and Taylor [31]; Gürtzgen and Rauscher [32]; Echazu and Heintzelman [33]; Gallucci et al., [34]; and Shapiro [35]) demonstrating that IIT, and exports quality and trade intensity improve the quality of the air and environment.

Subsequently, this investigation will present some conclusions and more details about empirical studies of IIT and the environment, namely the articles of Roy [13], Leitão and Balogh [14], Leitão [15], Kazemzadeh et al. [16], and Gallucci et al. [34]. In this context, the empirical study of Roy [13] analysed the determinants of IIT, considering the arguments of the gravity model. The author tested the effect of IIT, marginal IIT, and trade intensity on air quality and pollution emissions using panel data. The regressions showed that IIT aims to decrease the climate change generated by environmental improvements. In this line, Gallucci et al. [34] concluded that IIT could be considered an indicator of innovation, and this type of trade positively influences the environment with cleaner technologies.

Considering the European countries' experience, the work of Leitão and Balogh [14] used the fixed effects and generalized method of moments estimators. The authors concluded that IIT is negatively correlated with CO_2 emissions. On the other hand, Leitão and Balogh [14], based on a fixed effects model, concluded that renewable energy aims to decrease pollution emissions, and CO_2 emissions positively impact income per capita and agricultural land productivity. The extensive empirical study of Leitão [15], for the Portuguese case, using the autoregressive distributed lag (ARDL) model with a time series, demonstrated that trade intensity decreases CO_2 emissions. Nevertheless, the variables in energy consumption and income per capita increase pollution emissions, namely CO_2 emissions. In this line, the empirical study of Kazemzadeh et al. [16] considered the effects of economic complexity and export quality on pollution emissions in 98 countries between 1990 and 2014, using PQRs. The authors found that trade openness and export quality improve environmental and pollution emissions. Moreover, income per capita, population, and non-renewable energy are positively associated with climate change and ecological damage. However, when Kazemzadeh et al. [16] applied panel cointegration regressions, the results demonstrated that urban population and economic complexity are always negatively correlated with CO_2 emissions.

Another contribution applied to India developed by Aggarwal et al. [36] demonstrated that India IIT is characterised by the low quality of products because there exists a difference in environmental rules. The authors suggest that India should develop trade agreements with European Union countries and the United Kingdom to improve this issue.

Khan et al. [37] evaluated the link between international trade, renewable energy, and CO_2 emissions in the Group of Seven (G7) economies. They found that imports and income per capita increased pollution emissions in the long run. Nevertheless, exports, environmental innovations, and renewable energy decrease CO_2 emissions.

From the empirical studies referred to above, there appears to be a gap in the literature because the studies assess a set of countries or a country's total trade. Moreover, few studies seem to test the bilateral relationship between Portugal and Spain, namely the impact of IIT on Portuguese CO_2 emissions.

2.3. The Link between FDI and CO_2 Emissions

The literature review argues that two different opinions exist regarding the effect of FDI on CO_2 emissions. For instance, according to the pollution haven hypothesis proposed by Cole et al. [21], Kisswani and Zaitouni [23], Usman et al. [24], Zhu et al. [38], Teng et al. [39], and Zmami and Ben-Salha [40], there was a positive effect of FDI on CO_2 emissions. In contrast, the empirical studies of Demena and Afesorgbor [41] and Marques and Caetano [42] argue that FDI encourages an improvement in the environment (pollution halo hypothesis), explaining this effect to be based on innovation factors due to FDI.

Following this, this investigation will present some conclusions from the empirical work of Agyeman et al. [43], Lin et al. [44], and Huang et al. [45]. Using the cointegration panel for a set of 27 African countries, the study by Agyeman et al. [43] demonstrated that government policies allowed a reduction in CO_2 emissions, evaluating the environmental Kuznets curve (EKC) hypothesis. Furthermore, the dynamic ordinary least squares (DOLS) model shows that tourism and FDI positively correlate with CO_2 emissions.

The investigation of local, regional, and countrywide experiences in China by Lin et al. [44] showed that FDI reduces pollution emissions at the national level. Besides, the empirical study of Lin et al. [44] revealed that EKC hypotheses are valid at all levels, and energy consumption increases CO_2 emissions in local regions. A different position can be found in the studies of Usman et al. [24] and Huang et al. [45], which demonstrate that FDI accentuates climate change, explained by the pollution haven hypothesis.

A panel analysis of data for India, Pakistan, Sri Lanka, and Bangladesh was carried out by Mehmood [46], and the long-term effects through the ARDL estimator showed that economic growth and FDI accentuate CO_2 emissions. However, the interaction variables of renewable energy and FDI and the interaction of renewable energy and economic growth promote environmental improvements. Furthermore, the empirical study shows that government effectiveness and renewable energies stimulate a reduction in pollution levels.

The links between financial inclusion, globalisation, renewable energy, and CO_2 emissions were investigated by Qin et al. [47], where the study used panel data (PQRs and cointegration panel tests) and concluded that the EKC hypotheses are valid for the emerging seven economies (e.g., China, India, Brazil, Turkey, and Russia). Furthermore, the authors demonstrate that financial inclusion, globalization, and renewable energy electricity make it possible to reduce CO_2 emissions.

2.4. The Correlation between Renewable Energy and CO_2 Emissions

Several articles in energy economics (e.g., Shaari et al. [48]; Razzaq et al. [49]; Muço et al. [50]; and Balsalobre-Lorente et al. [51]) showed that renewable energy consumption mitigated the damage to the environment, showing with different econometric techniques that there is a negative impact of renewable energy on CO_2 emissions. The studies argue that renewable energy and clean technologies aim to decrease climate change. In this context, Muço et al. [50] applied a panel vector autoregression model to new European countries from 1990 to 2018. Considering the CO_2 emissions as a dependent variable, the authors found a negative effect of lagged renewable energy on CO_2 emissions, and that the lagged variable in income per capita is positively correlated with CO_2 emissions. Moreover, the lagged variable in energy use presents a positive effect on CO_2 emissions. However, the authors found a negative impact of lagged CO_2 emissions, showing that CO_2 decreases in the long run.

In the recent article of Mehmood [47] applied to four South Asian countries from 1990 to 2017, with the ARDL model, the author found that globalisation and financial inclusion are positively correlated with CO_2 emissions in the long run. Furthermore, the model also validates the hypothesis of the Kuznets curve. Finally, the variables in renewable energy decreased pollution emissions.

Shaari et al. [48] considered different economies from 1990 to 2017 in their research, using a panel ARDL model. Considering a PMG estimator, Shaari et al. [48] found that CO_2 emissions negatively impact renewable energy, and income per capita and population positively correlate with pollution in the long run.

The Middle East/North Africa countries were investigated by Omri and Saidi [52] using a panel data fully modified ordinary least squares (FMOLS) estimator, and they found that the EKC hypotheses are valid. The coefficients of trade, financial development and non-renewable energy positively affect climate change. However, the variable in renewable energy aims to decrease CO_2 emissions.

The case of Africa was investigated by Usman et al. [24], and the authors considered the impacts of corruption control, economic growth, renewable energy, and FDI on CO_2 emissions using the panel method of moments quantile estimators. The econometric models revealed that the variables in corruption control and economic growth are positively correlated with CO_2 emissions. Besides, the effect of FDI on CO_2 emissions is explained by pollution haven hypotheses, reflecting that FDI increases pollution emissions. However, renewable energy aims to decrease pollution emissions and improve the environment.

The empirical work of Pata [53] tested the United States of America's CO_2 emissions and ecological footprint. The results showed that economic complexity and the squared economic complexity index are according to the assumptions of EKC. Moreover, renewable and non-renewable energy are negatively and positively associated with CO_2 emissions.

The relationship between financial development, renewable energy, and CO_2 emissions in 11 economies was investigated by Wang et al. [54]. According to Goldman Sachs's criteria, the authors selected 11 economies and found that economic growth positively correlates with CO_2 emissions and financial development. Besides, renewable energy, globalisation and the interaction of financial development and renewable energy decrease the pollution effects, namely the CO_2 emissions.

The experience of South Africa was investigated by Ekwueme et al. [55] to evaluate the impacts of renewable energy, fiscal development, and FDI on CO_2 emissions. Considering the vector error correction model and ARDL (autoregressive distributed lag model), the authors found that in the long run, renewable energy, economic growth, and financial development are positively impacted by CO_2 emissions.

Adebayo and Kirikkaleli [56] considered the nexus between renewable energy, globalization, innovation, and CO_2 emissions in Japan using wavelet analysis. According to [56], economic growth and innovation stimulate climate change, but renewable energy decreases CO_2 emissions in the short and medium run.

In the context of the Environmental Kuznets curve, the empirical study by Safar [57] tests the relationship between income inequality and pollution emissions in France. The ARDL model shows that inequality can affect CO_2 emissions differently, i.e., it depends on the indicator the author used (Gini index or Atkinson). Furthermore, the work of Safar [57] demonstrates that net inequality improves the environment.

In the following section, the methodology and econometric model are going to be presented in this article.

3. Methodology and Econometric Model

The effects of IIT between Portugal and Spain and renewable energy on Portuguese CO_2 emissions from 2000 to 2018 are considered in this investigation. Moreover, this research also introduces the impact of FDI on Portuguese CO_2 emissions to test the pollution haven hypothesis versus innovation and product differentiation (pollution halo hypothesis). Following this, the last variable allows us to observe if FDI is associated with pollution emissions or decreases CO_2 emissions.

The index of IIT was calculated from Organisation for Economic Co-operation and Development (OECD) statistics and bilateral trade in goods by industry from the International Standard Industrial Classification. The dataset is organised in panel data, and this study used the PMG of an ARDL model and the PQR model. In the first phase, this investigation will focus on the coefficients obtained through the panel ARDL model; these were determined using the Akaike information criterion (AIC), and the specification is fixed. This strategy serves as an analysis tool to later analyse the heterogeneity of the variables under study through the PQR. In the first step, cointegration tests were considered (e.g., Kao et al. [58], Kao and Chiang [59], and Johansen [60]) to assess if there is a long-run relationship between the variables under study. Besides, this investigation will verify the panel unit roots, multicollinearity, and cross-sectional dependence tests.

The index of intra-industry trade (e.g., Grubel and Lloyd [26]) can be represented by:

$$IIT_{ij} = 1 - \frac{\left|\sum_{k=1}^{K} X_{ijk} - \sum_{k=1}^{K} M_{ijk}\right|}{\left(\sum_{k=1}^{K} X_{ijk} + \sum_{k}^{K} M_{ijk}\right)} \quad (1)$$

The index varies between 0 and 1. When IIT_{ij} = 1, all trade is intra-industry trade, but when IIT_{ij} = 0, the trade is inter-industry trade.

In our study, the selected sectors were total trade, intermediate goods, household consumption, capital goods, mixed end-use (personal computers, passenger cars, personal phones), precious goods, packed medicines, and miscellaneous. Based on the empirical studies (e.g., Roy [13]; Leitão and Balogh [14]; Balsalobre-Lorente et al. [51]; Zafar et al. [61]; and Dogan and Ozturk [62]), this investigation formulates the following model:

$$\begin{aligned}\Delta \mathrm{LogCO}_{2it} = {} & \alpha_{0it} + \alpha_{1it}\mathrm{LogCO}_{2i(t-1)} + \alpha_{2it}\mathrm{LogIIT}_{i(t-1)} + \alpha_{3it}\mathrm{LogRE}_{i(t-1)} + \alpha_{4it}\mathrm{LogRESP}_{i(t-1)} + \alpha_{5it}\mathrm{LogFDI}_{i(t-1)} \\ & + \sum\nolimits^{P}_{j=0}\gamma_1\mathrm{LogCO}_{2i(t-j)} + \sum\nolimits^{P}_{j=0}\gamma_2\mathrm{LogIIT}_{i(t-j)} + \sum\nolimits^{P}_{j=0}\gamma_3\mathrm{LogRE}_{i\,(t-j)} + \\ & \sum\nolimits^{P}_{j=0}\gamma_4\mathrm{LogRESP}_{i(t-j)} \sum\nolimits^{P}_{j=0}\gamma_4\mathrm{LogFDI}_{i(t-j)} + \psi\mathrm{ECT}_{i(i-t)} + \mu_{it}\end{aligned} \quad (2)$$

As seen in Equation (2), all variables are in natural logarithms. The components of white noise are represented by μit, the differences by Δ, and finally, ψECT represents error correction. As can be observed, the dependent variable is CO_2 emissions per capita. The explanatory variables are the index of IIT (LogIIT), Portuguese and Spanish renewable energy consumption (LogRE and LogRESP), and Portuguese FDI (LogFDI). All variables are collected from the World Bank Open Data [63].

The equation takes the following form in PQR:

$$Q\tau\,(\mathrm{LogCO}_{2it}) = (\mathrm{La})\tau + \beta_1\tau\mathrm{LogIIT}_{it} + \beta_2\tau\mathrm{LogRE}_{it} + \beta_3\tau\mathrm{LogRESP}_{it} + \beta_4\tau\,\mathrm{LogFDI}_{it} + \mu_{it} \quad (3)$$

where the model's parameters are βxτ (IIT, Portuguese renewable energy, Spanish renewable energy, and FDI); the model's constant is represented by (La)τ.

Next, this investigation will present the hypotheses, considering the literature that justifies the econometric model.

Hypothesis 1a (H1a). *Intra-industry trade is negatively correlated with CO_2 emissions.*

Hypothesis 1b (H1b). *Intra-industry trade is linked with environmental damage.*

Based on the literature of Roy [13], Leitão and Balogh [14], Leitão [15], Copeland and Taylor [31], Gürtzgen and Rauscher [32], Echazu and Heintzelman [33], Gallucci et al. [34], and Shapiro [35], IIT aims to improve the environment and to decrease pollution emissions. In this context, Khan et al. [37] showed that exports and innovation encourage improvements in the environment. However, the alternative hypothesis considers that bilateral trade can be explained by the pollution haven hypothesis (PHH) since it can stimulate polluting emissions.

Hypothesis 2. *Renewable energy consumption encourages air quality and decreases CO_2 emissions.*

The empirical studies of Shaari et al. [48], Razzaq et al. [49], Muço et al. [50], and Balsalobre-Lorente et al. [51] give support to our hypothesis. Furthermore, the studies demonstrate that renewable energy is negatively associated with CO_2 emissions.

Hypothesis 3a (H3a). *FDI is directly associated with CO_2 emissions and is explained by the pollution haven hypothesis (PHH).*

Hypothesis 3b (H3b). *FDI is described by innovation and product differentiation and aims to decrease pollution emissions.*

The empirical studies of Cole et al. [21], Singhania and Saini [22], Zhu et al. [38], Teng et al. [39], Demena and Afesorgbor [41], Marques and Caetano [42] and Qin et al. [47] described the hypotheses formulated. FDI—Portuguese FDI, net inflows (% of gross domestic product (GDP)). Table 1 below summarises the description of the variables used in the investigation and the expected signs.

Table 1. Explanation of variables.

Nomenclature (Variables)	Description	Expected Sign	Source	QR Codes
	Dependent variable			
$LogCO_2$	Portuguese carbon dioxide emissions per capita: dependent variable	n.a.	World Bank Open Data [63]	
	Independent variables			
α_{1} = $LogCO_{2t-1}$	A lagged variable of Portuguese carbon dioxide emissions per capita	+; −	World Bank Open Data [63]	
α_{2} = LogIIT	Index of intra-industry trade between Portugal and Spain	−; +	OECD [64]	
α_{3} = LogRE	Portuguese renewable energy consumption as a percentage of total energy consumption	−	World Bank Open Data [63]	
α_{4} = LogRESP	Spanish renewable energy consumption as a percentage of total energy consumption	−	World Bank Open Data [58]	
α_{5} = LogFDI	Portuguese foreign direct investment, net inflows (%of GDP)	+; −	World Bank Open Data [64]	

Notes: All variables are expressed in logarithm form; n.a. denotes not available.

After presenting the econometric model and variables used in this empirical investigation, it is necessary to show the methodology strategy that this investigation will use. Figure 1 below shows the methodology strategy this investigation will follow.

Subsequently presenting the methodology and econometric model, it is necessary to show the empirical results of this investigation. Section 4 below shows the empirical results found through the econometric approach.

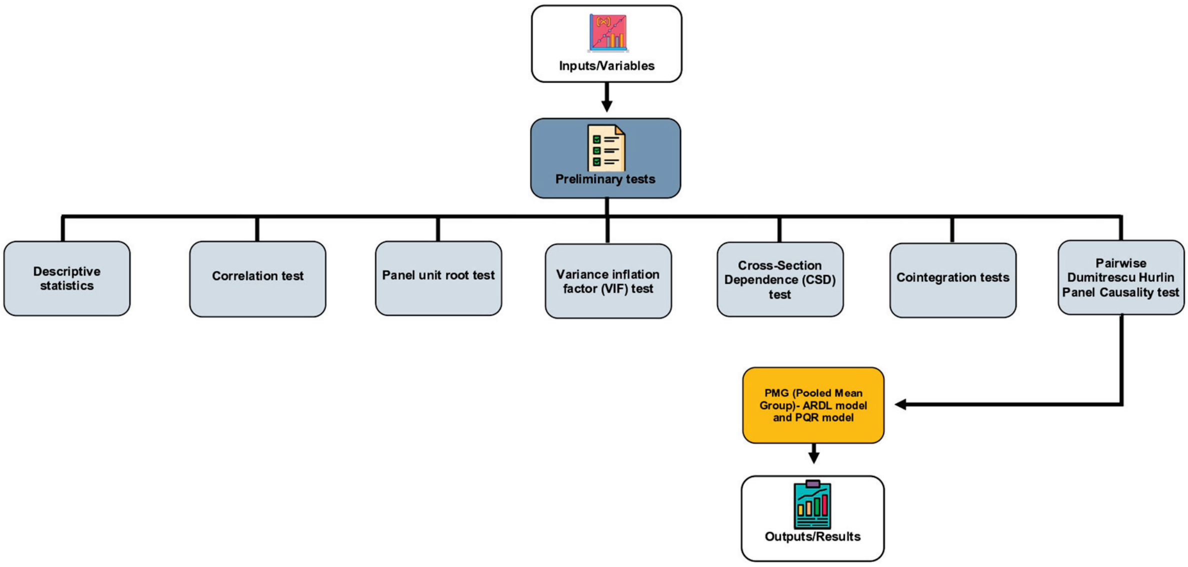

Figure 1. Methodology strategy. The authors created this figure.

4. Empirical Results

In this section, the investigation starts with the analysis of the variables, namely the descriptive statistics and the test of the properties of the variables (unit root test, cross-sectional dependence and cointegration tests). Finally, this study will present the estimates obtained through the PMG estimator and PQR. The descriptive statistics are discussed in Table 2 below.

Table 2. Descriptive statistics.

Statistics	LogCO$_2$	LogIIT	LogRE	LogRESP	LogFDI
Mean	4.740	−0.448	1.380	1.066	0.514
Median	4.751	−0.353	1.387	1.087	0.576
Maximum	4.817	−0.000	1.484	1.2403	0.995
Minimum	4.662	−1.762	1.257	0.863	−0.358
Std. Dev.	0.050	0.347	0.069	0.143	0.336
Skewness	−0.003	−1.242	−0.231	−0.069	−1.134
Kurtosis	1.569	4.410	1.932	1.275	3.739
Probability	0.000	0.000	0.005	0.000	0.000
Observations	189	189	189	189	189

Notes: All variables are expressed in logarithm form.

The variables in CO_2 emissions (LogCO$_2$), Portuguese renewable energy use (LogRE), and Spanish renewable energy use (LogRESP) present higher values of maximums. Therefore, considering the skewness, it can be observed that all variables exhibit a negative skewness. On the other hand, the Kurtosis statistic demonstrates that the variables used in this research show a positive kurtosis, and the IIT (LogIIT) and FDI (LogFDI) are the variables with higher values of kurtosis statistics.

Table 3 below presents the correlations between the variables under study. All explanatory variables (IIT, Portuguese renewable energy use, Spanish renewable energy use, and Portuguese FDI) present a negative correlation with the dependent variable (LogCO$_2$). These signs are according to the previous studies and the hypotheses formulated.

Table 3. Group of statistics studied: Correlations.

Statistics	$LogCO_2$	LogIIT	LogRE	LogRESP	LogFDI
$LogCO_2$	1.000				
LogIIT	−0.019	1.000			
LogRE	−0.794	0.019	1.000		
LogRESP	−0.801	0.014	0.937	1.000	
LogFDI	−0.014	−0.095	1.000	−0.059	1.000

Notes: All variables are expressed in logarithm form.

Table 4 below presents the stationarity of the variables used in this research, considering the Levin Lin, the Chu, ADF-Fisher Chi-square, Phillips–Perron, and Im–Pesaran–Shin tests; see, for instance, Maddala and Wu [65], Choi [66], Levin et al. [67], and Im et al. [68].

Table 4. Panel Unit Root Test.

Variables (Levels)	Levin, Lin & Chu t		Im, Pesaran and Shin W-Stat		ADF-Fisher Chi-Square		PP-Fisher Chi-Square	
	Statistic	*p*-Value	Statistic	*p*-Value	Statistic	*p*-Value	Statistic	*p*-Value
$LogCO_2$	0.195	(0.574)	2.054	(0.980)	5.154	(0.999)	5.682	(0.999)
LogIIT	−3.274 ***	(0.000)	−2.648 ***	(0.004)	39.213 ***	(0.006)	53.557 ***	(0.000)
LogRE	0.488	(0.687)	1.223	(0.889)	7.725	(0.994)	20.796	(0.409)
LogRESP	2.989	(0.999)	3.328	(0.999)	2.676	(1.000)	15.467	(0.749)
LogFDI	−6.578 ***	(0.000)	−5.172 ***	(0.000)	62.644 ***	(0.000)	121.062 ***	(0.000)
Variable (First Differences)	**Statistic**	***p*-Value**	**Statistic**	***p*-Value**	**Statistic**	***p*-Value**	**Statistic**	***p*-Value**
$\Delta LogCO_2$	−3.972 ***	(0.000)	−3.649 ***	(0.000)	45.501 ***	(0.000)	133.773 ***	(0.000)
ΔLogIIT	−7.193 ***	(0.000)	−6.754 ***	(0.000)	81.545 ***	(0.000)	204.244 ***	(0.000)
ΔLogRE	−4.895 ***	(0.000)	−7.391 ***	(0.000)	88.588 ***	(0.000)	220.650 ***	(0.000)
ΔLogRESP	7.290 ***	(0.000)	−3.625 ***	(0.000)	45.265 ***	(0.000)	288.5111 ***	(0.000)
ΔLogFDI	−9.139 ***	(0.000)	−9.259 ***	(0.000)	111.012 ***	(0.000)	2038.40 ***	(0.000)

Notes: *** denotes statistical significance at a (1%) level; all variables are in logarithm form.

As shown in Table 4 above, the variables under investigation are integrated into the first difference. Nevertheless, the variables in IIT (LogIIT) and FDI are simultaneously stationary in levels and the first differences. The multicollinearity and cross-sectional dependence are presented in Table 5 below.

Table 5. Multicollinearity (VIF) and Cross-sectional dependence (CSD) tests.

VIF test			CSD Test		
Variables	**VIF**	**1/VIF**	**Test**	**Statistic**	***p*-Value**
LogIIT	1.01	0.990	Breusch-Pagan LM	542.635 ***	(0.000)
LogRE	8.34	0.119	Pesaran scaled LM	52.455 ***	(0.000)
LogRESP	8.36	0.119	Pesaran CD	20.550 **	(0.000)
LogFDI	1.02	0.990	Breusch-Pagan LM	542.635 ***	(0.000)
Mean VIF	4.68				

Notes: ***, ** denote statistical significance at (1%) and (5%) levels, respectively; all variables are in logarithm form.

Table 5 above demonstrates that Portuguese FDI (LogFDI) and IIT (LogIIT) have no multicollinearity problems (i.e., have a VIF inferior to five, as suggested by Leitão [15] and

Fuinhas et al. [69]). As expected, there is collinearity between the Portuguese and Spanish renewable energy consumption variables. The tests of cross-sectional dependence show that the variables considered in this research have cross-sectional dependence between them.

Table 6 below presents a complementary test for each variable using the Pesaran methodology. Once again, cross-sectional dependence is found for the selected variables.

Table 6. Diagnostic tests of Cross-sectional dependence: Pesaran (CD test).

Variables	Statistic	*p*-Value
LogCO_2	29.084 ***	(0.000)
LogIIT	0.997	(0.312)
LogRE	25.575 ***	(0.000)
LogRESP	26.852 ***	(0.000)
LogFDI	−1.891 *	(0.058)

Notes: ***, * denote statistical significance at (1%), and (10%) levels, respectively; all variables are in logarithm form.

Next, Table 7 below presents the unit root test (second generation) considering the test of Pesaran (CIPS test). Again, the results reveal stationarity in the variables under study through the Pesaran test (CIPS).

Table 7. Unit root test: Second generation (CIPS).

Variables	Lags	t-Statistic	*p*-Value
LogCO_2	0	−3.088 ***	(0.000)
LogIIT	1	−2.831 ***	(0.000)
LogRE	1	−4.177 ***	(0.000)
LogRESP	1	−2.515 **	(0.050)
LogFDI	1	−3.673 ***	(0.000)

Notes: ***, ** denote statistical significance at (1%) and (5%) levels, respectively; all variables are in logarithm form.

Indeed, the cointegration test by Kao et al. [58] and Johansen and Fischer are presented in Table 8 below.

Table 8. Cointegration tests.

Johansen Cointegration Test					Panel Cointegration Test		
Hypothesized	**Fisher Stat.**		**Fisher Stat.**		**Kao Cointegration Test**	**t-Statistic**	***p*-Value**
No. of CE(s)	(from trace test)	*p*-value	(from the Max−Eigen test)	*p*-value	ADF	−3.296 ***	(0.000)
None	356.3 ***	(0.000)	259.3 ***	(0.000)	Residual variance	0.000	
At most 1	160.0 ***	(0.000)	100.9 ***	(0.000)	HAC variance	0.000	
At most 2	77.76 ***	(0.000)	43.91 ***	(0.001)			
At most 3	54.46 ***	(0.000)	37.30 **	(0.018)			
At most 4	57.6 ***	(0.000)	57.67 ***	(0.000)			

Notes: ***, ** denote statistical significance at (1%) and (5%) levels, respectively.

The results from Table 8 above demonstrate that there is a long-run relationship between the variables in used CO_2 emissions (LogCO_2), IIT, Portuguese renewable energy use (LogRE), and Spanish renewable energy use (LogRESP) and FDI (LogFDI).

Subsequently, this investigation presents the Pedroni test [70] in Table 9 below, where it can be observed that there is a significance for the Phillips−Perron panel (Panel PP statistics) and the Phillips−Perron Group statistic (Group PP statistics), confirming the previous test.

Table 9. Panel cointegration Pedroni.

		(WD)		
			Weighted	
	Statistic	**Prob.**	**Statistic**	**Prob.**
Panel v-Statistic	−1.746	(0.937)	−1.535	(0.937)
Panel rho-Statistic	−0.488	(0.373)	−0.324	(0.373)
Panel PP-Statistic	−7.418 ***	(0.000)	−6.584 ***	(0.000)
Panel ADF-Statistic	−2.529 ***	(0.005)	2.146	(0.984)
		(BD)		
	Statistic	**Prob.**		
Group rho-Statistic	1.143	(0.874)		
Group PP-Statistic	−6.563 ***	(0.000)		
Group ADF-Statistic	3.425	(0.999)		

Notes: *** denotes statistical significance at (1%) level. WD–represents within dimensions; BD–represents between dimensions.

Moreover, Table 10 below reveals the causality between the variables used in this research, which is considered the recent technique of the pairwise Dumitrescu−Hurlin panel [71].

Table 10. Pairwise Dumitrescu−Hurlin panel causality test.

Null Hypothesis:	W-Stat.	Zbar-Stat.	Prob.
LogIIT does not homogeneously cause $LogCO_2$	4.051 *	1.7642	(0.077)
$LogCO_2$ does not homogeneously cause LogIIT	5.453 ***	3.266	(0.001)
LogRE does not homogeneously cause $LogCO_2$	0.426 **	−2.119	(0.034)
$LogCO_2$ does not homogeneously cause LogRE	58.367 ***	59.946	(0.000)
$LogCO_2$ does not homogeneously cause LogRESP	29.964 ***	29.521	(0.000)
LogRE does not homogeneously cause LogIIT	6.095 ***	3.953	(0.000)
LogRESP does not homogeneously cause LogIIT	6.063 ***	3.9185	(0.000)
LogIIT does not homogeneously cause LogRESP	4.79625 **	2.56208	(0.010)

Notes: ***, **, * denote statistical significance at (1%), (5%), and (10%) levels, respectively; all variables are in logarithm form.

Table 10 above only presents the relationship between variables where a bidirectional and unidirectional causality exists. In this line, a bidirectional causality between IIT (LogIIT) and CO_2 emissions ($LogCO_2$) and Portuguese renewable energy use (LogRE) and CO_2 emissions ($LogCO_2$) can be observed. Moreover, bidirectional causality between Spanish (LogRESP) and IIT (LogIIT) also can be considered. The relationship between CO_2 emissions ($LogCO_2$) and Spanish renewable energy use (LogRESP) presents a unidirectional causality. Finally, we can also see a unidirectional causality between Portuguese renewable energy use (LogRE) and IIT (LogIIT). Figure 2 below summarises the causal relationship between the variables based on Table 10 above.

After presenting the results from the pairwise Dumitrescu−Hurlin panel causality test, it is necessary to observe the results from the PMG of the ARDL model and the PQR model. Therefore, Table 11 below shows the econometric results using the PMG model, which should be observed as a preliminary instrument that assesses the trend between the variables under study and their significance for later proceeding with the econometric interpretation via the PQR estimator. In addition, the Wald test (diagnostic test of coefficients) in Table 11 below demonstrates that all independent variables have statistical significance.

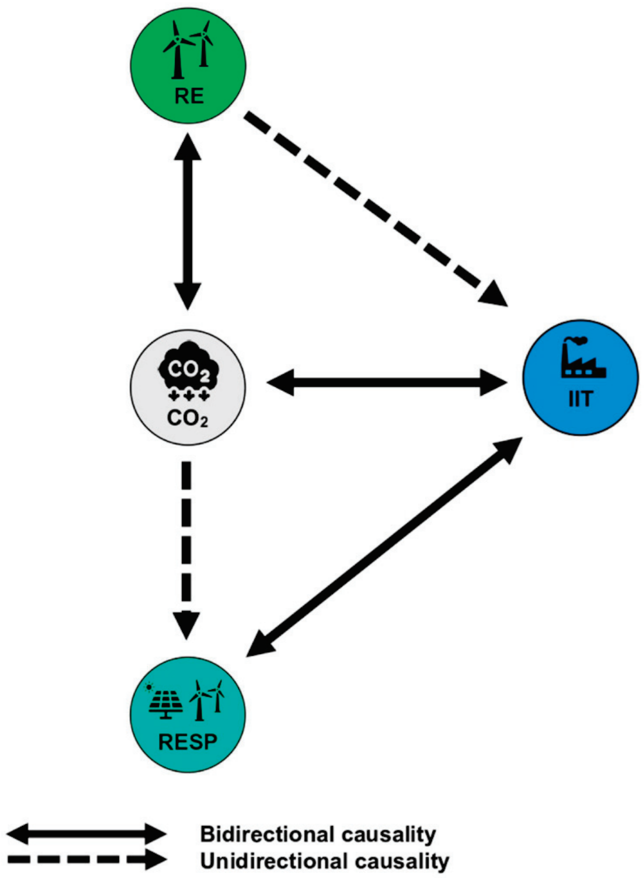

Figure 2. Summary of the causality relationship between the variables. The authors created this figure.

Table 11. Pooled mean group (PMG)—Autoregressive distributed lag (ARDL) model.

Independent Variables	**Coefficient**	**Std. Error**	**t-Statistic**	***p*-Value**
	Dependent Variable: LogCO_2			
Long Run Equation				
LogIIT	−0.0256 **	0.011	−2.323	(0.022)
LogRE	−0.417 ***	0.095	−4.403	(0.000)
LogRESP	−0.131 ***	0.045	−2.891	(0.004)
LogFDI	−0.032 ***	0.008	−4.021	(0.000)
Short Run Equation				
ECT	−0.470 ***	0.133	−3.541	(0.000)
Δ (LogIIT)	−0.028	0.025	−1.1085	(0.267)
Δ (LogRE)	0.2199 ***	0.050	4.371	(0.000)
Δ (LogRESP)	−0.092 ***	0.029	−3.153	(0.002)
Δ (LogFDI)	0.005	0.006	0.807	(0.421)
C	2.563 ***	0.725	3.536	(0.000)
Mean dependent var	−0.005	S.D. dependent var		0.024
S.E. of regression	0.022	Akaike info criteria		−4.407
Sum squared resid	0.062	Schwarz criteria		−3.309
Log-likelihood	480.501	Hannan−Quinn criteria		−3.9627
Wald test 279 (0.00) ***				

Notes: ***, ** denote statistical significance at (1%) and (5%) levels, respectively; all variables are in logarithm form.

The panel ARDL estimator has the advantage of considering short- and long-term effects. All independent variables are statistically significant in the long run, and the expected signs are according to the formulated hypotheses. Subsequently, this analysis considered the effects of the explanatory variables on CO_2 emissions in the long run and tested the hypotheses formulated in the methodology. The error correction adjustment (ECT) is negative and statistically significant at a (1%) level. The recent papers of Teng et al. [39] and Boufateh and Saadaoui [72] found a similar result.

The coefficient of the index of IIT (LogIIT) is statistically significant at a (5%) level. The result showed that intra-industry aims to decrease pollution emissions and improve the environment. The previous empirical studies of Roy [13], Leitão and Balogh [14], Leitão [15], Kazemzadeh et al. [16], and Khan et al. [37] support our result, showing that monopolistic competition assumptions validate the theory that two-way trade encourages and respects the rules of the environment.

Regarding Portuguese and Spanish renewable energy use (LogRE and LogRESP), it can be observed that the variables are negatively impacted by CO_2 emissions, showing that renewable energy aims decreased climate change. Furthermore, the studies of Leitão et al. [12], Balsalobre-Lorente et al. [51], Kirikkaleli [56], Zafar et al. [61], and Dogan and Ozturk [62] also found a similar relationship between renewable energy use and CO_2 emissions.

Finally, the coefficient of FDI (LogFDI) presents a negative effect on pollution emissions ($LogCO_2$), indicating that FDI can be associated with product differentiation and innovation and consequently seeks to decrease climate change and improve air quality (e.g., Teng et al. [39]; Demena and Afesorgbor [41]; and Marques and Caetano [42]). This result is according to the pollution halo hypothesis, i.e., multinational enterprises export cleaner technology to the host country and allow them to decrease the environmental damage (e.g., Kisswani and Zaitouni [23]). Figure 3 summarises the impact of independent variables on dependent ones. This figure is based on Table 11 above.

Based on the empirical studies by Khan et al. [73] and Alotaibi and Alajlan [74] in Table 12 below, the heterogeneity between the quantiles for the IIT (LogIIT), Portuguese and Spanish renewable energy (LogRE and LogRESP), FDI (LogFDI) and Portuguese CO_2 emissions ($LogCO_2$) can be assessed. The PQR was suggested by Koenker and Bassett [75]. The coefficients are considered for the quantile (e.g., 10th, 20th, 25th, 50th, 75th, 90th). The IIT coefficient (LogIIT) is statistically significant at (1%) for the 20th and 25th quantiles and (10%) and (5%) for the 50th and 75th quantiles. From the point of view of economic interpretation, the relationship between IIT and CO_2 emissions seems to be associated with an alternative hypothesis. That is, the pollution haven hypothesis explains IIT. It can be verified that only the 75th quantile presents a negative signal, demonstrating that the IIT contributes to environmental improvement (halo pollution hypothesis).

The coefficients of Portuguese (LogRE) and Spanish (LogRESP) renewable energy are always statistically significant across the quantiles. The Portuguese renewable energies (LogRE) present the signal advanced by the literature in the 50th, 75th and 90th quantiles. Regarding Spanish renewable energies (LogRESP), there is always a negative association between CO_2 emissions and statistical significance, validating the hypothesis formulated. As in the empirical study by Khan et al. [73], the result obtained for FDI is negative and insignificant. Figure 4 below shows the PQR results. Moreover, the shaded (95%) areas are confidence bands for the quantile regression estimates.

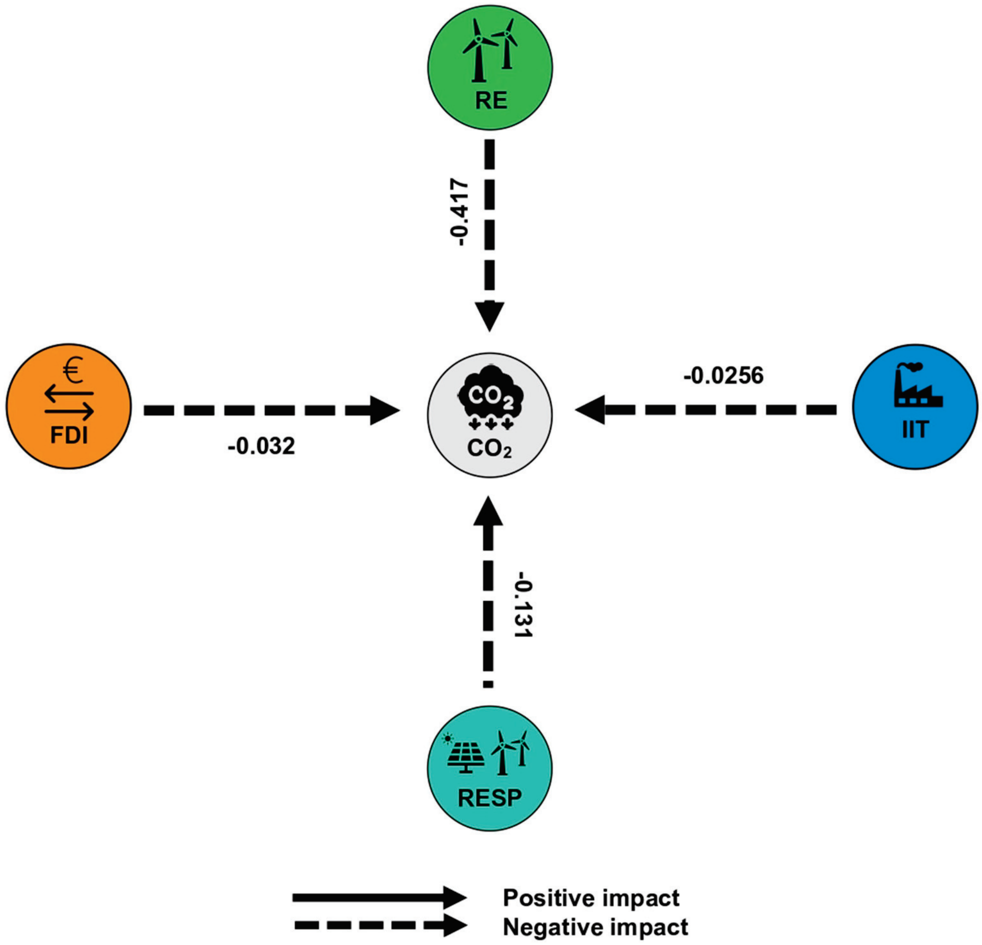

Figure 3. Summarises the impact of independent variables on dependent ones. The authors created this figure.

Table 12. Panel quantile regression.

Variables	10th	20th	25th	50th	75th	90th
LogIIT	-7.62×10^{-1}	0.002 ***	0.004 ***	0.005 *	−0.017 **	−0.001
LogRE	0.064 ***	0.063 **	0.072 *	−0.166 ***	−0.352 ***	−0.936 ***
LogRESP	−0.366 ***	−0.367 ***	−0.371 ***	−0.248 ***	−0.124 **	0.300 ***
LogFDI	-1.73×10^{-1}	0.0008	0.001	−0.005	−0.006	−0.013
C	5.017 ***	5.021 ***	5.016 ***	5.230 ***	5.371 ***	5.766 ***
Pseudo R^2	0.65	0.61	0.59	0.56	0.36	0.29

Notes: ***, **, * denote statistical significance at (1%), (5%), and (10%) levels, respectively; all variables are in logarithm form.

After presenting the empirical results, it is necessary to show the main conclusions of this investigation. Section 5 below shows this empirical investigation's main conclusions and policy implications.

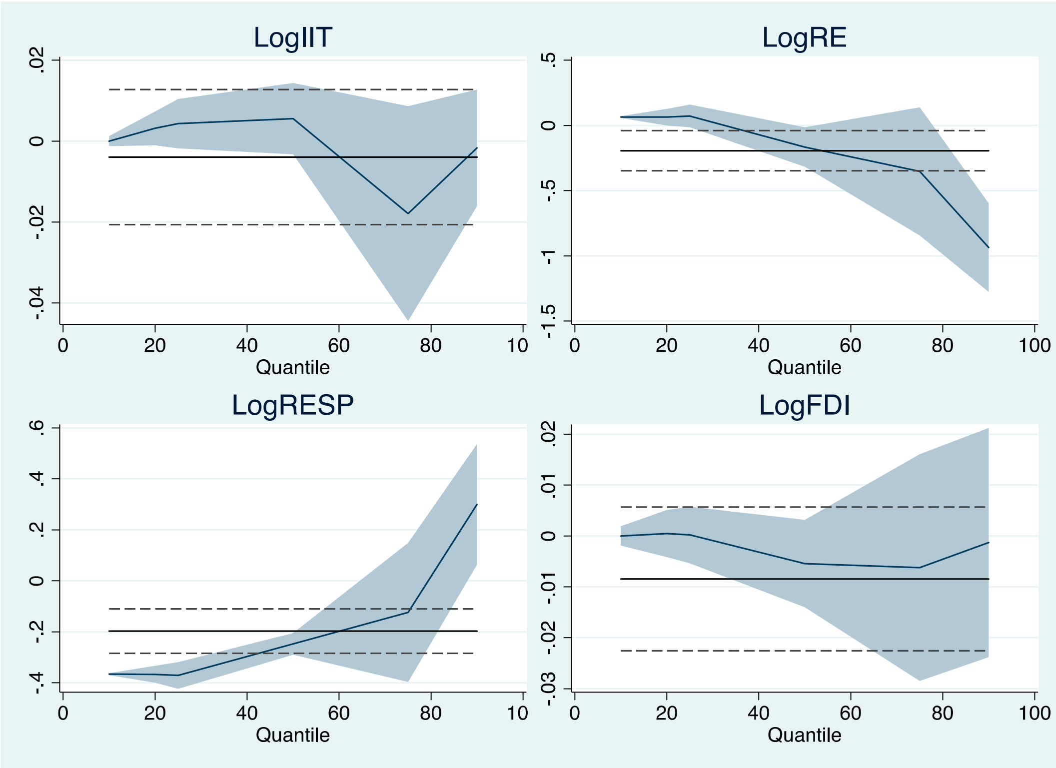

Figure 4. The quantile estimates.

5. Conclusions and Policy Implications

This paper investigated the role of IIT between Portugal and Spain, as well as of renewable energy, and FDI in Portuguese CO_2 emissions from 2000 to 2018. This investigation conducted a macroeconomic analysis using a panel with data from Portugal from 2000 to 2018. A PMG of an autoregressive distributed lag (ARDL) model and PQR, as well as the pairwise Dumitrescu−Hurlin panel causality test, were used to carry out this empirical investigation.

The results from the preliminary tests indicated that the variables in IIT and FDI are stationary at all levels. However, all variables considered in this research (CO_2 emissions, IIT, Portuguese and Spanish renewable energy use, and Portuguese FDI) are integrated at the first differences. We also used the second-generation unit roots (the Pesaran CIPS test), showing that the variables under study are stationary. Finally, the cointegration test showed that the variables used in this research are cointegrated in the long term.

Considering the methodology of Dumitrescu and Hurbin [71] to test the unidirectional and bidirectional causality with panel data, this investigation concluded that there is bidirectional causality between IIT and CO_2 emissions. Portuguese and Spanish renewable energy use also causes CO_2 emissions. In addition, the pairwise Dumitrescu−Hurlin panel demonstrated a bidirectional causality between Spanish renewable energy and IIT. Therefore, this investigation answered the main questions posed in the introduction section.

Regarding the empirical results, this investigation compared the econometric results between the panel ARDL model estimator and the PQR model, verifying heterogeneity between the coefficients obtained. Therefore, at first this investigation evaluated the panel ARDL as an analysis tool, and subsequently presented the main conclusions of this estimator.

Therefore, the results from thr PMG-ARDL model have indicated that the independent variables in natural logarithms, such as LogIIT, LogRE, LogRESP, and LogFDI, have a negative impact on the dependent variable LogCO_2 in the long run. In other words, the independent variables, such as LogIIT, had a negative impact of (−0.0256), while the variables, LogRE (−0.417), LogRESP (−0.131), and LogFDI (−0.032). Moreover, the independent variables in the first differences of natural logarithms, such as ΔLogRE, have a positive impact of (0.2199) on the dependent variable $\Delta LogCO_2$ in the short run, while the variable ΔLogRESP has a negative impact of (−0.092) on the dependent variable. However, the variables ΔLogIIT and ΔLogFDI are statistically insignificant.

Moreover, the PQR results indicated that independent variables in natural logarithms, such as LogIIT, positively impact the 20th, 25th, and 50th quantiles on the dependent variable $LogCO_2$ and have a negative impact on the 75th quantile. Therefore, the results obtained in the 75th quantile match those obtained in the main model in the long-run equation. The independent variable LogRE has a positive impact in the 10th, 20th, and 25th, quantiles on the dependent variable $LogCO_2$ and a negative impact in the 50th, 75th, and 90th quantiles. Therefore, the results obtained in the 10th, 20th, and 25th quantiles match those obtained in the main model in the short-run equation. Similarly, the results from the 50th, 75th, and 90th quantiles match those obtained in the main model in the long-run equation. The independent variable LogRESP negatively impacts all quantiles on the dependent variable $LogCO_2$. Therefore, the results obtained in all quantiles match the results obtained in the main model in the long- and short-run equation. However, the independent variable in natural logarithms, such as LogFDI, is statistically insignificant.

After this investigation presented the results above that were found in both the PMG-ARDL model and the PQR, the following question was elaborated —What are the possible explanations for the results that were found in this empirical investigation?

The negative correlation between IIT and climate change shows that cleaner trade based on innovation and product differentiation aims to decrease CO_2 emissions. This result is according to the previous studies (e.g., Roy [13]; Leitão and Balogh [14]; and Leitão [15]). Furthermore, based on the relationship between Portuguese and Spanish renewable energy and CO_2 emissions, this investigation obtained a negative expected sign, i.e., renewable energy consumption decreases global warming and promotes the improvement of the environment (e.g., Balsalobre-Lorente et al. [51]; Dogan and Ozturk [62]; Fuinhas et al. [69]; and Ebrahimi et al. [76]). Finally, the relationship between FDI and CO_2 emissions showed a negative correlation. This result allows us to conclude that FDI is associated with innovation, as in previous studies by Demena and Afesorgbor [41] and Marques and Caetano [42], and confirms the argument of the pollution halo hypothesis.

An important conclusion can be highlighted: the empirical results presented in this research are according to the goals of sustainable development foreseen in Agenda 2030 of the United Nations, namely climate action.

However, the results obtained through the PQR show a different conclusion with a particular focus on the IIT, which seems to be explained by the pollution haven hypothesis. Only the 75th quantile validates the negative signal, as the dominant theory pointed out by the literature, between IIT and CO_2 emissions.

Furthermore, as mentioned earlier in the literature review, there are few empirical studies on the impact of bilateral trade, i.e., IIT between Portugal and Spain, on Portuguese CO_2 emissions. In our understanding, this study has that advantage and can contribute to economic policymakers. Thus, IIT and renewable energies enable environmental improvements and reduce CO_2 emissions. In this context, Portuguese and Spanish economic policy should encourage support for industries that use differentiating factors and nascent industries that bet on cleaner energies and allow for sustainable development in both countries.

This investigation presented some lines for further investigation and policy recommendations considering our study's limitations. In this context, our research will be extended by European Union countries and Brazil, Russia, India, China, and South Africa (BRICS), applying the assumptions of the environmental Kuznets curve. Moreover, it should be necessary to test the impact of variables such as the globalisation index (KOF) and corruption or economic complexity. Concerning the effects of international trade, it is essential to test the structural adjustment, i.e., to understand the linkage between marginal IIT and labour markets and their adjustment in pollution emissions (e.g., Roy [13]), considering the assumptions of symmetric and asymmetric stock. In this line of investigation, it is interesting to assess the links between the economic complexity and corruption index and the effects of pollution emissions and bilateral trade between Portugal and Spain.

Based on the literature (e.g., Roy [13]), it is believed that marginal IIT, or trade intensity (e.g., Leitão [15]), allows adjustment and decreases pollution emissions once this type of trade increases productivity via innovation in the context of monopolistic competition. In addition, this methodology provides for considering dynamic indicators and lagged variables over time [12]. Furthermore, in this context of product differentiation and its association with consumer preferences for high- or low-quality products, it is essential to assess the impact of the horizontal IIT and vertical IIT on CO_2 emissions. In terms of disaggregation and separation of the horizontal IIT-HIIT and vertical IIT-VIIT see, for example, Greenaway et al. [5]; Faustino and Leitão [6]; Jambor and Leitão [8].

From theoretical models, it can be seen that labour-intensive products tend to use less sustainable or less clean energy. In contrast, capital-intensive products or sectors certainly use more sustainable measures. This analysis will be necessary for bilateral trade between Portugal and Spain to understand regional clusters' impact on climate change. Another question for future work concerns the effects of income inequality on economic growth and the environment, as well as the impact of the inflation rate and the increase in fuel consumption (e.g., Ullah et al. [77]; and Sreenu [78]).

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Article

The Race to Zero Emissions in MINT Economies: Can Economic Growth, Renewable Energy and Disintegrated Trade Be the Path to Carbon Neutrality?

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Abstract: The current paper evaluates the role of disintegrated trade, financial development, and renewable energy on consumption-based carbon emissions (CCO_2) in MINT nations between 1990Q1 and 2019Q4. This paper utilizes the novel Bootstrap Fourier Granger causality in quantiles (BFGC-Q) to evaluate this connection. This approach produces tail-causal and asymmetric causal connections between the indicators within the Fourier approximation, contrary to the Toda–Yamamoto causality and other conventional Granger tests. The outcomes uncover a unidirectional causality from economic growth and renewable energy to CCO_2 emissions in each MINT nation. Moreover, unidirectional causality emerged from financial development to CCO_2 for Indonesia, Nigeria, and Turkey. Moreover, exports have predictive power over CCO_2 in Indonesia, Turkey, and Mexico, while imports only have predictive power over CCO_2 emissions in Turkey. Lastly, financial development causes CCO_2 in Indonesia, Nigeria, and Mexico. In summary, green energy and exports are essential factors that decrease CCO_2 emissions and therefore decrease ecological deterioration in Mexico, Indonesia, and Turkey. On the flip side, imports only trigger CCO_2 emissions in Turkey and Mexico. Lastly, the financial development effect on CCO_2 emissions is positive in Mexico, Indonesia, and Nigeria, while an insignificant impact is found in Turkey. Based on these findings, policy ramifications are initiated.

Keywords: CCO_2 emissions; disintegrated trade; financial development; renewable energy; MINT nations

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1. Introduction

The difficulties of environmental degradation and climate change have rapidly surfaced in recent years, posing serious concerns for the international community's and policymakers' pursuit of sustainable development. The global economy has entered a phase of fast growth following the industrial revolution, and the wealth disparity has been growing [1,2]. Ecological contamination is a problem that arises concurrently with economic growth and poses a danger to human life. Huge industrial waste, intensive use of natural resources, and the usage of energy based on fossil fuels are the main causes of these problems [3,4]. Various nations have established the targets for carbon emission peaks and reductions at the recent summits (COP21, COP26) on ecological regulation and climate change in order to attain net zero emissions and achieve harmonized sustainable environment and growth. In order to accomplish zero emissions in the next decades, global leaders are working to put regulations/policies in place that will result in net-zero emissions.

Trade economists are the first to evaluate the issue of ecological deterioration [5]. These scholars offer a fundamental basis for comprehending how trade and the environment are correlated. One of the CO_2 emissions drivers is international trade [6,7]. On the one hand, international trade has augmented the flow of services and goods, thus boosting economic operations. Nevertheless, it has unfavorable effects on the ecosystem. According to [1], international trade allows nations to transfer their polluting sectors to other nations, contributing to environmental deterioration. However, trade raises nations' economic levels, which may be utilized to slow down ecological damage in its latter phases [5]. Nations worldwide are reallocating their resources to effective initiatives and implementing eco-friendly technologies to harmonize the relationship between CO_2 emissions and trade.

Overusing energy puts a lot of strain on the ecosystem [8]. Nevertheless, green energy (such as solar, biomass, wind, hydro, and geothermal) results in less CO_2 than using fossil fuels, which are thought to be the primary cause of global warming and CO_2 emissions [9]. Therefore, renewable energy sources are one of the most vital strategies to curb CO_2 [10,11]. After the well-known COP 21 and Kyoto Protocol in 2005, most advanced nations embraced renewable energy sources as a propelling tactic to attain a target of low GHG emissions. Various studies have incorporated renewable energy (REC) as a significant variable in the CO_2 emissions framework due to its significance in reducing CO_2 emissions [12,13].

Financial development (FD) also contributes significantly to a nation's growth. A robust and enhanced financial sector boosts the financial system's effectiveness while promoting economic development and growth [14]. Although energy is the main driver of economic expansion, it also has an unavoidable impact on the environment. As a result, the flow of financial resources is correlated with the need for energy. More funds are required for manufacturing to increase energy efficiency and deploy superior technologies to promote economic growth. Due to this, financial development has increasingly been a significant factor in economic growth [15–17]. Financial development boosts the economy, but it also has disadvantages since it may have an adverse effect on the environment and deplete natural resources in many ways. Particularly, the growth of finance pushes people to purchase more homes, machines, cars, and gadgets, intensifying the increasing need for energy [18,19].

In light of the preceding debate, this paper aims to inspect the impact of disintegrated trade, renewable energy, and financial development on consumption-based carbon emissions (CCO_2) in MINT nations. Brazil, Russia, India, China, and South Africa, together known as the BRICS nations, are powerful emerging blocs that have drawn significant attention recently. Moreover, Ref. [20] also acknowledged additional emerging markets in 2013, such as Mexico, Indonesia, Nigeria, and Turkey (MINT). The MINT nations account for between 1 and 2 percent of the global economy and have a good chance of surpassing other nations' economies in terms of economic size and technological advancement in the next decades. Although the USA likewise anticipates a 5% growth rate for each MINT country globally, Gold Sachs predicts consistent, steady growth for MINT nations [21]. Now the question arises, does developing nations like MINT economies uphold sustainable development with financial development and disintegrated trade without damaging the environment? The present investigation is carried out to provide an answer to this question.

This paper adds to the ongoing literature in three distinct ways: Firstly, the present investigation considered the impact of disintegrated trade by evaluating the role of imports and exports on CCO_2 emissions. Secondly, unlike prior studies such as [8,22–25] that used CO_2 emissions to gauge environmental degradation, the current investigation used CCO_2 emissions to measure ecological deterioration. As stated by [26], the CCO_2 is a comprehensive measure of ecological damage because it helps differentiate emissions produced in one country and consumed in another. Thus, emissions from imports and exports are taken into consideration when using this metric. Thirdly, the research employed BFGC-Q, initiated by [27], for the MINT nations between 1990Q1 and 2019Q4. This approach produces tail-causal and asymmetric causal connections between the indicators within the Fourier approximation, contrary to the Toda–Yamamoto causality and other conventional Granger tests.

A synopsis of relevant investigations is presented in the next part, and then Section 3 contains the data and methodology. In Section 4, study results and analyses are reported, and Section 5 brings the research to a close.

2. Literature Review

2.1. Synopsis of Studies between Environmental Quality and Financial Development, and Renewable Energy

Studies on the nexus between ecological quality (EQ) and financial development and green energy have been conducted in the empirical literature. For instance, Ref. [28] inspect the role of green energy (GRN)and export diversification on Indonesia's ecological quality (EQ) using the novel Fourier quantile causality method from 1965Q to 2014Q4. The findings indicate that there is one-way causation from fossil fuel to EQ at all quantiles. Still, the causes of EQ at the intermediate and higher quantiles include income, green energy, and export diversification. The EQ is most significantly raised by green energy and export diversification. In contrast, a rise in real growth and the use of fossil fuels lower EQ. Moreover, Ref. [29] revisits the nexus between green energy, financial development, and EQ towards attaining sustainable development in China. The research assesses updated time series data for China between 1988 and 2018 and employs cutting-edge econometric methods, including the Maki cointegration and frequency domain causality test. The empirical finding demonstrates that EQ is enhanced by increased financial development and using REC. Income, on the other hand, lowers EQ. Additionally, the 2008 structural break year and financial development raise EQ. The strong correlation between financial development and EQ confirms the school of belief that relates financial development with sustainability.

Using data from 1980 to 2018, Ref. [30] inspected the nexus between renewable energy, financial development, and EQ in selected Asian nations using panel methods between 1990 and 2014. The empirical study indicates that while economic expansion and financial development lower EQ, renewable energy helps raise it, while agriculture has less influence. The findings propose that all regressors can forecast EQ in the chosen countries, and the causality between the variables is tested using the variance decomposition and impulse response function approaches. Likewise, Ref. [31] inspected the environmental effects of financial development and REC using Driscoll–Kraay Panel Corrected Estimators for 16 developing nations between 2000 and 2018. The findings show that REC and financial development strengthen EQ. The developing nations have already passed the EKC tipping threshold for internet usage, wherein EQ rises as internet penetration increases. Furthermore, robustness testing using bootstrapped panel-quantile regression also supports the notion that financial development and REC promote EQ in each quantile.

Likewise, Ref. [32] evaluates how renewable energy and financial development promote EQ using global data between 1990 and 2018. The research used the estimators' DOLS, CCR, and FMOLS to assess the nexus. The long-term interrelationship between the indicators is supported by empirical research. Their findings also discover that worldwide economic expansion lowers EQ globally, whereas financial development and green energy consumption have a long-term significantly favorable impact on EQ. Ecological issues in the era of industrialization were evaluated by [33] by incorporating financial development and REC as control variables. The study used panel data from NICs for the years 1990 to 2019. The study used panel data from NICs for the years 1990 to 2019. The augmented mean group (AMG) results indicate that EQ in these nations is significantly impacted by financial development. On the other hand, using renewable energy greatly raises EQ over time. Additionally, these findings are in line with long-term and disaggregated level estimates. The panel causality test findings also found a unidirectional causation relationship from REC to EQ. Additionally, it was shown that EQ and financial development had a reciprocal causal interrelationship.

Using data from 1960Q1 to 2019Q4, Ref. [34] evaluated the environmental cost of economic progress, financial development, and renewable energy in Pakistan using non-parametric causality-in-quantiles techniques. The research indicated that EQ strongly correlates with financial development and REC, showing asymmetric prediction over ecological dispersion. Additionally, there is a connection between financial development and EQ at higher quantiles.

2.2. Synopsis of Studies between Environmental Quality and Exports and Imports

Mahmood [35] used spatial regression analysis to assess the effect of trade (imports and exports) on EQ in GCC nations, utilizing data from a period between 1990 and 2019. Exports have positive spillovers, direct and total impacts on EQ, and negative direct effects on EQ. The fact that exports negatively impact EQ indicates that exports are lowering EQ in domestic economies. On the other hand, the positive direct impact of exports on EQ demonstrates how exports enhance EQ in domestic economies.

Hasano et al. [36] assessed the impact of international trade on EQ in oil-exporting nations using both consumption and territory emissions accounting. The error correction and cointegration models indicate that imports and exports have significant statistical effects of opposing signs on EQ in both the short and long-term, and that the consequences of alterations in the trade-CCO_2 connection will be entirely assimilated in three years. Nevertheless, regarding territory-based CO_2 emissions, imports and exports are statistically insignificant. Moreover, Ref. [26] inspected the role of international trade in G7 countries on consumption-based carbon emissions using second-generation approaches. The findings support a consistent long-term connection between CO_2 emissions and trade. In the long term, exports reduce CCO_2, whereas imports increase it. The outcomes are also supported by the CCEMG and AMG methodologies. Based on the findings of the Granger causality test conducted by [37], it is said that any policy that targets imports and exports has a considerable impact on CCO_2 emissions.

Similarly, Ref. [38] evaluated the theoretical framework for the effect of trade (exports and imports) on CCO_2. The data from the BRICS nations for 1990 to 2017 are then used to evaluate this connection. The research also considers the panel data's integration, cointegration, heterogeneity aspects, and cross-country interdependence, resulting in reliable findings and well-founded policy recommendations. According to their findings, export size contributes to EQ growth, whereas import size dampens EQ. Furthermore, Ref. [39] using the BRICS nations evaluates the nexus between trade and CCO_2 using data from 1990 to 2018. The study evaluates these interactions using the AMD and CCEMG causality methodologies. The study results show that in the BRICS economies, exports reduce CCO_2, however, imports increase CCO_2. Furthermore, all the parameters can predict CCO_2 emissions according to the panel causality results. To achieve carbon neutrality for the G7 nations, Ref. [7] evaluated the disintegrated trade effect on EQ using data from 1990 to 2018. The results suggested that exports and imports are factors of CCO_2 in the G7 nations. In addition, exports curb CCO_2 while imports upsurge CCO_2 emissions.

In a variety of ways, this research contributes to the expanding body of scholarship on ecological deterioration. Firstly, the analysis is new because it uses the newly formed CCO_2 emissions, which determine emissions based on domestic fossil fuel usage plus incorporated emissions from net exports (export minus import). For the purpose of developing an effective climate strategy to address ecological issues, a precise assessment of CO_2 emissions is crucial. Following the Paris climate summit (COP, 21), it is possible to propose a pertinent climate policy response based on trade-adjusted data on CO_2 emissions. Secondly, the research employed BFGC-Q initiated by [27], for the MINT nations between 1990Q1 and 2019Q4. This approach produces tail-causal and asymmetric causal connections between the indicators within the Fourier approximation, in contrast to the Toda–Yamamoto causality and other conventional Granger tests.

3. Data and Methodology

3.1. Data

The current research evaluates the causal/interrelationship between CCO_2 emissions and imports, green energy, exports, financial development, and economic growth in the MINT nations. The study used data from 1990 to 2019 to assess the interrelationship. The dependent variable is CCO_2 while imports, renewable energy, financial development, exports, and GDP are the regressors. To minimize issues with small observations, all the yearly frequency data are adjusted to logarithmic values utilizing the quadratic match-sum approach and then normalized to quarterly frequencies. It is favored over other interpolation approaches because it takes seasonality into account by minimizing data changes when it switches from low to high frequency [4,25,40]. Statistical descriptions for quarterly data are provided in Tables 1 and 2. The six variables in each MINT country are not distributed normally, as shown by the Jarque–Bera test probability values. It is preferable to utilize median-based quantile causality tests for non-normally distributed series rather than mean-based conventional Granger causality tests [25,41]. Premised on this, we use the Fourier causality test to assess the factors affecting CCO_2 emissions. Figure 1 presents the flow of the study.

Table 1. Descriptive Statistics.

	Mexico					
	CCO_2	FD	REC	GDP	IMP	EXP
Mean	448.20	0.3344	10.949	8747.9	28.249	26.666
Median	469.80	0.3282	10.228	8820.9	27.674	26.142
Maximum	547.74	0.4008	15.187	9954.3	41.454	39.410
Minimum	312.54	0.2521	8.9487	7343.5	15.156	11.459
Std. Dev.	71.262	0.0468	1.6589	735.07	6.6390	7.0045
Skewness	−0.4887	−0.1151	0.5316	−0.2295	0.1749	−0.1450
Kurtosis	1.8650	1.5927	1.8958	2.0920	2.4342	2.6829
Jarque–Bera	11.218	10.167	11.748	5.1754	2.2127	0.9236
Probability	0.0036	0.0061	0.0028	0.0751	0.3307	0.6301
	Indonesia					
Mean	357.44	0.3122	2423.7	25.676	40.485	28.481
Median	317.97	0.3075	2159.1	25.309	41.515	26.742
Maximum	693.81	0.4001	3931.9	44.226	58.833	54.776
Minimum	132.54	0.2383	1462.1	16.601	18.943	16.979
Std. Dev.	159.57	0.0415	691.89	4.6656	10.914	7.1238
Skewness	0.4235	−0.0019	0.6322	1.5145	−0.1826	1.4132
Kurtosis	1.8527	2.0246	2.1623	7.7038	2.1152	5.8497
Jarque–Bera	10.169	4.7569	11.501	156.50	4.5811	80.553
Probability	0.0061	0.0926	0.0031	0.0000	0.1012	0.0000

Table 2. Descriptive Statistics.

	Nigeria					
	CCO_2	FD	GDP	IMP	REC	EXP
Mean	76.929	0.1898	1969.8	15.379	85.064	21.893
Median	80.407	0.1893	1916.9	14.378	85.168	22.052
Maximum	131.12	0.2739	2705.1	23.428	88.842	37.157
Minimum	33.529	0.1167	1411.3	8.595	80.541	8.8927
Std. Dev.	33.004	0.0352	470.43	3.9310	2.2691	6.4406
Skewness	0.1886	−0.0619	0.1982	0.4743	−0.2275	0.0526
Kurtosis	1.6725	2.6520	1.4011	2.1677	1.9715	2.6046
Jarque–Bera	9.5224	0.6819	13.568	7.9636	6.3246	0.8368
Probability	0.0085	0.7110	0.0011	0.0186	0.0423	0.6580

Table 2. *Cont.*

	Turkey					
Mean	306.00	0.4006	7941.7	24.680	17.005	22.299
Median	288.51	0.4053	7475.6	25.105	16.010	22.840
Maximum	445.09	0.5311	12022.	31.515	24.712	32.760
Minimum	206.13	0.1920	5286.7	16.568	11.208	12.629
Std. Dev.	82.533	0.1010	2179.5	4.2417	4.4882	4.4437
Skewness	0.2293	−0.4415	0.5619	−0.2954	0.4453	−0.1846
Kurtosis	1.4464	2.0872	1.9781	2.1182	1.7070	3.5362
Jarque–Bera	13.120	8.0644	11.536	5.6326	12.325	2.1200
Probability	0.0014	0.0177	0.0031	0.0598	0.0021	0.3464

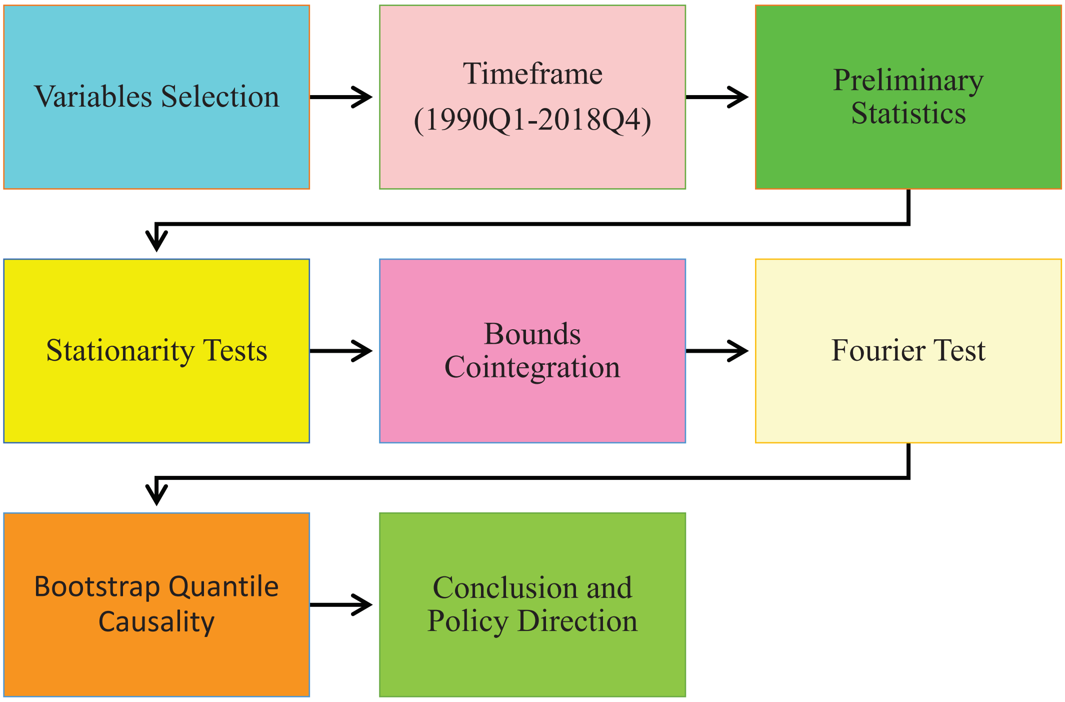

Figure 1. Flow of the study.

3.2. Theoretical Framework

This section explains the theoretical procedure through which imports and exports, economic growth, financial development, and renewable energy impact CCO_2 emissions. CCO_2 emissions encompass both household and government final domestic consumption demand, gross fixed capital formation, inventory changes, and purchases made overseas by residents [9,42]. This indicator is trade-adjusted, covers the entire carbon chain, and aids in identifying the production of carbon emissions in one nation and their absorption in another [7,43,44]. As a result, the impact of international trade in this research is calculated by separating imports and exports. According to the theory, increased exports give more products and services to recipient nations to consume while leaving less for local consumption. Exports include services and goods produced in one nation and used in another. As a result, the receiving nation's CO_2 from exports must be emitted. Thus, EXP is anticipated to decrease CCO_2 emissions, i.e., $\beta_2 = \left(\frac{\theta CCO_2}{\theta EXP} < 0\right)$.

On the other hand, imports encompass services and goods manufactured by a foreign nation and used locally, and must release CO_2 domestically. It is projected that boosting exports will cut CCO_2 emissions in the host nation, whereas expanding imports will boost CCO_2 emissions in the recipient state. Aside from imports and exports, carbon emissions from the process of production are retained in the host nation [36,38,45,46]. Theoretically, an increase in imports is associated with increased consumption because it is regarded as one of the essential parts of any nation's overall consumption level, which is particularly true in the case of MINT nations. The MINT economies are emerging economies, and their imports include a significant share of intermediate and final services and goods consumed by the host economies. Several studies, such as [35,38,47], have already noticed this behavior. Thus, REC is anticipated to decrease CCO_2 emissions, i.e., $\beta_2 = \left(\frac{\theta CCO_2}{\theta IMP} > 0\right)$.

Likewise, GDP is a gauge of the economy's health and includes several parts, such as consumption, investment, government spending, and net exports. Since consumption accounts for the majority of GDP, increased consumption is positively related to CCO_2 emissions [48,49]. Thus, GDP is anticipated to increase CCO_2 emissions, i.e., $\beta_3 = \left(\frac{\theta CCO_2}{\theta GDP} > 0\right)$. The theoretical foundation for the renewable energy consumption and CCO_2 emissions negative connection is that renewable energy technologies use sustainable and greener energy sources that meet future and current demands [50,51]. Based on the above principles, renewable energy usage is predicted to reduce CO_2 emissions. Thus, REC is anticipated to decrease CCO_2 emissions, i.e., $\beta_5 = \left(\frac{\theta CCO_2}{\theta REC} < 0\right)$.

A stable financial market has the potential to support sustainable energy, which would be advantageous for the ecosystem. Likewise, some investigations contend that the stock market will help to preserve the ecosystem by increasing financial access, expanding financial networks, mobilizing the capital needed to invest in eco-friendly infrastructure and lowering manufacturing costs. According to some analyses, financial development may attract FDI and spur innovative research to enhance the ecosystem. As per [52], financial development may facilitate investment in energy conservation technologies to increase ecological integrity. On the other hand, some studies have cautioned that higher financial development may lead to more CO_2 [25,53]. According to [54], a stable financial system can encourage investment but also damage the environment by increasing energy use. Thus, financial development is anticipated to decrease CCO_2 emissions, i.e., $\beta_5 = \left(\frac{\theta CCO_2}{\theta FD} < 0\right)$ or increase CCO_2 if not eco-friendly, i.e., $\beta_5 = \left(\frac{\theta CCO_2}{\theta FD} > 0\right)$.

3.3. Methodology

Nonlinearities and structural break (s) are not considered by the traditional [55] causality test. Moreover, Ref. [56] improved the vector autoregression (VAR) model by including Fourier approximations to avoid causality analysis by ignoring structural breaks. This allowed for the inclusion of smooth structural break(s) in the causality analysis. Nevertheless, the method in [56] does not guard against information loss over the long term. As a result, the [57] causality test was updated by [58] to include the Fourier approximation to safeguard against long-term information loss and consider smooth structural modifications. In this approach, termed Fourier-TY, the technique of [59] is utilized as shown in Equation (1).

$$\alpha(t) = \alpha_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) \quad (1)$$

where sin and cos represent sine and cosine, optimal frequency is shown by k; the trend is depicted by t, the observation number is shown by T, and π is roughly equal to 3.145. The TY causality test in Equation (2) is replaced by α(t) in this Fourier approximation.

$$y_t = \alpha(t) + \delta_1 y_{t-1} + \ldots + \delta_{j+pmax} y_{t-(j+pmax)} + e_t \quad (2)$$

where the time intercept is denoted by $\alpha(t)$ time-dependent intercept, the optimal lag is denoted by j, the maximum integration order of variables is denoted by pmax, and the error term is shown by e_t. The presumption that the constant term does not shift with time is relaxed by [58] by replacing the Fourier approximation in Equation (1) for $\alpha(t)$. As a result, the TY causality test considers smooth structural transitions with an undetermined structure, date, and number, as depicted in Equation (3).

$$y_t = \alpha_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + \delta_1 y_{t-1} + \ldots + \delta_{j+pmax} y_{t-(j+pmax)} + u_t \quad (3)$$

In Equation (3), the cos and sin significance are evaluated with an F-test to help ascertain whether their coefficients are equal to 0 ($\gamma_1 = \gamma_2 = 0$). It is suitable to employ the Fourier approximation if the coefficients differ from 0. Therefore, the causality interrelationships between indicators can be evaluated as $\delta_1 = \ldots \delta_j = 0$.

While the FTY causality test initiated by [58] has several benefits, the conventional least squares approach is ineffective when the series is distributed normally and has a non-linear form. Hence, based on quantile regression, [27] recommended using the Fourier TY causality test. This novel method, termed "Bootstrap Fourier Granger causality in quantiles" (BFGC-Q), is shown below in Equation (4).

$$y_t(\tau|Z) = \alpha_0(\tau) + \sum_{k=1}^{n} \mu_1(\tau) \sin\left(\frac{2\pi k * t}{T}\right) + \sum_{k=1}^{n} \mu_2(\tau) \cos\left(\frac{2\pi k * t}{T}\right) + \delta_1(\tau) y_{t-1} + \ldots + \delta_{j*+pmax}(\tau) y_{t-(j*+pmax)} + v_t \quad (4)$$

where $k*$ and $j*$ are the optimal frequency and lag length, respectively, τ and Z represent a specific quantile and covariate matrix. The following can be used to test the null of non-causality in various quantiles by estimating Equations (5) and (6):

$$H_0 : \hat{\delta}_1(\tau) = \hat{\delta}_2(\tau) \ldots \hat{\delta}_{j*} = 0,\ \forall\, \tau \in (0,1) \quad (5)$$

$$Wald = \left[T\left(\left(\hat{\delta}(\tau)\right)'\right)\left(\hat{\Omega}(\tau)\right)^{-1}\left(\hat{\delta}(\tau)\right)\right] / \tau(1-\tau) \quad (6)$$

Following that, the BFGC-Q causality test's Wald statistics are computed. The critical values acquired from the bootstrap simulations are then contrasted with the Wald statistics gathered using Equation (6). The occurrence of causation can be determined if the Wald statistic for the relevant quantile is higher than the threshold value.

4. Empirical Results

4.1. Stationarity Test Results

In this paper, we employ the BFGC-Q method to test the causality between CCO_2 emissions and IMP, EXP, FD, GDP, and REC in the MINT nations, utilizing data between 1990Q1 and 2019Q4. The maximum integration order of the series is verified in the first phase of the investigation using conventional unit root tests, and the findings are presented in Table 3. The ERS and ADF unit root test findings uncover that all the indicators are stationary at the first difference (I(1)).

Table 3. Results of unit root tests.

	Mexico		Indonesia		Nigeria		Turkiye	
				ADF				
Variables	T-stat.	Lag	T-stat.	Lag	T-stat.	Lag	T-stat.	Lag
$\Delta LnCCO_2$	−5.583 *	8	−3.748 ***	8	−3.249 ***	8	−3.995 **	5
ΔLnGDP	−3.454 ***	7	−3.497 **	5	−3.350 **	7	−3.683 ***	8
ΔLnREC	−3.692 **	11	−3.401 ***	8	−4.385 *	9	−3.275 ***	8
ΔLnFD	−6.855 *	4	−3.612 ***	8	−3.224 ***	8	−4.639 *	5
ΔLnEXP	−4.714 *	7	−6.840 *	7	−3.669 **	12	−3.683 **	8
ΔLnIMP	−10.783 *	9	−4.396 *	8	−3.616 **	12	−3.976 **	8

Table 3. *Cont.*

	Mexico		Indonesia		Nigeria		Turkiye	
				ERS				
$\Delta LnCCO_2$	−5.747 *	6	−3.154 **	12	−3.273 ***	8	−3.153 ***	4
ΔLnGDP	−4.452 *	10	−3.396 ***	5	−3.284 **	6	−3.691 *	8
ΔLnREC	−2.858 ***	8	−2.770 ***	12	−3.190 **	8	−2.858 **	7
ΔLnFD	−4.139 *	4	−2.832 ***	8	−2.877 ***	8	−2.919 ***	4
ΔLnEXP	−2.975 ***	5	−6.846 *	7	−3.089 ***	12	−3.691 **	8
ΔLnIMP	−2.926 ***	12	−4.124 *	8	−2.935 **	12	−3.330 **	8

Note: *, ** and *** show the rejection of the null of unit root at 1%, 5% and 10% significance levels, respectively.

4.2. Cointegration

The current study proceeded by testing the cointegration between CCO_2 emissions and the regressors. In doing so, we used the bounds test with the results presented in Table 4. The outcomes disclose evidence of cointegration among the variables in each country.

Table 4. Bounds Test Results.

Countries	Models	F-Statistics	Lag Selection	Cointegration
Mexico	$LnCCO_2$ = f(LnGDP, LnIMP, LnEXP, LnREC, LnFD)	8.937 *	1, 2, 1, 1, 0, 0	Yes
Indonesia	$LnCCO_2$ = f(LnGDP, LnIMP, LnEXP, LnREC, LnFD)	5.971 *	1, 1, 1, 0, 2, 1	Yes
Nigeria	$LnCCO_2$ = f(LnGDP, LnIMP, LnEXP, LnREC, LnFD)	5.836 *	1, 0, 0, 2, 2, 1	Yes
Turkey	$LnCCO_2$ = f(LnGDP, LnIMP, LnEXP, LnREC, LnFD)	7.530 *	1, 2, 1, 1, 0, 0	Yes

Note: * depicts a significance level of 1%.

4.3. Fourier Test Results

In the second phase of the research, we analyze the Fourier terms' significance by utilizing the F-test (see Table 5), after the indicators' order of integration is affirmed. The results uncover that the Ho hypothesis of the absence of Fourier parts, i.e., $\gamma 1 = \gamma 2 = 0$, is dismissed at a significance level of 5% in the MINT nations.

Table 5. Results of F-test.

Models	Mexico	Indonesia	Nigeria	Turkey
Optimum Frequency	0.8	2.2	0.8	2.0
Optimum Lag	6	6	6	6
F-statistics for Fourier expansion	12.968 *	14.858 *	8.474 *	10.968 *
10% CV	10.211	12.032	6.184	7.211
5% CV	10.882	12.772	6.846	8.204
1% CV	11.317	13.460	7.503	8.995

Notes: * signify 1% levels of significance respectively. The optimal Frequency (k*) and optimal lag lengths (p*) were selected based on AIC.

4.4. Fourier Quantile Causality Results

In the final phase of the investigation, we apply the BFGC-Q test to examine the causal effects of imports, economic growth, exports, financial development, and renewable energy on consumption-based carbon emissions (CCO_2). The outcomes of the BFGC-Q causality test for the MINT nations are shown in Tables 6–9.

Table 6. Bootstrap Quantile Causality test (Mexico).

		H_0: LnGDP↛LnCCO$_2$		
quantile	Wald stat.	10% CV	5% CV	1% CV
0.1	31.978	63.388	67.092	81.577
0.3	26.653	51.287	52.845	61.023
0.5	25.818	51.568	56.829	67.076
0.7	17.751	64.849	73.141	101.56
0.9	**87.062 *** (+)**	82.583	87.108	117.63
		H_0: LnREC↛LnCCO$_2$		
0.1	9.0119	16.482	18.31736	23.171
0.3	**29.125 * (−)**	13.597	15.20117	21.076
0.5	**15.323 ** (−)**	11.576	14.42830	15.608
0.7	4.7447	14.835	16.14676	21.377
0.9	1.9978	27.162	28.40824	34.811
		H_0: LnEXP↛LnCCO$_2$		
0.1	8.3898	28.373	32.80566	55.1
0.3	7.6605	25.010	32.53499	36.648
0.5	**19.1422 *** (−)**	18.639	22.62982	24.484
0.7	**28.5644 *** (−)**	27.881	33.61882	41.403
0.9	11.895	32.187	34.80926	46.525
		H_0: LnIMP↛LnCCO$_2$		
0.1	13.146	20.018	21.44194	26.673
0.3	**9.0842 *** (+)**	8.7170	10.36571	15.382
0.5	**9.8575 *** (+)**	7.5424	9.569465	10.425
0.7	4.0832	8.2339	9.546957	14.768
0.9	13.324	15.074	17.28618	26.622
		H_0: LnFD↛LnCCO$_2$		
0.1	12.64739	24.178	29.077	38.807
0.3	**13.80425 *** (+)**	12.672	13.942	19.690
0.5	6.280467	9.9456	13.971	16.627
0.7	2.005601	12.055	13.820	17.593
0.9	2.778037	17.914	18.573	23.587

Note: ***, ** and * denote the dismissal of the null of no-causality at and 10%, 5% and 1% significance levels, respectively. CV represent critical values. (+) and (−) illustrate positive and negative effects.

Table 7. Bootstrap Quantile Causality test (Indonesia).

		H_0: LnGDP↛LnCCO$_2$		
quantile	Wald stat.	10% CV	5% CV	1% CV
0.1	**155.016 *** (+)**	152.07	169.6371	182.03
0.3	54.3869	115.58	150.2648	163.12
0.5	53.3321	104.68	112.4484	136.03
0.7	64.3851	142.37	159.7852	170.04
0.9	76.1747	222.61	241.0449	316.92

Table 7. *Cont.*

		H_0: LnREC↛LnCCO$_2$		
0.1	**46.606 ** (−)**	41.780	46.295	113.77
0.3	**29.447 *** (−)**	28.860	31.215	43.643
0.5	9.5617	22.751	25.283	50.833
0.7	4.6260	26.136	29.177	64.730
0.9	12.265	39.507	51.031	75.474
		H_0: LnEXP↛LnCCO$_2$		
0.1	8.7534	173.89	182.84	218.72
0.3	4.7759	149.94	163.65	183.70
0.5	4.8257	136.53	157.20	167.85
0.7	2.0517	146.86	166.26	205.21
0.9	6.7543	175.68	206.35	253.02
		H_0: LnIMP↛LnCCO$_2$		
0.1	8.5628	177.87	187.94	211.6
0.3	1.9128	74.241	100.72	148.80
0.5	5.5059	37.284	38.902	72.992
0.7	1.9302	32.128	46.606	51.729
0.9	5.085	47.377	58.787	72.820
		H_0: LnFD↛LnCCO$_2$		
0.1	**102.967 * (+)**	56.141	67.663	97.104
0.3	**40.66 ** (+)**	25.050	27.437	42.239
0.5	9.0807	14.700	19.357	35.294
0.7	7.4778	19.663	25.182	30.660
0.9	36.756	45.243	50.380	73.003

Note: ***, ** and * denote the dismissal of the null of no-causality at and 10%, 5%, and 1% significance levels, respectively. CV represents critical values. (+) and (−) illustrate positive and negative effects.

Table 8. Bootstrap Quantile Causality test (Nigeria).

		H_0: LnGDP↛LnCCO$_2$		
quantile	Wald stat.	10% CV	5% CV	1% CV
0.1	27.220	43.719	49.391	57.726
0.3	**45.567 ** (+)**	32.852	37.150	47.866
0.5	**32.972 *** (+)**	31.719	33.170	46.260
0.7	**48.859 *** (+)**	35.334	41.658	51.812
0.9	15.253	42.8749	43.440	50.842
		H_0: LnREC↛LnCCO$_2$		
0.1	**19.316 *** (−)**	18.620	20.738	26.566
0.3	**17.158 *** (−)**	15.859	22.644	24.593
0.5	8.8579	17.022	20.349	33.701
0.7	10.757	25.134	30.30	61.526
0.9	14.192	38.486	45.18	59.555

Table 8. *Cont.*

		H_0: LnEXP↛LnCCO$_2$		
0.1	24.551	31.168	33.907	56.850
0.3	12.032	17.394	21.465	29.676
0.5	5.7322	12.492	13.865	16.700
0.7	4.7990	11.424	14.101	17.905
0.9	**29.685** *** **(−)**	24.913	29.192	33.831
		H_0: LnIMP↛LnCCO$_2$		
0.1	2.4349	11.527	13.534	23.828
0.3	3.5846	7.1759	8.6019	9.5594
0.5	3.5608	6.0437	8.5011	11.572
0.7	5.5401	7.2298	9.7265	10.753
0.9	4.3756	18.724	19.768	28.575
		H_0: LnFD↛LnCCO$_2$		
0.1	10.564	24.939	30.925	32.743
0.3	5.6160	15.779	22.195	35.045
0.5	**19.540** ** **(+)**	11.978	15.302	21.349
0.7	13.008	16.530	20.794	22.502
0.9	19.834	27.332	29.549	45.254

Note: ***, and ** denote the dismissal of the null of no-causality at and 10%, and 5% significance levels, respectively. CV represent critical values. (+) and (−) illustrate positive and negative effects.

Table 9. Bootstrap Quantile Causality test (Turkey).

		H_0: LnGDP↛LnCCO$_2$		
quantile	Wald stat.	10% CV	5% CV	1% CV
0.1	36.428	66.243	80.359	86.919
0.3	28.057	49.487	60.666	63.138
0.5	18.002	40.485	46.294	56.863
0.7	**44.586** *** **(+)**	44.487	49.658	53.456
0.9	18.721	47.58500	57.543	73.676
		H_0: LnREC↛LnCCO$_2$		
0.1	10.197	39.429	53.859	67.185
0.3	5.2158	25.054	27.767	33.596
0.5	**31.358** * **(−)**	19.444	20.862	30.186
0.7	**25.154** ** **(−)**	20.586	24.542	36.920
0.9	5.9246	38.479	42.183	54.410
		H_0: LnEXP↛LnCCO$_2$		
0.1	5.2356	41.212	46.597	60.857
0.3	**72.227** ** **(−)**	34.444	36.143	47.222
0.5	**30.658** *** **(−)**	30.024	31.161	50.435
0.7	**43.076** ** **(−)**	32.715	36.800	43.846
0.9	125.51	43.520	46.856	73.936

Table 9. *Cont.*

		H_0: LnIMP↛LnCCO$_2$		
0.1	6.6256	26.208	45.458	93.274
0.3	12.670	17.397	17.999	40.338
0.5	**24.698 * (+)**	16.254	20.574	21.229
0.7	14.644	19.519	25.487	31.232
0.9	22.369	36.157	44.813	80.656
		H_0: LnFD↛LnCCO$_2$		
0.1	19.485	23.438	25.57	34.017
0.3	4.3859	14.253	18.2903	22.908
0.5	10.468	13.323	15.213	18.944
0.7	10.041	16.003	16.681	19.989
0.9	8.4628	27.354	34.427	47.014

Note: ***, ** and * denote the dismissal of the null of no-causality at and 10%, 5% and 1% significance levels, respectively. CV represent critical values. (+) and (−) illustrate positive and negative effects.

The outcomes of the BFGC-Q causality test for Mexico are depicted in Table 5. The outcomes reveal unidirectional causality from economic growth to CCO2 emissions in the higher quantiles (0.90). Likewise, in the lower (0.30) and middle (0.50) quantiles, unidirectional causality from renewable energy to CCO_2 emissions surfaced. Furthermore, a unidirectional causality emerged in the middle (0.50) and higher (0.70) quantiles from exports to CCO_2 emissions. Moreover, in the lower (0.30) and middle (0.50) quantiles, unidirectional causality from imports to CCO_2 emissions emerged. In the middle quantile (0.30), financial development Granger cause CCO_2 emissions. These results disclose that the interrelationship between financial development, imports, economic growth, exports, and renewable energy is sensitive to quantiles.

Regarding the sign of the effect, economic growth impacts CCO_2 positively in Mexico. This result is anticipated, given that Mexico is a developing nation, and initiatives towards economic expansion are often favored at the expense of the ecosystem. A similar result in the case of Mexico is documented by [60,61]. Furthermore, we observe the negative effect of clean energy on CCO_2, which is as expected. This shows that renewable energy use in Mexico contributes to a significant reduction in CCO_2 emissions. This outcome is as anticipated given the recent development in Mexico's renewable energy. According to the Mexican government's energy growth plan, 328,597.98 GWh of electricity were produced in Mexico in 2021, with 29.5% of that energy coming from renewable sources, including efficient cogeneration, solar photovoltaic, wind, biofuel, geothermal, nuclear power, and hydroelectric. Wu et al. [8,62,63] reported similar results. Moreover, the effect of imports on CCO_2 is positive while the effect of exports on CCO_2 is negative, which corroborates the theoretical framework. The results also disclosed that financial development impacts CCO_2 positively, suggesting that an upsurge in financial development triggers the intensification of CCO_2. The studies [64,65] documented similar findings. Figure 2 portrays the summary of findings for Indonesia.

Table 7 presents the causal/interrelationship between CCO_2 and the regressors in Indonesia. We fail to accept the Ho hypothesis of no causality from GDP to CCO_2 emissions in each quantile. This finding shows that GDP has predictive power over CCO_2 in each quantile. Furthermore, in the lower quantile (0.1–0.30), renewable energy has predictive power over CCO_2 emissions, which is in line with the studies of [2,22,66]. Surprisingly, exports and imports do not have predictive power over CCO_2 in each quantile. These outcomes contradict the studies [31,67]. At the lower tails (0.10–0.30), we find causality from financial development to CCO_2, suggesting that financial development has predictive power over CCO_2.

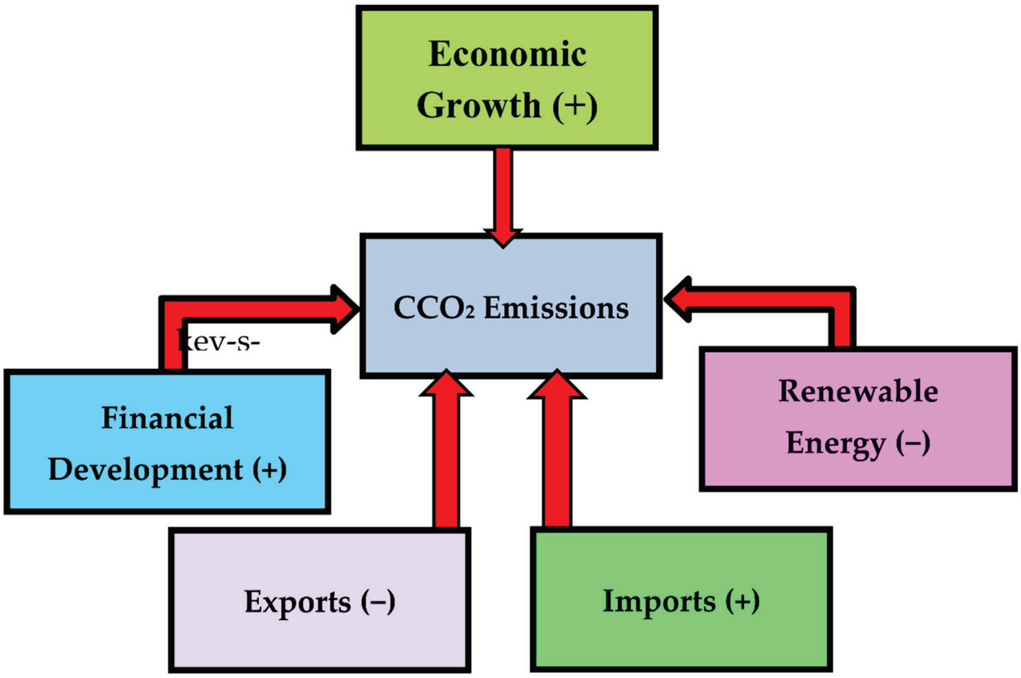

Figure 2. BFGC-Q results for Mexico.

Regarding the sign of the interrelationship, we found a positive effect of economic growth on CCO_2. Similar to Mexico, Indonesia is a developing nation where priority is given to constant economic expansion while neglecting ecological sustainability. For instance, between 1999 and 2019, Indonesia witnessed a 115% increase in GDP (World Bank, 2022). This growth is accompanied by a 76% increase in CO_2 emissions per capita (World Bank, 2022, https://data.worldbank.org/country/indonesia, assessed on 5 January 2022). Furthermore, the decreasing effect of renewable energy on CCO_2 suggests that the intensification of green energy upsurges ecological quality in Indonesia. The investment in renewable energy in Indonesia is responsible for this favorable impact of renewable energy on ecological quality. For instance, as of April 2021, Indonesia's energy mix had 13.83% renewable energy, with hydropower accounting for 7.9%, geothermal for 5.6%, and other renewable energy providing 0.33% (https://www.ashurst.com/en/news-and-insights/legal-updates/indonesia-renewable-energy-laws-and-regulations-2022/, assessed on 4 October 2022). Indonesia contributes approximately 12% of the country's renewable energy. Indonesia can only achieve this goal by shifting energy investment toward renewable resources. Shahbaz et al. [9,68,69] documented similar findings. Similar to Mexico, imports and exports do not significantly influence CCO_2 emissions, which is in line with the studies of [64], who found an insignificant connection between CO_2 and financial development in Malaysia. Figure 3 portrays the summary of findings for Nigeria.

Table 8 presents the causal/interrelationship between CCO_2 and the regressors in Nigeria. In the lower (0.3), middle (0.50), and higher (0.70) quantiles, a unidirectional causality emerged from GDP to CCO_2 emissions, which is similar to the results obtained for Mexico and Indonesia. Furthermore, in the lower (0.1–0.30) tails, renewable energy Granger cause CCO_2 in Nigeria, demonstrating the predictive power of renewable energy over CCO_2. Similar to Mexico, exports have predictive power over CCO_2 emissions in the extreme higher (0.90) quantile.

The sign of the relationship shows that economic growth upsurges CCO_2 which is expected given that Nigeria is an emerging nation. Emerging nations such as Nigeria are pro-growth, which implies that they are pro-growth in their policies. Little or no attention is given to their ecosystem. The studies [1,61] documented similar results. Likewise, the negative effect of green energy is observed, demonstrating that clean energy boosts ecological integrity in Nigeria. The findings of [29,33] comply with this finding. Similarly, exports boost ecological quality as shown by the negative effect of exports on CCO_2 which is in line with the study of [26]. Lastly, financial development contributes to the devastation of the ecosystem, as shown by the positive effect of financial development on CCO_2. The studies [29,34] documented similar findings. Figure 4 portrays the summary of results for Turkey.

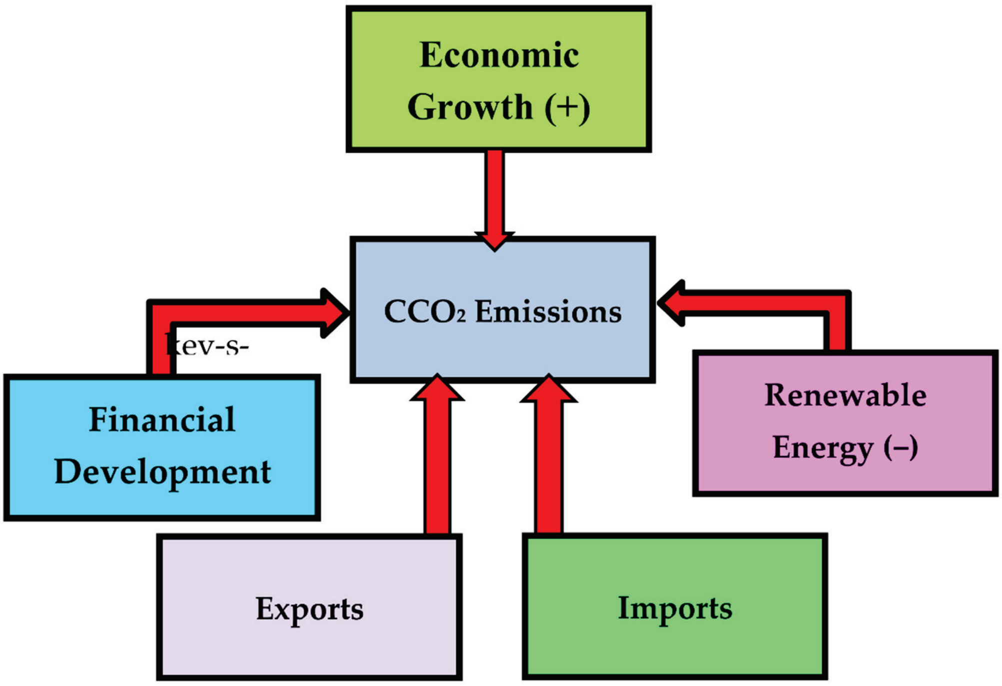

Figure 3. BFGC-Q results for Indonesia.

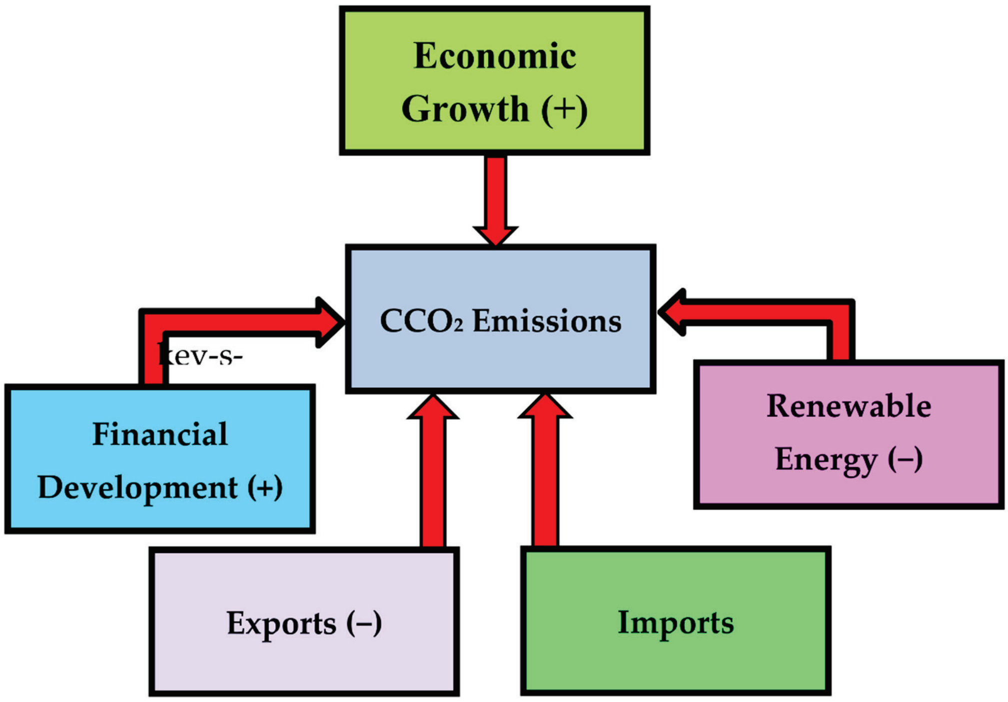

Figure 4. BFGC-Q results for Nigeria.

Table 9 presents the causal/interrelationship between CCO_2 and the regressors in Turkey. In the higher (0.70) quantile, a unidirectional causality surfaced from GDP to CCO_2 emissions, similar to the results obtained for Mexico, Nigeria, and Indonesia. In the middle (0.5) and higher (0.70) tails, renewable energy has predictive power over CCO_2. Moreover, we observe a unidirectional causality from exports to CCO_2 in the middle (0.50) and higher (0.70) quantiles. Likewise, in the middle (0.50) quantile of imports, Granger causes CCO_2 emissions.

Regarding the effect, economic growth impacts CCO_2 positively, which is anticipated given that Turkey is an emerging nation. Emerging nations such as Turkey need to improve the standard of living of their citizens. As a result, they always prefer increasing their GDP while paying less attention to environmental sustainability. For instance, Turkey witnessed 92% economic growth between 1999 and 2019. This growth is accompanied by a 54% increase in CO_2 emissions per capita [70]. Prior studies [25,63,71] reported similar results. Moreover, the effect of clean energy on CCO_2 is negative, as expected, demonstrating that renewable energy boosts the integrity of the environment in Turkey. Over the previous five years, Turkey's renewable energy capacity increased by 50%. The year 2019 saw Turkey add the 5th highest amount of new renewable capacity in Europe and the 15th highest globally. Given its abundant resource endowment, Turkey, according to the IEA research, may attain even higher growth in renewables, particularly wind, solar, and geothermal energy. Its robust prospect for expanding renewable energy sources applies to the heating industry and power generation. Importantly, Turkey employs barely 15% of its onshore wind capacity and an estimated 3% of its solar potential. With expenditures reaching about USD 7 billion, Turkey built the highest renewable capacity in a single year in 2020, at around 4800 megawatts (MW) (https://www.iea.org/news/turkey-s-success-in-renewables-is-helping-diversify-its-energy-mix-and-increase-its-energy-security, assessed on 10 September 2022). This outcome aligns with the studies of [72,73] for Turkey; however, the study of [74] contradicts this finding.

As expected, the effect of exports on CCO_2 is negative, demonstrating that intensification in Turkey's exports boosts ecological quality. A similar result is documented by the studies [1,75]. Furthermore, Turkey's imports contribute to ecological quality decrease, as shown by the negative sign. The studies [4,71] also reported similar results. Lastly, an insignificant nexus exists between financial development and CCO_2 emissions, which is anticipated given that Turkey's financial system is in the initial phase. At this phase, financial development is expected not to boost EQ. The research of [64] also documented similar results. Figure 5 presents the summary of results.

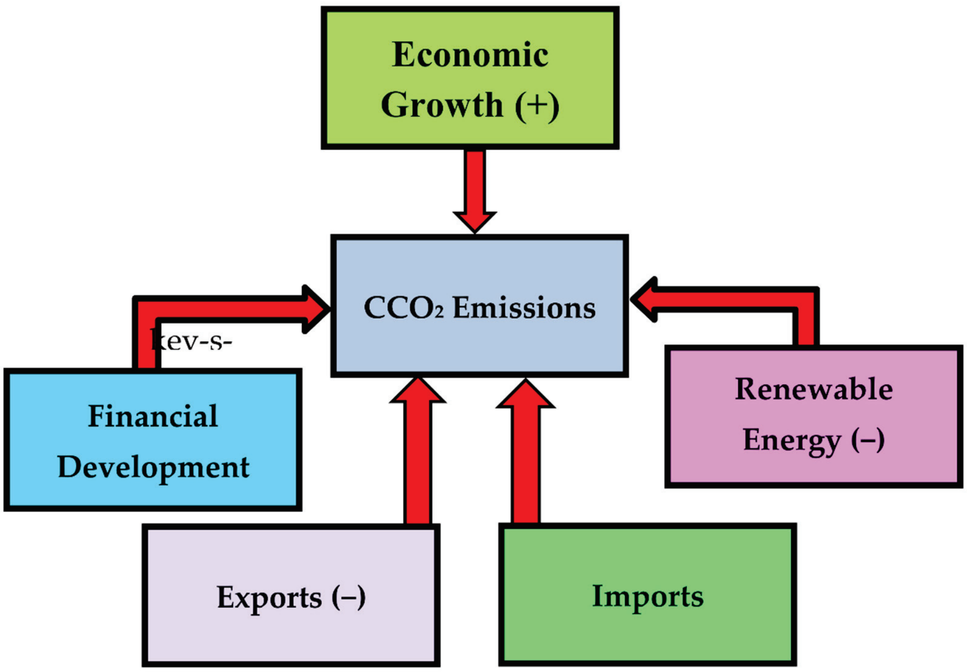

Figure 5. BFGC-Q results for Turkey.

5. Conclusions and Policy Ramifications

5.1. Conclusions

The MINT (Mexico, Indonesia, Nigeria, and Turkey) nations are among the top energy consumers and emitters of CO_2 emissions. Notwithstanding the well-known Kyoto Protocol and Paris Accord, the globe's temperature is rising, and CO_2 emissions are at an all-time high. This has prompted scholars to look into the undiscovered factors that influence CCO_2 emissions. In the literature, energy trade and consumption are well-known major contributors to CO_2 emissions. Nonetheless, renewable energy is among the most effective strategies to reduce CO_2 emissions. Therefore, to promote sustainable development, nations all over the globe are choosing eco-friendly strategies. The study utilizes BFGC-Q for the MINT nations between 1990Q1 and 2019Q4. This approach produces tail-causal and asymmetric causal connections between the indicators within the Fourier approximation, in contrast to the Toda–Yamamoto causality and other conventional Granger tests. The outcomes uncover a unidirectional causality from economic growth and renewable energy to CCO_2 emissions in each MINT nation.

5.2. Policy Ramifications

This paper's conclusions suggest that domestic consumption levels should be prioritized, particularly in those more energy-intensive sectors contributing to rising carbon emissions, to lessen the impact of imports and economic expansion on CCO_2. Initiatives that do not impede trade and simply focus on reducing carbon emissions should be used to curb emissions-oriented imports. Since transportation and production machinery make up most of these nations' imports, these nations should prioritize acquiring eco-friendly manufacturing equipment, which would lessen the impact of import emissions and the externality effect brought on by exports via trade. The role of the governmental initiative to completely assimilate it will be realized via international trade and CCO_2 emissions initiatives. Moreover, taxing imported products that produce a lot of emissions would raise funds, tighten ecological rules and reduce import emissions. However, such a policy ramification might not be ideal.

Secondly, using renewable energy drastically reduces CCO_2 emissions in the MINT nation. So, in terms of energy consumption, non-renewable energy or fossil fuel should be reduced, and green energy should be given priority to lower CCO_2 emissions. In this context, additional funding is required to expand the sources of clean energy through supporting wind, hydro, and solar energy, as well as by encouraging and providing incentives for the general public to use energy-efficient appliances and technologies. For this, developing and implementing an appropriate energy policy is necessary. Thirdly, CO_2 emissions rise as the economy expands. Thus, a major factor in reducing CO_2 emissions is the execution of inclusive economic development, growth, and initiatives that do not affect the environment. Moreover, sustainable development will be ensured through green technology implementation, green growth, green urbanization, and green industrialization. Fourth, export quality reduces CCO_2 emissions. Therefore, emphasizing cleaner, more effective, and eco-friendly industrial practices for producing goods promises to reduce CO_2 emissions. In light of this, extensive and broad-based policy initiatives focused on improving export quality will be useful for enhancing ecological integrity in these nations without compromising the intended economic expansion.

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Article

How Do Institutional Quality, Natural Resources, Renewable Energy, and Financial Development Reduce Ecological Footprint without Hindering Economic Growth Trajectory? Evidence from China

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Abstract: Institutional quality, financial development, and natural resources primarily determine how economic representatives support their operational and production behaviors towards escalating the renewable energy share in the whole energy mix and protecting ecological quality. In this way, this paper is the first to investigate the influence of institutional quality, natural resources, financial development, and renewable energy on economic growth and the environment simultaneously in China from 1996 to 2020. The cointegration approaches verify the presence of a long-run association between the selected variables. The autoregressive distributed lag model outcomes reveal that institutional quality and renewable energy utilization greatly diminish ecological footprint. At the same time, other prospective indicators such as financial expansion and natural resources significantly enhance ecological footprint levels in the short- and long-run. Furthermore, institutional quality, financial expansion, renewable energy, and natural resources significantly trigger economic growth. Besides this, this study has revealed the unidirectional causal association from institutional quality and financial expansion to ecological footprint. In contrast, bidirectional causality occurs between renewable energy, natural resources, ecological footprint, and economic growth. The current research results offer some policy implications that will help to reduce the detrimental influence of environmental deprivation, without hindering the economic growth trajectory in the case of China.

Keywords: ecological footprint; institutional quality; natural resources; financial development; economic growth; China

1. Introduction

In the current era, one of the primary objectives in a global society is to diminish the amount of environmental pollution, especially concerning carbon emissions threatening human health. On the other hand, the economic expansion goal is also key for all emerging and high-income nations seeking to increase the living standards of their people. Since 1990, intermediary/transitional economies, such as China, have made significant transformations in their social and economic structures, and achieved elevated growth rates. During this procedure, China's economy has increased the deployment of energy-intensive resources, such as fossil fuels (e.g., oil, gas, and coal). Their contribution to global environmental pollution increased manifold. Owing to significant greenhouse gas emissions, the sustainable development goal does not seem pragmatic in the short term.

In 1949, the Chinese Communist Party came into power, and initiated reforms in the late 1980s. China has become the world's fastest-growing country, with a constant growth rate of approximately 9%. Trade openness is approximately 38% of the GDP in China, it being the biggest exporter and second-leading importer of goods in the world, which is remarkable [1]. In the early 1950s, economists found that countries that were rich in resources grew slower compared to those deprived, which is a question of concern. Resources are the base of development. Those nations that are abundant in natural resources are more capable of converting resources into development, so more production leads to more exports. Countries that enjoy a wealth of natural resources tend to have more incentives to avoid economic diversification (Dunning, 2005).

It can be observed that strong institutions lead to a strong nation and a base of economic development for that country. Differences in regional growth are basically due to institutional differences. The natural resource growth in a country creates two types of effects; one is the output effect, and the other is an institutional effect [2,3]. The Heckscher–Ohlin theory and bulk product theory support the argument that a country abundant in natural resources can promote growth better than those with less abundant resources [4]. In contrast, this is not seen as valid in all cases. The countries endowed with natural resources are less economically developed compared to developed economies that are less abundant in natural resources. In China, natural resources are not evenly distributed between provinces and coastal areas such as Jiangsu, which has educated its people to develop more natural and human resources to improve industrial productivity. Theories have been devised regarding this question, primarily the Dutch disease model [5] and institutional quality.

Several studies have investigated the significance of institutional excellence, as a result of which abundant resources may increase economic growth and thus lead to corruption and rent-seeking actions [6–9]. In this regard, Ross [10] argued that institutions can endogenously encourage economic growth via resource endowments. However, the existing literature claims that institutional excellence can explain many cross-country differences in economic expansion [11]. The quality of institutions varies between provinces in a country. In China, provinces have homogeneous legal and constitutional systems, while institutional superiority differs from a historical perspective.

Furthermore, conventional and new economic theories have extensively addressed economic development. Current studies on institutional economics have attempted to provide a framework for institutional quality and the measurement of this qualitative subject [12]. A high-quality institutional framework increases the growth pace by incentivizing economic activities, for instance, improving efficiency and resource allocation more competently. Protecting property rights and reducing transaction costs and rent-seeking behavior supports freedom of choice, and eases economic growth scenarios [13].

Environmental deprivation occurs owing to the unnecessary deployment of natural resources to prepare and extract diverse raw substances/materials that directly affect the atmosphere, such as via water shortfalls, soil erosion, halting biodiversity, worldwide warming aggravation, and the destruction of environmental capacities. The consumption of such raw substances has become the primary source of greenhouse gas (GHG) emissions in the atmosphere. In contrast, the deployment of natural resources has a twofold impact on GDP growth: the prompt use of natural resources boosts the production level and intensifies the diminution rate. The consumption of natural resources has particular effects on diverse investors that stipulate GDP growth. Conversely, the excessive use of (overexploited) natural resources also increases the exhaustion rate and rapidly reduces resources. Overdependence on the consumption of natural resources is not a helpful approach for achieving a sustainable environment and economic development [14].

The studies also found an indirect effect of institutional value on economic growth through trade openness. Institutional quality has strengthened economic growth, giving rise to trade as the best institutional value. Conversely, developing economies have fewer trade advantages, raising concerns about the reduction in institutional value. Institutional quality escalates economic growth and facilitates technology and knowledge transfer among the countries. It is essential and time-consuming to discover the association within the natural resource, growth, energy, institutional quality, and environmental nexus. Institutions are different from one another. They have their mechanisms and policy statements. Finally, the authors conclude that institutions have specific characteristics, so comprehensive analysis is required based on theoretical and empirical analysis to derive robust results regarding their impact on growth and the environment in the presence of energy and natural resources. The main novelty of this paper is that, from an analytical and theoretical perspective, the institutional factors, along with financial development, energy use, and natural resources, are assessed in relation to economic growth and the environment simultaneously, which is under-investigated in the existing literature. Secondly, renewable energy is used in exploring this nexus, because China is paying more attention to this factor, and trying to achieve growth along with a stable environment. The novelty of this study is that it provides new arguments regarding the influence on economic growth of renewable energy, financial expansion, institutional quality, and natural resources in both the short- and long-run. In the most recent literature, institutional economics has emerged in determining economic growth and the environment, and recent studies have tried to determine the impact of institutional quality on the environment. The outlook of this research is an effort to explore this nexus in the case of the Chinese economy.

Moreover, economic growth theories, models, and their quantitative impact via human capital, physical capital, labor, and technology have been analyzed. However, in recent times, it has been observed that institutional quality, financial expansion, and natural resources have a strong effect on the environment and economic growth. Hence, this study tries to investigate how institutional quality, natural resources, alternative and renewable energy use, and financial progress trigger economic activities and protect ecological excellence in the case of China.

The remaining sections of the present research are reported as follows: Section 2 contains a literature review. The data, economic modeling, and methods are explored in Section 3. Empirical findings and the discussion are given in Section 4, and further, this section outlines the robustness checks. Finally, the conclusion and policy suggestions are provided in Section 5 accordingly.

2. Review of Literature

The attempt to reduce ecological footprints and protect the environment is essential today. Studies that analyze the relationship between economic growth and variables such as human capital, physical capital, and natural resources are becoming increasingly essential. The works in the literature show the different statistical methods used, highlighting the wide variety of possible methods, such as Panel ARDL or the Generalized Method of Moments.

Several studies argue that energy affects country growth [15–17]. Ji et al. [18] analyzed the interaction among natural resource abundance, GDP growth, and institutional excellence. They found that natural resources have a constructive influence on economic growth in the case of China. Similarly, Asghar et al. [19] attempted to elucidate the influence of institutional value on GDP growth in emerging Asian nations using panel ARDL. This study found that institutional eminence significantly enhances GDP growth. Moreover, Nguyen et al. [20] observed the effects of institutional worth on GDP growth for 29 developing countries from 2002 to 2015 through sys-GMM (Generalized Method of Moments) estimators. The empirical outcomes revel that institutional quality boosts economic growth.

Conversely, Poshakwale and Ganguly [21] analyzed the transmission channels of international shocks on the GDP growth of developing markets, and found that the mean impact of international shocks on developing markets' growth is insignificant. However, there is variation both over time and across sections. Taken as a whole, there is an important effect on GDP growth. Chan et al. [22] examined the moderating role of institutional structure on the impact of market attentiveness in ASEAN-5 countries (Indonesia, Malaysia, the Philippines, Singapore, and Thailand). They observed that higher bank attentiveness diminishes the competence level in the case of commercial banks. They used the Slack-Based Measures Data Envelopment Analysis and the Generalized Method of Moments system.

On the other hand, an improved institutional structure considerably advances bank competence, which results in higher industry concentration. An institutional system can affect a firm's choices. In contrast, in countries with low legal institutional quality and economic development, imports of technological equipment have an insignificant impact on provincial innovation potential [23]. Similarly, in developing countries, Peres et al. [24] showed that the impact of institutional excellence is not significant because of the weak institutional structure, and governance indicators tend to be key in attracting the inflow of foreign investment. The role of institutions at the provincial level is also analyzed in the literature. For example, using panel data, Qiang and Jian [25] employed provincial longitudinal data from 2005 to 2018, and categorized institutional indicators by the degree of market openness, market resource allocation, and property rights diversification. The authors show that the "resource curse" proposition is appropriate for provincial-level data in China.

Furthermore, it was found that increasing market openness could ease the resource curse in all studies, with mixed results. In this context, Tsani [26] studied the association between governance, institutional excellence, resource funds, and their role in tackling the resource curse. They harmonized the debate on the resource curse and institutional quality and governance determinants. They found that resource funds are important when addressing the worsening of governance and institutional quality as a result of resource wealth. Similarly, Shuai and Zhongying [27], based on the resource curse hypothesis, revealed a negative relationship between real income growth and energy utilization. However, a sector-wise study of institutional excellence and income growth in African and Asian countries found contrary results.

In the context of financial expansion, Jalil and Feridun [28], using the autoregressive distributed lag (ARDL), inspected the role of financial improvement in influencing environmental deprivation in the case of China. The outcomes show that financial development has led to reduced environmental degradation. However, the environmental Kuznets curve (EKC) relationship is valid in the case of China. The EKC hypothesis holds that the relationship between environmental degradation and per capita income follows an inverted U-shaped path. Similarly, Al-Mulali et al. [29] found that financial growth promotes atmospheric quality worldwide. Adebanjo and Shakiru [30] found that the EKC shows that economic growth has positively and negatively impacted Jordanian air pollution. In contrast, Boutabba [31] reported that a robust financial sector significantly increases CO_2 emissions.

Additionally, the Granger causality test reports that unidirectional causality pertains from financial expansion to energy utilization and CO_2 emissions in the case of the Indian economy. In a massive study by Omri et al. [32], found a similar bidirectional causality between CO_2 emissions and real income was observed. This study also considered the long-term link between real income, financial expansion, and carbon emissions for MENA countries. The findings of the simultaneous equation model reveal that bidirectional causality exists between CO_2 emissions and real income growth. In this regard, Zaidi et al. [33] indicated that the financial progress of an economy encompasses purchasers, and attains reliability and durability in commodities, which enhances the overall energy demand and environmental damages.

Early studies, such as that of Hartwick [34], argued that natural resource wealth positively affects the production of renewable energies, as it would increase the capital available for investment. There are also works focusing on some specific areas, such as that of Baloch et al. [35] for BRICS, which shows that natural resources are not environmentally friendly in the case of South Africa due to the unsustainable consumption of natural resources. Adebanjo and Adeoye [36] concluded that natural resources significantly negatively influence economic growth in 10 sub-Saharan African countries. The abundance of natural resources tends to favor renewable energy production in a country. Still, certain natural resources, such as oil, can be detrimental due to their potentially corrosive effect on the economy and governance [37]. Dagar et al. [38] demonstrated that renewable energy consumption and natural resources contribute to reducing environmental degradation. In addition, they assert that financial development, GDP growth, and natural resources promote expansion in cleaner energy diligence, and enable governments and policy makers to reduce pollution levels.

Epo and Faha [39] probed the functions of institutional quality, natural resources, and income growth in 44 African economies from 1996 to 2016. They a conducted cross-sectional instrumental variables analysis, dynamic panel data instrumental variables regression, and panel smooth transition regression. The connection between real income growth and natural resources varies with natural resources and institutional quality measures. Egbetokun et al. [40] concluded in the case of Nigeria that institutional value protects environmental quality in the context of the economic growth trajectory. Furthermore, Khan et al. [41] studied the financial development and natural resource nexus by assessing the critical role of institutional superiority using ARDL dynamic simulations. The results reveal that natural resource have an adverse impact on financial expansion.

Furthermore, institutional excellence has a moderate impact on resource finance, while the threshold level of the impact is ambiguous sometimes; it is sometimes positive and sometimes negative. Conversely, the impact of institutional quality and financial expansion on the environment was investigated by Godil et al. [42], who found that institutional quality has a constructive impact on carbon emissions in the long-run. Moreover, the ICT sector and financial development have adverse impacts on carbon emissions. Similarly, Elsalih et al. [43] inspected the association between environmental performance and institutional value in 28 oil-producing economies from 2002 to 2014, revealing that institutional excellence plays a vital role in enhancing ecological performance, and supporting the theoretical background of the EKC hypothesis. In addition, Yousaf et al. [44] studied the impact of the ecological footprint of energy and fossil consumption in the case of Pakistan using ARDL and fully modified ordinary least squares (FMOLS). They found that fossil fuel is a leading factor in environmental degradation. Population growth and fossil fuel negatively impact the environment. In the same context, in the case of China, the ecological footprint increases growth driven by fossil fuels. The study explored this issue within the literature, but hardly found any studies examining the associations between institutional quality, financial expansion, natural resources along with renewable energy, and ecological footprints to investigate the impact of environmental degradation and income growth simultaneously in China. Therefore, this research is an attempt to expand the literature on the subject in the Chinese context.

3. Data, Model, and Methodology

3.1. Data and Functions Description

The major objective of this paper is to discover the influence of institutional quality, financial expansion, natural resources, and renewable energy on ecological footprint and economic growth from 1996 to 2020 in China. Regarding the description of the variables, institutional quality (INSQ) represents a broad concept that encompasses law, individual rights, regulation, and high-quality government services. This paper measures institutional quality based on the international country risk guide (ICRG) index. This index is based on 22 variables encompassing three risk groups: political, financial, and economical. This index is calculated for each of these groups (the political risk index is based on 100 points, the financial risk index on 50 points, and the economic risk index on 50 points), from which the ICRG index is obtained. The index scores range from 0 to 100, with low risk from 80 to 100 points and very high risk from 0 to 49.9 points.

Financial expansion is the capacity to strengthen the financing of a country, region, or company. The authors define financial development as financial credit offered by the financial sector as the % of GDP [45]. Furthermore, natural resources are raw materials found in nature that can be used for production or consumption. We measure natural resources, NR, via natural resource rent which is a ratio of all natural resource rents to GDP calculated as Constant 2010 USD. It comprises coal, oil, mineral, gas, and forest rents. The authors applied this proxy for a couple of reasons. Firstly, this is the most suitable proxy for resource revenue because it measures resource revenues that are extra effective for rent-seeking, etc. Secondly, this proxy has been extensively used in recent literature [46].

For the comprehensive analysis, we have used two models; one is used to discover the impact of the variables mentioned above on growth, and the second model is used to find the effect of such time series on the environment. Table 1 explores the study variables' description and the data source.

$$\textbf{Model 1: } \mathrm{EFP} = \mathrm{f}\,(\mathrm{INSQ}, \mathrm{FD}, \mathrm{NR}, \mathrm{REN}) \quad (1)$$

$$\textbf{Model 2: } \mathrm{GDP} = \mathrm{f}\,(\mathrm{INSQ}, \mathrm{FD}, \mathrm{NR}, \mathrm{REN}) \quad (2)$$

Table 1. Variables' description and data source.

Acronyms	Variables	Description	Variables Justification
GDP	Gross domestic product	Constant 2010 USD	[19,30,32,45,47]
INSQ	Institutional quality	ICRG index	[9,23,46,48,49]
FD	Financial development	Domestic credit to the private sector (% of GDP)	[29,50–52]
NR	Natural resource rents	% of GDP	[25,53–56]
REN	Renewable energy use	Share of all final energy use	

Equations (1) and (2) explain the functional relation of dependent and independent variables. To address the issues of heteroscedasticity, scale equivalence, data sharpness, and autocorrelation, this study transformed the model into a logarithmic form.

$$\mathrm{Ln}(\mathrm{EFP_t}) = \alpha_0 + \alpha_1\mathrm{Ln}(\mathrm{INSQ_t}) + \alpha_2\mathrm{Ln}(\mathrm{FD_t}) + \alpha_3\mathrm{Ln}(\mathrm{NR_t}) + \alpha_4\mathrm{Ln}(\mathrm{REN_t}) + \varepsilon_\mathrm{t} \quad (3)$$

$$\mathrm{Ln}(\mathrm{GDP_t}) = \beta_0 + \beta_1\mathrm{Ln}(\mathrm{INSQ_t}) + \beta_2\mathrm{Ln}(\mathrm{FD_t}) + \beta_3\mathrm{Ln}(\mathrm{NR_t}) + \beta_4\mathrm{Ln}(\mathrm{REN_t}) + \varepsilon_\mathrm{t} \quad (4)$$

Equations (3) and (4) explain the econometric model of the concerned variables, where Ln denotes the natural logarithm algorithm, EFP denotes ecological footprint, INSQ is institutional quality, FD represents financial development, NR illustrates natural resources, and REN shows renewable energy. The subscript t of every variable shows the time dimension of the respective variable. Moreover, α_0 and β_0 represent the intercept terms of their respective functions. The terms $\alpha_1 \rightarrow \alpha_4$ and $\beta_1 \rightarrow \beta_4$ indicate the regressors' elasticity and ε_t indicates the stochastic error term.

3.2. Empirical Methodology

A comprehensive econometric process involves the three steps of (i) time series unit root analysis, (ii) cointegration analysis, and (iii) long-run and short-run elasticity estimation.

3.2.1. Time Series Unit Root Test

The stationary analysis is the first phase in the time series data analysis because the outcomes from regression analysis provide misleading/inconsistent information if the candidate regressors show a stochastic trend [57]. The empirical regression outcomes are misleading and spurious if this stochastic trend is detected in a minimum of one regressor and a dependent variable, or if both of these time series have no cointegration [58]. To evade this issue, the Phillips–Perron (PP) [59] and Augmented Dickey–Fuller (ADF) [60] stationarity tests were performed on the candidate time variables. Both ADF and PP unit root tests have a lower ability to determine the integration order of the selected variables due to the small sample size (<20) for China. In this regard, we have applied the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test developed by Kwiatkowski et al. [61] to examine the integration order and stationarity of the selected time series variables for a small sample size. The mathematical approach of ADF and PP stationarity tests can be explored in the first-order autoregressive (AR) model, the autoregressive model with consistency but no trend, and the autoregressive model with consistency and trend.

The first-order AR model:

$$\Delta X_t = \Psi \Delta X_{t-1} + \sum_{j=2}^{q} \delta_j \Delta X_{t-j+1} + \mu_1 \tag{5}$$

The AR model with only consistency:

$$\Delta X_t = \Psi \Delta X_{t-1} + c + \sum_{j=2}^{q} \delta_j \Delta X_{t-j+1} + \mu_1 \tag{6}$$

The AR model with both consistency and trend:

$$\Delta X_t = \Psi \Delta X_{t-1} + c + bt + \sum_{j=2}^{q} \delta_j \Delta X_{t-j+1} + \mu_1 (\text{with} \sim > \mu_t \sim > BB\left(0, \sigma_\varepsilon^2\right) \tag{7}$$

The models above apply to the null hypothesis (H_0), stating that the study variables contain mean, auto-covariance, and non-constant variance. Considering this, the PP stationary method also employs analogous models; however, it is dissimilar from other approaches because it relies on non-parametric correction for the recognition of serial correlation.

3.2.2. Johansen Cointegration Test

This study explores the long-run association between selected variables in the second step. In this way, the two time series are interpreted to be cointegrated over the long term if they progress simultaneously over time, and the distance between them is constant. Even when all the selected variables are integrated in the same order, the Johansen maximum likelihood test [62] is applied to check the long-run cointegration association between the selected variables. Consequently, the long-run cointegration association reveals the existence of a long-run steady-state equilibrium, towards which the system of economics converges in due course. The differences (or error terms) in the long-run cointegration relationship equation are deduced as the distorted error for a particular point in time.

This study applies the Johansen [63] long-run cointegration approach to test the long-term constancy and steady-state equilibrium between candidate variables via the following mathematical expressions/equation:

$$\Delta Y_t = \lambda_{t-1} + \sum_{i=1}^{q-1} \theta_i \Delta Y_{t-1} + \delta x_t + \mu_t \tag{8}$$

$$\lambda = \sum_{i=1}^{q} M_i - I,\ \theta_i = -\sum_{i=t+1}^{q} M_j \tag{9}$$

In Equations (8) and (9), the term λ is a parameter matrix of the adjusted disequilibrium. The stacking of coefficient M increased the unobserved factor's change speed to offset the disequilibrium association. The term θ is applied to confine the dynamic short-run adjustment [63,64].

3.2.3. Autoregressive Distributed Lag (ARDL) Bound and Other Long-Run Estimation Tests

The bounds cointegration test for the long-run association among series, also known as the autoregressive distributed lag (ARDL) method, is extensively employed owing to its numerous benefits. This process addresses many problems, such as the inability to assess the hypotheses on the approximated parameters in the long-run, and endogeneity issues. The ARDL test can check for the presence of long-term connections among the studied time series in levels, even if the underlying explanatory variables are entirely level I(0), purely different I(1), or mutually/mixed cointegrated I(0,1). Moreover, the ARDL test can approximate both the model's long- and short-run elasticities. In addition, the bound testing method has more advanced small sample properties (micro-numerasticity) than multivariate ones [65,66].

In contrast to the error correction model (ECM) and ordinary least square (OLS) regression, the ARDL test applies imbalanced error correction term parameters to investigate the long-run cointegration/association among the selected time series variables. This uneven use of parameters is useful for the application of the ARDL bounds approach, which can be further applied to establish the long-term relationship [67], as mentioned in Equations (10) and (11):

$$\Delta Y_t = \delta_0 + \sum \delta_i \Delta Y_{t-i} + \sum \pi_j \Delta X_{1,t-j} + \sum \beta_k \Delta X_{2,t-k} + \Phi ECT_{t-1} \tag{10}$$

$$\Delta Y_t = \delta_0 + \sum \delta_i \Delta Y_{t-i} + \sum \pi_j \Delta X_{1,t-j} + \sum \beta_k \Delta X_{2,t-k} + \xi_0 Y_{t-1} + \xi_1 X_{1,t-1} + \xi_2 X_{2,t-1} + \varepsilon_t \tag{11}$$

where Equation (12) portrays the unrestricted estimated error correction model just before long-run relationship testing with the ARDL bounds test, as follows:

$$\begin{aligned} \Delta CE_t = \theta &+ \sum_{i=1}^{k} \delta_0 \Delta CE_{t-i} + \sum_{i=1}^{k} \delta_1 \Delta X_{1,t-i} + \sum_{i=1}^{k} \delta_2 \Delta X_{2,t-i} + \sum_{i=1}^{k} \delta_3 \Delta X_{3,t-i} + \sum_{i=1}^{k} \delta_4 \Delta X_{4,t-i} + \lambda_0 ln \Delta CE_{t-i} \\ &+ \lambda_1 ln X_{1,t-i} + \lambda_2 \ln X_{2,t-i} + \lambda_3 \ln X_{3,t-i} + \lambda_4 \ln X_{4,t-i} + \delta_5 T + \delta_6 B + \mu_t \end{aligned} \tag{12}$$

where i denotes the cross-section, t presents the time span, and Δ shows the first difference operator. The null hypothesis concerning the absence of a long-term connection between the time series indicators can be reported in Equation (13) as:

$$\lambda_0 = \lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = 0 \tag{13}$$

$$\begin{aligned} \Delta \ln CE_t = \theta &+ \sum_{i=1}^{k} \delta_0 \Delta \ln CE_{t-i} + \sum_{i=1}^{k} \delta_1 \Delta X_{1,t-i} + \sum_{i=1}^{k} \delta_2 \Delta X_{2,t-i} + \sum_{i=1}^{k} \delta_3 \Delta X_{3,t-i} \\ &+ \sum_{i=1}^{k} \delta_4 \Delta X_{4,t-i} + \delta_5 T + \delta_6 B + \delta_7 ECT_{t-1} + w_t \end{aligned} \tag{14}$$

The ARDL bounds method employs non-standard asymptotic distribution and the joint F-statistic with the H_0 of the nonexistence of a long-run connection based on Equations (15) and (16). This process entails calculating two sets of critical values, the upper critical and the lower critical bound. The null hypothesis will be discarded if the approximated joint F-statistic value is higher than the upper bound. The null hypothesis will be accepted when the approximated joint F-statistic value is less than the lower bound limit.

3.2.4. Short-Run Elasticity Estimates

After variable transformation, the short-term elasticity of the variables mentioned above was approximated using the ARDL-based error correction model as:

$$\ln Y_t = \Psi_0 + \sum_{i=1}^{q} \Psi_{1i} \ln Y_{t-i} + \sum_{i=0}^{q} \Psi_{2i} \ln X_{1,t-i} + \sum_{i=0}^{q} \Psi_{3i} \ln X_{2,t-i} + \sum_{i=0}^{q} \Psi_{4i} \ln X_{3,t-i} + \sum_{i=0}^{q} \Psi_{5i} X_{4,t-i} + \lambda ECM_{t-1} + \varepsilon_t \tag{15}$$

In Equation (15), ECM_{t-1} shows the error correction term that was acquired by employing the following equation:

$$ECM_t = \ln Y_t - \beta_0 - \sum_{i=1}^{q} \beta_{1i} \ln Y_{t-i} - \sum_{i=0}^{q} \delta_{2i} \ln X_{1,t-i} - \sum_{i=0}^{q} \delta_{3i} \ln X_{2,t-i} - \sum_{i=0}^{q} \delta_{4i} \ln X_{3,t-i} - \sum_{i=0}^{q} \delta_{5i} X_{4,t-i} \quad (16)$$

where λ denotes the convergence speed from short- to long-run stable equilibrium, and all coefficients, such as Ψ_1, Ψ_2, Ψ_3, Ψ_4, Ψ_5, and Ψ_6, illustrate the parameters to be estimated.

3.2.5. Granger Causality Test

After detecting the short-run and long-run elasticity of the regressors, it is vital to determine the causal link between the study's time series. To do this, the Granger causality approach [68] can discover the association (either negative or positive), and whether the assessed variable influences explanatory variables or not. In the Granger causality approach, Granger [68] advocates vector autoregressive model approximations of the causal link between selected time series. In this regard, the present study follows the process of discovering the causal connections between variables as presented in Equations (17) and (18):

$$Y_t = \beta_0 + \sum_{i=1}^{m} \beta_i Y_{t-i} + \sum_{i=1}^{m} \eta_i X_{t-i} + \mu_t \quad (17)$$

$$X_t = \beta_0 + \sum_{j=1}^{k} \alpha_j Y_{t-j} + \sum_{j=1}^{k} \beta_j X_{t-j} + \mu_t \quad (18)$$

4. Results and Discussion

4.1. Descriptive Statistics and Correlation Matrix

Table 2 reports descriptive information of the findings related to all time series of the models, and the results of the Jarque–Bera test show that the data are linear in nature, so it is suitable to apply the ARDL technique to data to estimate the short- and long-run effects or elasticities of the series in model 1 and model 2. Figure 1 shows the trends of the different variables of the model except for natural resources; all the variables show a positive trend or time path.

Table 2. Descriptive statistics.

Stats.	LnEFP	LnGDP	LnINSQ	LnFD	LnNR	LnREN
Mean	1.015826	15.18082	4.227274	4.823501	1.009460	6.396785
Median	1.071201	15.34033	4.197310	4.812964	0.909565	6.498880
Maximum	1.316077	16.50490	4.391596	5.206381	2.272676	7.677059
Minimum	0.605814	13.66904	4.020657	4.493742	0.046189	5.244948
Std. Dev.	0.283064	1.008818	0.101559	0.181415	0.645114	0.827324
Skewness	−0.366602	−0.116624	0.009308	0.345490	0.281985	0.051068
Kurtosis	1.478193	1.454101	2.014166	2.330393	1.951863	1.602862
Jarque-Bera	2.972379	2.546051	1.012724	0.964403	1.475681	2.044195
Probability	0.226233	0.279983	0.602684	0.617422	0.478145	0.359839
Sum	25.39565	379.5204	105.6818	120.5875	25.23650	159.9196
Sum Sq. Dev.	1.923009	24.42511	0.247540	0.789873	9.988143	16.42716
Observations	25	25	25	25	25	25

Table 3 shows the outcomes of the correlation matrix, which shows the association between the two individual variables. Most variables show a positive relationship, but natural resources show a negative correlation between LnEFP and LnINSQ. The value of the correlation coefficient is small for all variables except REN, which means that the overall results are good, so there is no issue of multicollinearity. Moreover, Figure 2 denotes a box chart summary of the selected variables.

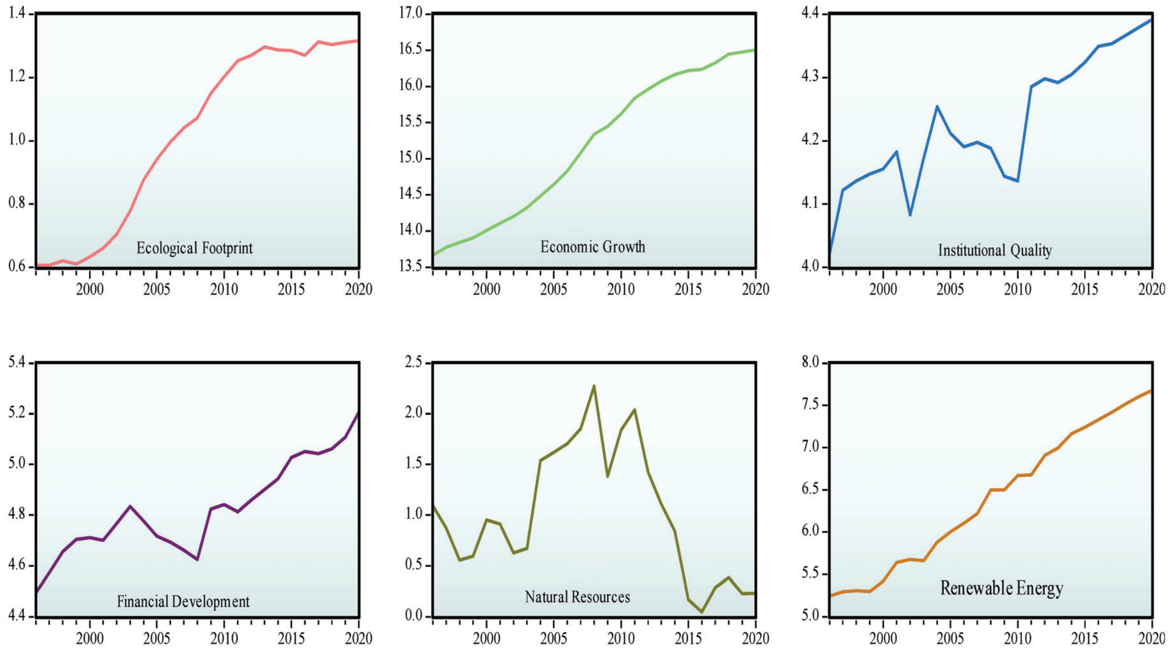

Figure 1. Trend analysis of analyzed variables.

Table 3. Correlation matrix.

Series	LnEFP	LnGDP	LnINSQ	LnFD	LnNR
LEFP	1.0000				
	0.9849	1.0000			
LnGDP	[27.316]	----			
	(0.0000)	----			
	0.8175	0.5677	1.0000		
LnINSQ	[6.8097]	[4.3479]	----		
	(0.0000)	(0.0000)	----		
	0.7842	0.7549	0.6766	1.0000	
LnFD	[6.0611]	[5.9049]	[5.7397]	----	
	(0.0000)	(0.0000)	(0.0000)	----	
	−0.0481	0.1894	−0.3758	0.5743	1.0000
LnNR	[−0.2313]	[0.9238]	[−1.9453]	[3.3644]	----
	(0.8191)	(0.3656)	(0.0641)	(0.0027)	----
	0.9641	0.792317	0.685002	0.6852	−0.2635
LnREN	[17.431]	8.46536	4.716052	[4.1269]	[−1.3101]
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.2031)

Note: the values in [ ] and ( ) denote the t-stats and *p*-value, respectively.

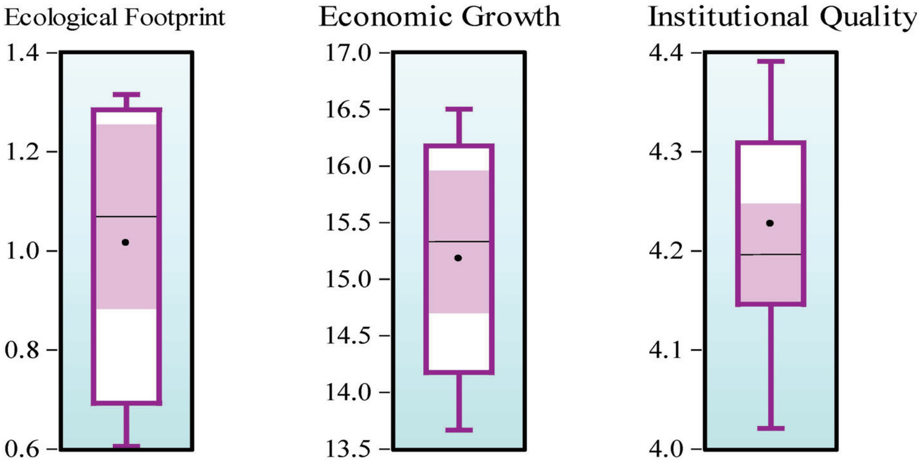

Figure 2. *Cont.*

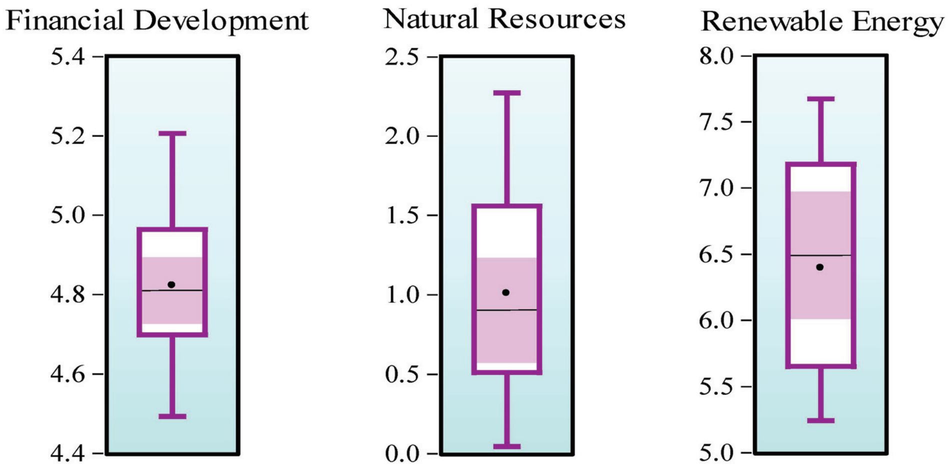

Figure 2. Box chart summary of selected variables.

4.2. Results of Unit Root Tests

The most important step of the econometric process is to detect the stationarity properties of the candidate time series using the ADF and PP stationarity tests. Both of these methods were evaluated to ascertain the unit root property of the current research data series. Table 4 reveals the results of stationarity tests, such as the ADF and PP, with constant and constant linear trends. The empirical results denote that all the selected series show no stationarity at a given level while following the stationary property at their first difference at constant. However, in terms of consistency and trend, institutional quality (considering the ADF test) and renewable energy (considering the PP test) are significant at the 10% level. At the same time, all other variables are insignificant, showing nonstationarity at level I(0). In contrast, all the selected indicators are integrated at the first difference I(1). Considering this phenomenon, Pesaran et al. [65] recommended that the most useful method to approximate unbiased, reliable, and robust coefficients is the ARDL test for econometric analysis.

Table 4. Stationarity analysis.

Series	Constant		Constant and Trend	
	Level	First Difference	Level	First Difference
Augmented Dickey–Fuller (ADF) test statistics				
LnEFP	−1.2421	−4.2629 *	0.09053	−4.5683 *
LnGDP	−2.2085	−4.9241 *	−2.6933	−4.7351 *
LnINSQ	−1.6423	−5.2242 *	−3.3688 ***	−5.1013 *
LnFD	−0.4157	−3.9707 *	−1.6592	−3.9039 **
LnNR	−1.2022	−4.70628 *	−1.3577	−4.7589 *
LnREN	0.3464	−6.1466 *	−3.5158 **	−6.0668 *
Phillips–Perron (PP) test statistic				
LnEFP	−1.0388	−4.4594 *	−0.8027	−4.4613 *
LnGDP	−0.8544	−4.8106 *	−0.7928	−4.9009 *
LnINSQ	−1.5731	−11.288 *	−3.4069 ***	−12.404 *
LnFD	−0.4401	−3.8759 *	−1.6590	−3.8420 *
LnNR	−1.2540	−4.7074 *	−1.3278	−4.8142 *
LnREN	0.5687	−6.3631 *	−3.5152 ***	−6.2619 *
Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test statistic				
LnEFP	0.7831 *	0.2193	0.1481 **	0.0962
LnGDP	0.7164 **	0.2050	0.1273 ***	0.1075
LnINSQ	0.6924 **	0.2910	0.2370 *	0.1030
LnFD	0.6752 **	0.1278	0.2277 *	0.1101
LnNR	0.6024 **	0.1673	0.1603 **	0.1008
LnREN	0.8249 *	0.1749	0.2536 *	0.0913
Critical values	1% / 5%	10%	1% / 5%	10%
	0.7390 / 0.4630	0.3470	0.2160 / 0.1460	0.1190

Note: *, **, and *** refer to 1%, 5% and 10% significance levels, respectively. The null hypothesis of the KPSS unit root test is the presence of stationarity.

Furthermore, this study applied the Kwiatkowski et al. [61] unit root test to test the selected variables' integration order. The findings of this test show that there is no stationarity at a given level. However, after transforming the first differences of the variables, all the selected variables became stationary, confirming the null hypothesis of stationarity for the selected variables.

4.3. Results of ARDL Bound and Johansen Cointegration Testing Approaches

Approximating the cointegration connection between the selected time series variables is essential. In this regard, the cointegration association between these indicators should be checked. The outcomes of the bound test of model 1 (dependent variables, economic growth and ecological footprint) are presented in Table 5, showing that both the lower and upper bounds affirm the rejection of H_0: the nonexistence of long-run cointegration among variables is rejected at the 1% significance level. Furthermore, Table 6 shows the outcomes from the Johansen long-run cointegration analysis.

Table 5. Results of the ARDL bound test.

Test Statistics	**F-Stats. Value**	**K**	**Cointegration**
Ecological footprint function	5.3805 *	4	Yes
Economic growth function	7.6401 *	4	Yes
Significance level	Lower bound	Upper bound	
	Bounds critical value		
10%	2.45	3.52	
5%	2.86	4.01	
2.5%	3.25	4.49	
1%	3.74	5.06	

Note: * denotes 1% level of significance.

Table 6. Results of Johansen cointegration test.

Unrestricted Cointegration Rank Test (Trace)				
Hypothesized No. of CE(s)	**Eigenvalue**	**Trace Statistic**	**0.05 Critical Value**	**Prob.**
None	0.910642 *	173.4677	107.3466	0.0000
At most 1	0.821034 *	115.5052	79.34145	0.0000
At most 2	0.748597 *	74.21168	55.24578	0.0005
At most 3	0.595942 **	41.07490	35.01090	0.0100
At most 4	0.370777 **	19.32620	18.39771	0.0370
At most 5	0.289643 *	8.207713	3.841466	0.0042
Unrestricted Cointegration Rank Test (Maximum Eigenvalue)				
Hypothesized No. of CE(s)	**Eigenvalue**	**Max-Eigen Statistic**	**0.05 Critical Value**	**Prob.**
None	0.910642 *	57.96258	43.41977	0.0007
At most 1	0.821034 *	41.29348	37.16359	0.0009
At most 2	0.748597 **	33.13677	30.81507	0.0255
At most 3	0.595942 **	21.74871	24.25202	0.0135
At most 4	0.370777	11.11848	17.14769	0.3025
At most 5	0.289643 *	8.207713	3.841466	0.0042

Note: * and ** refer to the 1% and 5% significance levels, respectively.

The Johansen long-run association approach [63] offers two test statistics: trace test statistics and maximum eigenvalue test statistics. In this way, to prove the long-run cointegration among candidate variables, a rejection of the null hypothesis is needed to verify the long-run relationship between variables at a 5% significance level. The trace test statistic shows the significance of all six cointegrated equations at a 5% significance level. However, the maximum eigenvalue test statistics show that the five equations are significant at a 5% significance level. Since these test statistics are statistically significant, it can be revealed that there are significant long-run cointegrating associations among the time series in the cases of both functions. For this reason, in the context of such outcomes, it can be observed that there are significant long-run relations between China's ecological footprint, economic growth, financial expansion, institutional excellence, natural resources, and the proportion of renewable and alternative energy figures. Taking into account the results from the stationarity tests and Johansen's [63] long-run cointegration tests, the ARDL analysis is performed to estimate the long- and short-run elasticities/coefficients of ecological footprint and GDP growth in opposition to positive shocks to the levels of the independent variables.

4.4. Long- and Short-Run Elasticity Estimates (Ecological Footprint Function)

To estimate the dynamic effects of regressors such as institutional quality, natural resources, renewable energy, and financial expansion on the ecological footprint in the case of China, the authors have proceeded further in this regard. Table 7 shows that institutional quality has an adverse impact on ecological footprint, which shows that with enhancements in institutional quality, environmental damages will be reduced, increasing the environmental quality and bringing the ecological footprint down. More clearly, a 1% positive change in institution quality diminishes the total footprint by 0.5868% and 0.1735% in the long- and short-run, respectively. Strong political management and institutions can manage and redesign strategies and investments that encourage climate-smart progress, essential low-emission building blocks, and climate-flexible culture [45,69]. This supports the empirical findings of Zakaria and Bibi [50], Zhang et al. [12], and Usman and Jahanger [45], who stated that greater institutional quality reduces the pressure on the environment. Institutional quality plays a vital role in the economic, governance, and social readiness to curb global warming and its effects. For this reason, stringent governance, social and economic policies, and reforms are needed by political institutions in order to make adjustment choices [8]. As it stands, China has low climate variation exposure given its willingness; on the other hand, adaptation choices for climate variations are still demanding and exigent.

Table 7. Results of ARDL model for ecological footprint (1,0,0,0,0).

Variables	Coefficient	S.E.	T-Statistics	Prob.
		Long-run estimates		
LnINSQ	−0.5868 *	0.0994	−5.8994	0.0000
LnFD	0.7371 *	0.2846	2.5891	0.0002
LnNR	0.4487 *	0.1675	2.6785	0.0000
LnREN	−0.8525 *	0.2548	−3.3441	0.0000
C	−4.1086 *	0.9807	−4.1887	0.0000
		Short-run estimates		
D(LnINSQ)	−0.1735 *	0.0657	−4.1608	0.0000
D(LnFD)	0.2934 *	0.0935	3.1328	0.0058
D(LnNR)	0.0629 *	0.0128	4.8671	0.0001
D(LnREN)	−0.5824 *	0.0905	−6.4911	0.0000
ECM_{t-1}	−0.4978 *	0.1201	−4.1372	0.0000
R-squared	0.9953		Mean dependent var	1.0329
Adjusted R-squared	0.9941		S.D. dependent var	0.2757
S.E. of regression	0.0212		Akaike info criterion	−4.6481
Sum squared resid	0.0085		Schwarz criterion	−4.3535
Log-likelihood	61.7763		Hannan–Quinn criter.	−4.5699
F-statistic	767.0225		Durbin–Watson stat	1.9476
Prob (F-statistic)	0.0000			

Note: * refers 1% level of significance.

Furthermore, the financial development effect on ecological contamination is positive and significant. Specifically, a 1% change in financial expansion would contribute 0.7371% and 0.2934% more environmental damages in the long- and short-run, respectively. This econometric result is in line with a few earlier studies developed by Farhani and Ozturk [70] for Tunisia, Ehigiamusoe et al. [71] for Africa, Zakaria and Bibi [50] for South Asia, and Ahmad et al. [8] for emerging economies. Hence, the financial institutions and their associated firms and markets do not consider all regulations from the perspective of financial expansion to condense atmosphere quality. They also raise production levels to take advantage of revenue with increased economic growth. Another reason could be that China's economy has utilized financial expansion for capitalization processes to encourage small-scale industrial growth. Such diminutive industries achieve a small degree of payback in economies of scale in the deployment of natural resources and pollution reduction. For that reason, carbon emissions have increased in China following financial growth [50]. Similarly, this study's results verify that capitalization determines the influence of technology.

Furthermore, this finding shows that the financial sector is not sufficiently established to distribute funds to eco-friendly ventures, and does not support investment in modern fuel-sufficient industries. Moreover, financial markets and their affiliated institutions in China do not offer loans for investments that have some capability to promote energy efficiency, energy savings, and alternative and clean energy. Hence, the findings of this paper are consistent with those of Acheampong [72] regarding 46 Sub-Sahara African economies, and those of Ibrahiem [73] for Egypt. In contrast, Baloch et al. [74] looked at OECD nations, and found that financial growth diminishes emission level via the effect of technology.

Moreover, the impact of natural resources is significant and positive in the long- and short-run. Particularly, a 1% enhancement in natural resources will increase the ecological footprint by 0.4487% and 0.0629% in the long- and short-run, respectively. This shows that the abundance of natural resource rents harms ecological excellence by escalating the pollution level in the region. The main reason behind the positive role of natural resources in boosting environmental pollution related to China's economy is mainly linked with real income growth, which increases the excessive and unsustainable utilization of natural resources and assists in affirming the country's dependence on non-renewable imports. Similarly, the sources of fossil fuel energy are indefensible and inadequate, and in due course, this gives rise to worse ecological circumstances. This study's results are in line and consistent with the earlier findings of Zafar et al. [54], Wang et al. [75], Danish et al. [76] and Ibrahim et al. [77].

By analyzing the impact of renewable/alternative energy use on environmental damages in China, the econometric results verify that renewable energy is a vital means of increasing environmental quality. Particularly, it is observed that a positive 1% boost in renewable energy abates the ecological footprint by 0.8525% and 0.5824% in the long- and short-run, respectively. This implies that renewable energy can be a useful substitute for non-renewable energy, which means that an augmentation in renewable energy deployment will mitigate ecological pollution in China. This result is similar to those of Dong et al. [78], Pata and Caglar, [55] for China, and Zafar et al. [54] for Asian countries. As a result, this study recommends that policymakers and the government in China design useful policies to encourage investment in the renewable energy sector, and deploy/generate transversely economic activities, ultimately ensuring economic sustainability in China.

The ARDL model also estimates the error correction model (ECM) related to the mixed stationarity of variables, such as I(0) and I(1). Moreover, Table 7 also shows that the ECM value is useful in endorsing this theory (with a negative sign), and indicates a 49.70% convergence speed from short- to long-term annual stability in these candidate regressors. Figure 3 refers to the actual, fitted, and residual plots of the ecological footprint function.

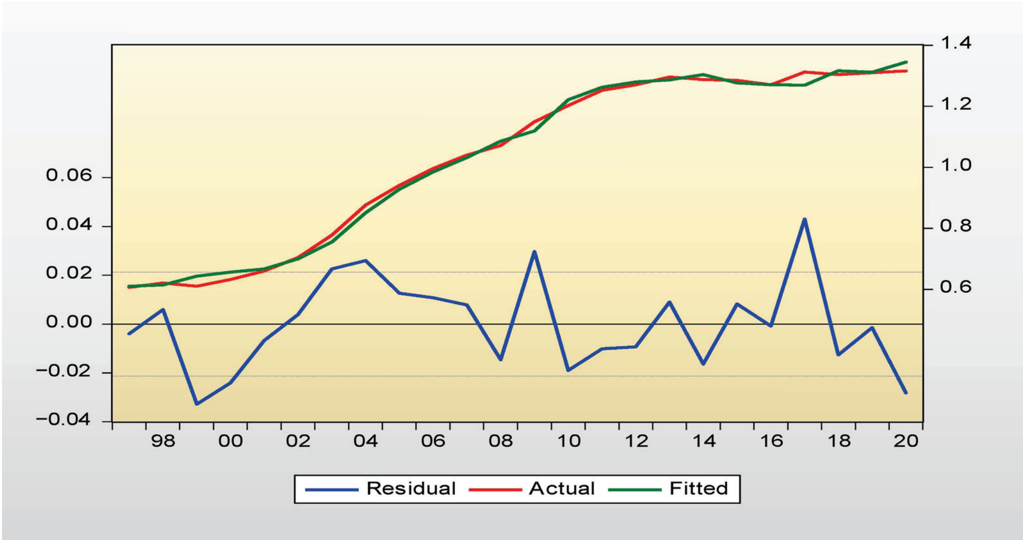

Figure 3. Actual, fitted, and residual plot of the ecological footprint function.

4.5. Long- and Short-Run Elasticity Estimate (Economic Growth Function)

We sought to determine the dynamic effects of independent variables, such as institutional quality, financial development, natural resources, and renewable and alternative energy, on GDP growth in the case of China. Table 8 shows that institutional quality has a positive effect on GDP, which shows that economic growth will increase with the increase in institution quality. More clearly, a 1% positive alteration in institution quality increases the GDP by 0.7657%. Considering this constructive effect of Chinese institutions, the development of institutional excellence assists in the progression of several non-resource subdivisions, as well as aiding the growth of resource segments, with the intention those superior institutions construct resources that turn out to be less imperative. This finding is in alignment with the earlier findings of Lajqi and Krasniqi [79], Bhattacharya et al. [80], and Epo and Faha [39]. This shows that elevated economic freedom is positively linked with economic production. Healthier institutions facilitate policy integration, legislative implementation, economic efficiency, leadership, and stakeholder contribution to accelerate consumption. To further reinforce this finding, the authors observed the functional impacts of foreign investment, private sector services, and industrialization on real income growth—all became stronger and more effective in Chinese regions with improved institutional worth. The typical illustration is the Ningxia, Guizhou, and Qinghai regions [18]. All of these regions suffer severely from low institutional excellence. Their economic growth consequently mainly depends on natural resource wealth, while the segments with fewer resources are inadequately developed. In contrast, the Jiangsu, Tianjing, Guangdong, and Zhejiang regions are among the top-ten regions in terms of institutional superiority, and the subdivisions of their less natural resources, such as the industrialization and research and development private segments, are among the best. The natural resources in such regions only serve to reduce real income growth.

The influence of financial expansion on income growth is positive and significant, which means that if financial growth is increased by 1%, it will increase economic expansion by 0.5221%. Furthermore, the effect of natural resource rent on GDP is constructive and significant, which means that a 1% boost in natural resource rent will increase the income growth by 0.2824%. This finding noticeably challenges the resource curse hypothesis. This result corroborates the conclusion of earlier studies [81,82], while it supports the findings of Brunnschweiler and Bulte [83] that the profusion of resources encourages real income growth, which can be described via the "Windfall" model of economic profit from resource utilization. Further, a constructive influence of the excessive extraction of resources is predominantly felt in provinces with feeble institutional quality, and the impact reduces as institutional value increases. Strong and healthy institutions encourage extra willingness on the part of investors to invest in multinational firms, and increase the usefulness of communal governance, consequently combining strong and developed institutions with a vigorous financial structure [18].

Table 8. Results of ARDL model for economic growth function (1,0,0,0,0).

Variables	Coefficient	S.E.	T-Statistics	Prob.
		Long-run estimates		
LnINSQ	0.7657 *	0.1397	5.4791	0.0000
LnFD	0.5221 *	0.1181	4.4175	0.0000
LnNR	0.2824 *	0.0755	3.7409	0.0004
LnREN	0.9185 *	0.1916	4.7943	0.0000
C	4.1721 *	1.2635	3.3019	0.0006
		Short-run estimates		
D(LnINSQ)	0.7809 *	0.1489	5.2451	0.0000
D(LnFD)	1.4503	1.7515	0.8284	0.4185
D(LnNR)	0.9799	0.6433	1.5231	0.1451
D(LnREN)	1.4088 *	0.2975	4.7339	0.0002
ECM_{t-1}	−0.2841 *	0.0550	−5.163	0.0000
R-squared	0.8993	Mean dependent var		15.2431
Adjusted R-squared	0.8992	S.D. dependent var		0.9796
S.E. of regression	0.0274	Akaike info criterion		−4.1407
Sum squared resid	0.0136	Schwarz criterion		−3.8462
Log-likelihood	55.6881	Hannan–Quinn criter.		−4.0625
F-statistic	5848.113	Durbin–Watson stat		2.0249
Prob(F-statistic)	0.0000			

Note: * refers 1% level of significance.

The impact of renewable energy on income growth is positive and significant, which means that a 1% increase in renewable energy resources increases the GDP by 0.9185%, which confirms that alternative energy deployment is an imperative constituent of the economic growth process in China. This result is consistent with Bhattacharya et al. [80], Pao and Fu [84] and Salman et al. [85]. As China is the world's number one growing economy, it has broad prospects in terms of sustainable growth and development. Due to its consistent growth pattern, the country's institutions have developed at a higher level and perform effectively. Finally, this study finds that institutions play a vital role in growth, and institutional quality is necessary to achieving long-term sustainability and reducing the resource curse [86,87]. In the current period, financial development promotes and facilitates growth. Nowadays, the most recent research outcomes support the argument that a strong linkage exists between natural resources and financial development, which is also seen in the results of the long-term equations. Figure 4 shows the actual, fitted, and residual plots of the economic growth footprint function.

The ARDL model also provides short-run estimates and an error correction model (ECM). Table 8 shows the outcomes of short-run elasticities of income growth relating to the series mentioned above. This result verifies that institutional quality negatively and significantly affects economic growth. A 1% increase in institution quality increases the GDP by 0.78%, and this is consistent with long-term results. The impact of financial development on income growth is positive but insignificant, which means that a 1% increase in financial expansion leads to an increase in income growth by 1.45%. The impact of natural resources is positive on income growth, but insignificant, which means that a 1% boost in natural resources leads to an increase in economic growth of 0.97%. Similarly, consistent with the long-run results, the effect of renewable energy on income growth is positive and significant, which means that a 1% increase in renewable energy resources increases income growth by 1.40%, which helps in increasing income growth. The coefficient of the ECM term supports the theory, and shows a 28.41% convergence speed from short- to long-run stable equilibrium.

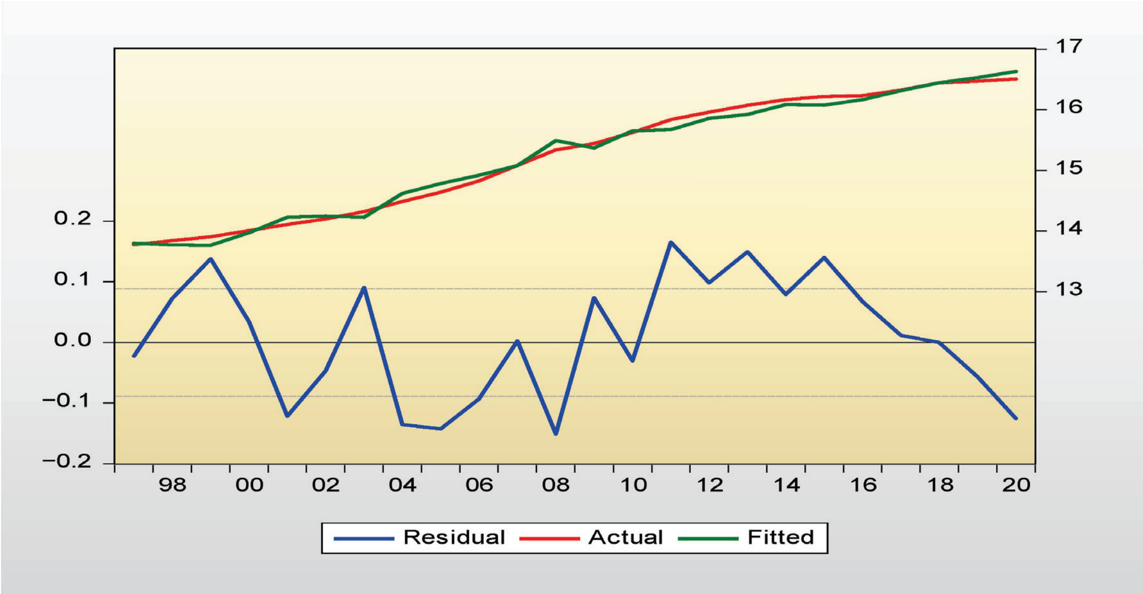

Figure 4. Actual, fitted, and residual plot of the economic growth footprint function.

The findings of the diagnostic tests are presented in Table 9. The robustness/diagnostic analyses of both (EFP and GDP) functions show that the findings of ARDL models are normally distributed and consistent. Furthermore, the BG serial correlation LM test findings reveal that both functions are not serially correlated. The ARCH and BPG-LM test for heteroscedasticity confirm that the selected models have no issue of heteroscedasticity.

Table 9. Diagnostic test of both (EFP and GDP) functions.

Tests	Ecological Footprint Function		Economic Growth Function		
Robustness Analysis	**F-Stats**	**Prob.**	**F-Stats**	**Prob.**	**Remarks**
Jarque–Bera test for normality	0.5596	0.7559	2.9700	0.2264	Normality exists
BG Serial correlation LM test	0.5618	0.5810	0.5708	0.5881	No serial correlation
ARCH test for heteroscedasticity	0.2896	0.5961	0.5842	0.4532	No heteroscedasticity
BPG-LM test for heteroscedasticity	0.5546	0.7331	0.1860	0.9642	No heteroscedasticity

4.6. Robustness Check

Finally, this study assesses the effectiveness and accuracy of the main outcomes by executing some additional tests. Besides the ARDL estimator, this study also estimated the main findings by performing fully modified ordinary least square (FMOLS), dynamic ordinary least square (DOLS), and canonical cointegrating regression (CCR) tests. Table 10 explores the long-run elasticity estimates derived from these approaches. The findings of these tests provided similar econometric findings to the ARDL estimator. Consequently, it can be assumed that the approximated long-run elasticity of these candidate series is reliable, robust, and stable. The robustness estimator parameters are consistent with the coefficient of ARDL, which means there is no large diversion in the results, all the variables are significant in all models, and the signs adhere to expectations. All four approaches indicate that institutional quality and renewable energy can protect the atmosphere in China, whereas financial development and natural resources damage the environment. In addition, all potential factors boost economic growth in the long-term; for this reason, China's per capita economic growth, which was USD 634 in 1987, increased to USD 7308 in 2016 [55].

Table 10. Robustness analysis (FMOLS, DOLS, and CCR).

Variable	FMOLS Regression		DOLS Regression		CCR Regression	
	EFP Function	GDP Function	EFP Function	GDP Function	EFP Function	GDP Function
LnINSQ	−0.1578 *	1.1708 **	−0.1429 *	1.9198 *	−0.2267 **	0.1623 *
LnFD	0.7971 *	0.7608 ***	0.6679 *	0.9629 **	0.4124 *	1.8319 *
LnNR	0.1191 *	0.2794 *	0.1206 *	0.2141 *	0.1209 *	0.2956 *
LnREN	−0.3382 *	0.9807 *	−0.3405 *	1.0492 *	−0.3367 *	0.8707 *
R-squared	0.9723	0.9830	0.9984	0.9968	0.9688	0.9299
Adjusted R-squared	0.9665	0.9804	0.9937	0.9936	0.9622	0.9193
S.E. of regression	0.0504	0.1367	0.0211	0.0765	0.0536	0.2779
Long-run variance	0.0013	0.0128	0.0032	0.0070	0.0013	0.0128
Mean dependent var	1.0329	15.243	1.0394	15.1891	1.0329	15.2431
S.D. dependent var	0.2756	0.9796	0.2659	0.9625	0.2756	0.9796
Sum squared resid	0.0483	0.3749	0.0022	0.0645	0.0545	1.5453

Note: *, ** and *** refer to 1%, 5%, and 10% levels of significance, respectively.

Moreover, the stability of the model is also confirmed through cumulative sum (CUSUM) and cumulative sum of square (CUSUMsq), which show the distinctions between the long- and short-run coefficients of both ecological footprint and income growth models. Following this procedure, it is necessary to confirm parameter stability, as it makes the policy implications more reliable. Figures 5 and 6 show the CUSUM and CUSUMsq of the recursive residual plot for the EFP function, while Figures 7 and 8 denote the CUSUM and CUSUMsq of the recursive residual plot for the GDP function, respectively. In these figures, the blue line lies between the red lines at a 5% level of significance, which means that the models of ecological footprint and economic growth are properly specified. Finally, this study verifies that the parameters are free of all issues, and that the estimated parameters are reliable and stable.

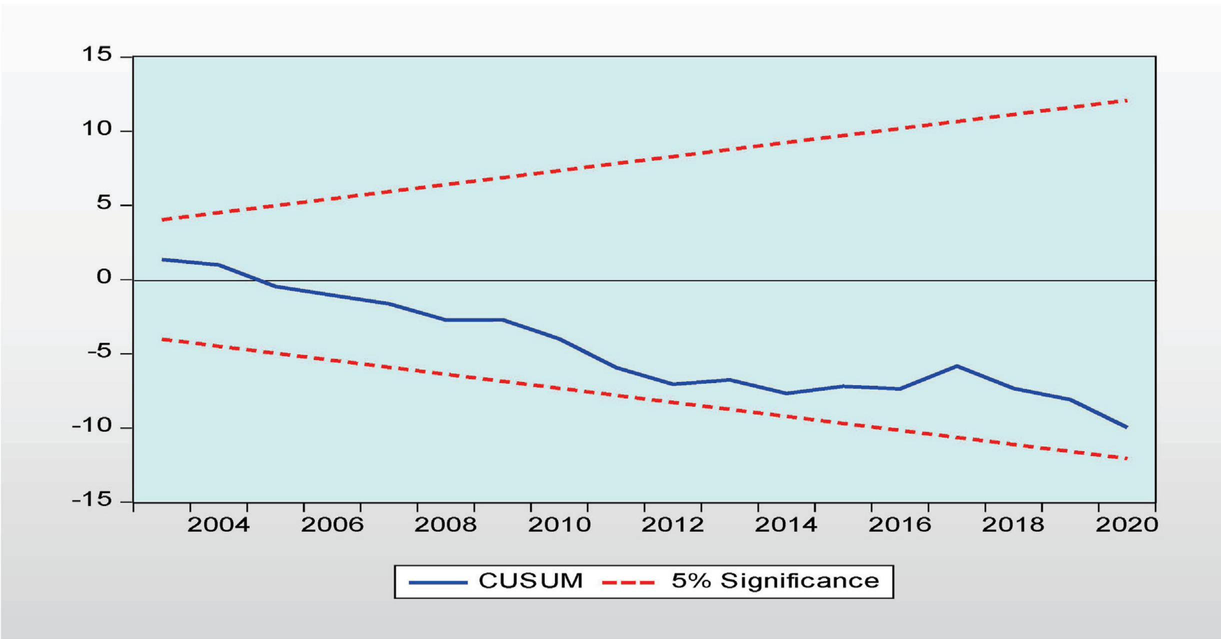

Figure 5. The cumulative sum of the recursive residual plot (EFP function).

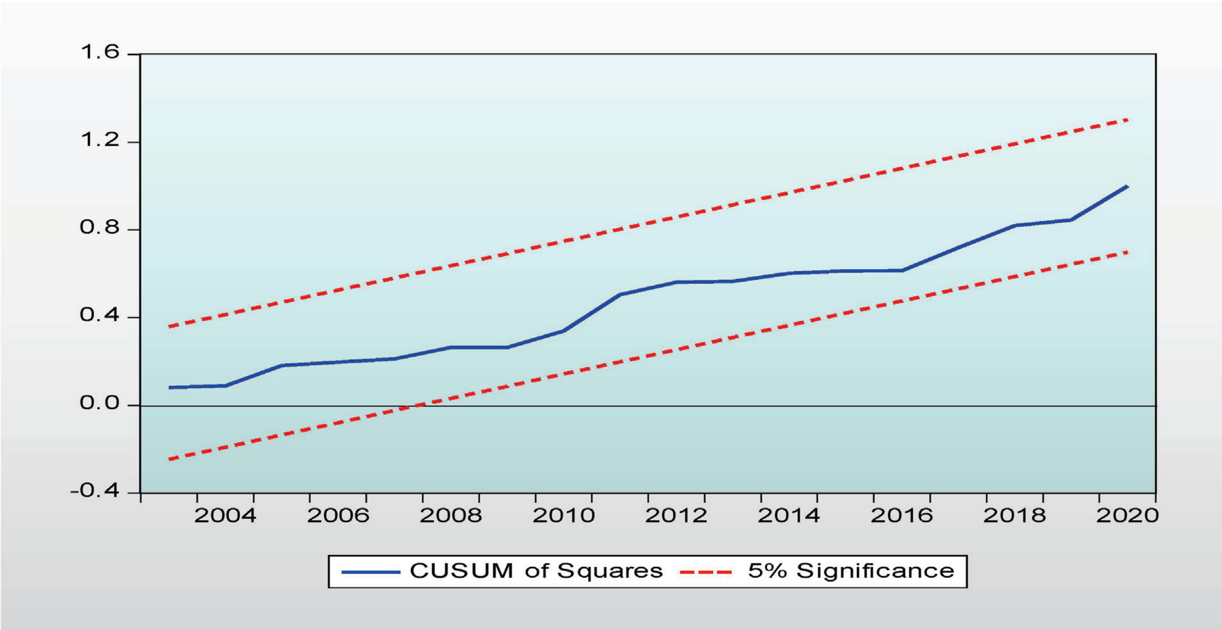

Figure 6. The cumulative sum of the square of the recursive residual plot (EFP function).

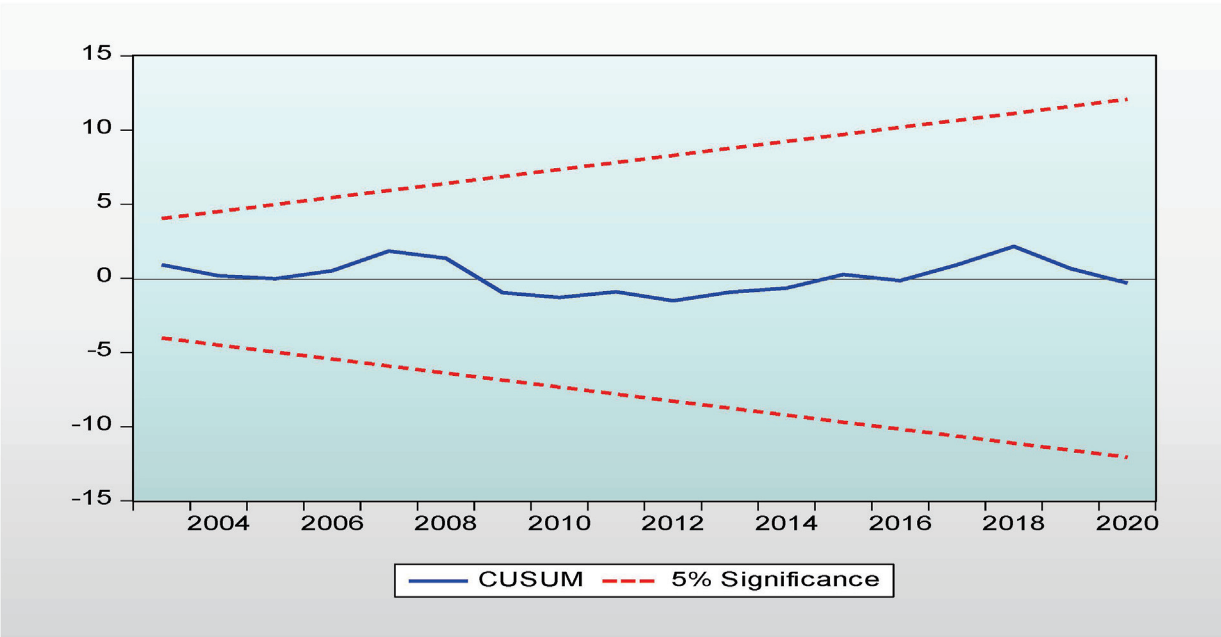

Figure 7. The cumulative sum of the recursive residual plot (GDP function).

4.7. Granger Causality Analysis

The casual relationship is a very important variable, because long-run relationships exist among the variables; hence, the Granger causality estimation technique is used. For this purpose, one-way or two-way causality among the variables will be tested for if the series has a unit root. If the current value of x is estimated by utilizing the lag value of y, then Granger causality shall pertain between two series (y and x) [88]. The Granger causality test, as shown in Table 11, confirms the existence of one-way causality, resulting from institutional quality and ecological footprint, from natural resources to GDP, financial development and renewable energy to institutional quality and natural resources, renewable energy to financial development, as well as renewable energy consumption to natural resources. These findings are consistent with those of Ahmad et al. [8] for emerging countries, Aslan and Altinoz [53] for Asian and European panel countries, and Zahoor et al. [14] for China. The relationships of the above variables are helpful in making the environmental policy more stable and effective, which thus helps in attaining the Sustainable Development Goals (SDG). The two-way causality between environment, institutional quality, and GDP shows the association between these variables, and helps in attaining growth.

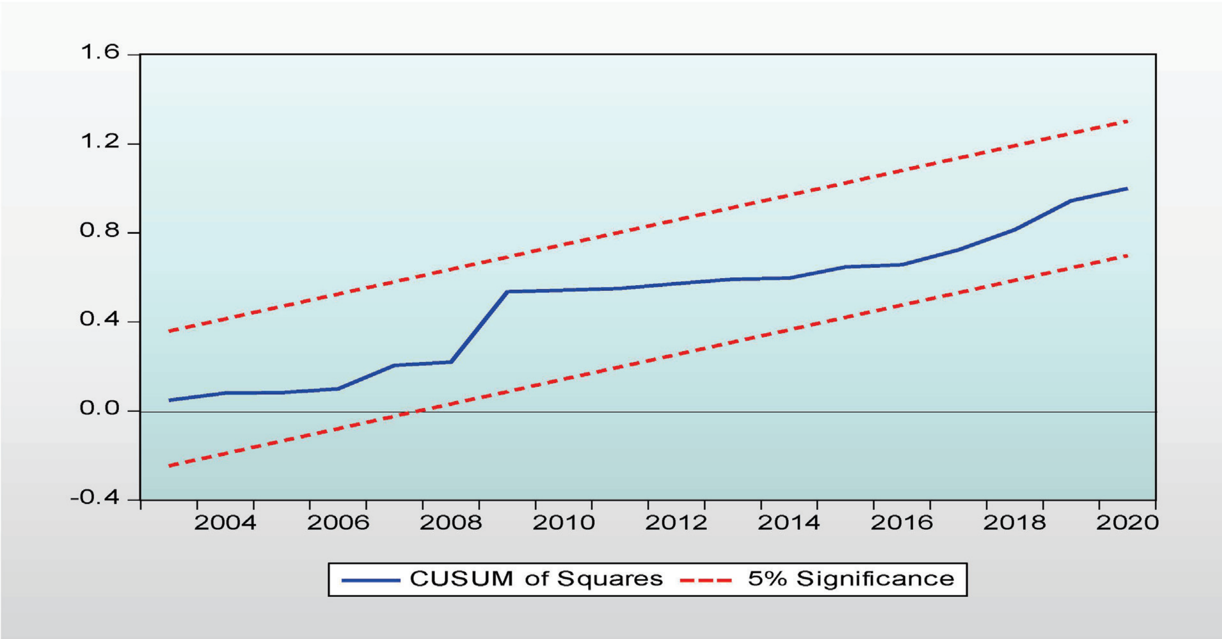

Figure 8. The cumulative sum of the square of the recursive residual plot (GDP function).

Table 11. Results of pairwise granger causality test.

Null Hypothesis: H_0	F-Stat.	Prob.	Inference
LnGDP $\nRightarrow$ LnEFP	22.9606	0.0000	Bidirectional causality exists
LnEFP $\nRightarrow$ LnGDP	32.0585	0.0000	
LnINSQ $\nRightarrow$ LnEFP	1.52547	0.2304	Unidirectional causality exists
LnEFP $\nRightarrow$ LnINSQ	4.42810	0.0476	
LnFD $\nRightarrow$ LnEFP	0.24018	0.6292	Unidirectional causality exists
LnEFP $\nRightarrow$ LnFD	12.8565	0.0000	
LnNR $\nRightarrow$ LnEFP	4.48132	0.0464	Bidirectional causality exists
LnEFP $\nRightarrow$ LnNR	8.85693	0.0008	
LnREN $\nRightarrow$ LnEFP	11.7392	0.0000	Bidirectional causality exists
LnEFP $\nRightarrow$ LnREN	4.60448	0.0437	
LnINSQ $\nRightarrow$ LnGDP	3.19242	0.0884	Bidirectional causality exists
LnGDP $\nRightarrow$ LnINSQ	6.48541	0.0188	
LnFD $\nRightarrow$ LnGDP	7.45656	0.0001	Bidirectional causality exists
LnGDP $\nRightarrow$ LnFD	3.20905	0.0877	
LnNR $\nRightarrow$ LnGDP	15.4327	0.0008	Unidirectional causality exists
LnGDP $\nRightarrow$ LnNR	1.41670	0.2472	
LnREN $\nRightarrow$ LnGDP	3.50403	0.0752	Bidirectional causality exists
LnGDP $\nRightarrow$ LnREN	7.78740	0.0110	

Table 11. *Cont.*

Null Hypothesis: H_0	F-Stat.	Prob.	Inference
LnFD $\nRightarrow$ LnINSQ	15.8894	0.0007	Unidirectional causality exists
LnINSQ $\nRightarrow$ LnFD	0.51712	0.4800	
LnNR $\nRightarrow$ LnINSQ	1.35149	0.2581	No causality exists
LnINSQ $\nRightarrow$ LnNR	1.77524	0.1970	
LnREN $\nRightarrow$ LnINSQ	6.88710	0.0158	Unidirectional causality exists
LnINSQ $\nRightarrow$ LnREN	1.90390	0.1822	
LnNR $\nRightarrow$ LnFD	10.0872	0.0000	Unidirectional causality exists
LnFD $\nRightarrow$ LnNR	0.07514	0.7867	
LnREN $\nRightarrow$ LnFD	5.02007	0.0360	Unidirectional causality exists
LnFD $\nRightarrow$ LnREN	0.13566	0.7163	
LnREN $\nRightarrow$ LnNR	4.58333	0.0091	Unidirectional causality exists
LnNR $\nRightarrow$ LnREN	1.06181	0.3145	

Note: $\nRightarrow$ denotes "does not Granger cause".

5. Conclusions and Policy Options

This study examines the long-term, short-term and dynamic influence of institutional quality, natural resources, financial development, and renewable and alternative energy use on economic growth and the environment simultaneously in China, employing series data from 1996 to 2020. To the best of the authors' knowledge, no earlier research has examined this link in the Chinese context. The Johansen and ARDL bound long-run cointegration approaches were applied to discover the cointegration relationship. Both methods confirm that long-term cointegration was apparent among institutional quality, natural resources, GDP growth, financial expansion, renewable energy, and ecological footprint. The empirical outcomes of the ARDL test show that institutional quality and renewable and clean energy help to protect environmental quality. However, financial progress and total natural resources reduce environmental quality, showing that institutional quality and alternative energy deployment can play a crucial role in diminishing environmental damage in an economy. Further, healthy and sound development in the financial sector can make more funding available at a cheap rate (as the financial markets and institutions are dominated by industrial banks that play a major role in offering credits to both private and public sectors for a variety of developmental ventures) for speculation in ecological projects.

Moreover, all the candidate variables significantly increase economic growth in the long term. In this scenario, when the prospect of the demand for carbon emission protuberance is measured, the significance of financial markets and institutions should also be included as functions of traditional indicators, for instance, energy and income. In addition, an augmentation of alternative and green energy deployment can assist in diminishing ecological damage in China. The findings of the Granger causality method show a two-way causal association between ecological footprint and economic growth. Besides this, there is evidence of a unidirectional causal association from natural resources toward economic growth and institutional quality to the ecological footprint in China.

Based on the above empirical findings, the current research suggests some appropriate policy inferences, as follows: (i) The government of China must be cautious when redesigning economic growth strategies that will make ecological sustainability vulnerable at the national level. (ii) The overall energy mix must be transformed by replacing the fossil fuel energy sources with alternative and renewable energy deployment, since green power sources aid in diminishing ecological damages in China. (iii) Well-developed and advanced carbon trading institutions and markets for public–private partnerships in environmental finance hasten the development and research, and the organization, of a nationwide integrated environmental pollution scheme. This develops a market structure based on active ecological exchanges across China, which enables pilot cities, provinces, and regions to institute their own emissions, authorize allotment schemes/systems and trading methods, and ascertain district emission trading proposals by sharing municipal and provincial information. It also helps establish economic commissions, power preservation, and pollution diminution groups, and advances some other key sectors; consequently, China's carbon pricing authority can be developed as soon as possible to encourage low-carbon industrial development. In addition, this will vigorously support the R&D of low-carbon technology, which is amongst the main indicators in China's evolution to a low-carbon nation. This will help in developing new technologies for green growth, reducing coal and gas power consumption, advancing CO_2 storage and capture, develop circular systems for all sectors, thus building up a circular economy, and dynamically endorsing household and industrial waste reprocessing.

The present research features some restrictions and limitations, and formulates suggestions for upcoming research. The first caveat of the present research is the use of EFP as the explained series. In upcoming studies, all sub-components of the ecological footprint must be determined as explained variables, and their link with institutional quality, financial development, natural resources, and renewable energy should be investigated. Second, this study has applied only the time series approach. In upcoming studies, the influence of financial development, institutional quality, natural resources, and renewable energy on a universal scale can be examined by employing panel nonlinear and dynamic ARDL. Third, this study was majorly constrained by data availability (1996 to 2020); upcoming research should increase the data size of these variables. In the end, findings derived from novel econometric approaches and vast data ranges can be compared to those of this study.

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Sustainable Energy Supply, Finance, and Domestic Investment Nexus in West Africa

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Abstract: This study examines the impact of financial deepening and sustainable energy supply on domestic investment in West African countries. The data for the study range from 1990 to 2020 and were sourced from the World Development Indicator database. We used the cross-sectional autoregressive distributed lag (CS-ARDL) estimator for the analysis. Empirical findings showed that credit to the private sector significantly impacts domestic investment in West Africa. It was also revealed that access to electricity significantly impacts domestic investment in West Africa. This demonstrates that funding for the private sector and adequate power generation improve the investment in any economy. The study concludes that financial deepening has a significant impact on domestic investment. The study therefore recommends that the management of banks should be encouraged to pursue policies that will deepen the efficient allocation of financial services for domestic investment in the region.

Keywords: financial deepening; financial development; sustainable energy supply; domestic investment; autoregressive distributed lag model (ARDL)

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1. Introduction

The importance accorded to domestic investment as one of the major movers of any economy has been a growing phenomenon and has remained a recurrent issue in recent years. One of the most crucial economic activities that nations place a high value on is a domestic investment, which serves as the primary driver of national economic development and the economic cycle (Bakari [1]). Domestic investment is a tool of an unhindered efficient economic system that plays a significant role in determining how much an economy grows. The governments of developed countries have renewed efforts in promoting domestic investment, after many years of economic adjustment and various economic reform programs. Having realized the importance of domestic investment, successive governments in West Africa have tried implementing some trade reforms and other macroeconomic reforms to improve domestic investment in their various countries and the region in general; however, the available relevant economic indicators show slow and minimal improvement in domestic investment (Ekpo [2]). The domestic investment in West Africa has continuously remained low compared to North Africa and other regions in the world.

According to the United Nations Economic Commission for Africa (UNECA) [3], domestic investment in West African countries, particularly public investment, is still inadequate and has not improved much despite the region's political and economic situations getting better over the past two decades. Moreover, the private domestic investments for West African countries have been deteriorating over the last two decades, while the performance of some countries was far below the regional average. The failure of several programs on domestic investment has particularly led to interest in discussions and research on how financial deepening could lead to improved domestic investment in Africa. It has been acknowledged globally that financial deepening plays a catalytic role in the economic development of nations (Sanusi [4]). According to Giovanni [5], financially robust markets, whether assessed by size or the liquidity made available to businesses, increase their ability to acquire the capital they need to carry out investment initiatives that they might otherwise have to postpone. Additionally, dependable, sufficient, and high-quality infrastructure boosts economic productivity, reduces production costs, raises the nation's regional and worldwide competitiveness, and aids in the modernization of the economy. Infrastructure is there to meet needs, which can be social or economic. Economic infrastructures have been crucial for a long time in fostering domestic investment. For instance, improved infrastructure facilities enhance intra-regional trade and investment flows, which are essential for the development of regional markets, acceleration of growth, and eradication of poverty (United Nations Conference on Trade and Development (UNCTAD) [6]).

Several studies (such as Frank and Eric [7], Ajide and Lawanson [8], and Ang and McKibbin [9]) on financial deepening and domestic private investment have been conducted on a single country analysis, while relatively less is known for cross-country investigation such as in West African countries. For instance, Frank and Eric [7] and Ajide and Lawanson [8] focused on the finance–growth relation in a bivariate framework for Ghana and Nigeria. Meanwhile, Ang and McKibbin [9] incorporated some control variables such as real interest rate and extent of financial repression into the finance–growth model for Malaysia. Similarly, most of these studies (Ndikumana [10]; Le [11]; Deltuvaite and Sineviciene [12]; Onuonga [13]; Odedokun [14]) concentrated on the impact of financial deepening on economic growth while neglecting the impact on domestic investment in West Africa.

Moreover, Onwumere, Ibe, Ozoh, and Mounanu [15] and Aye [16] carried out studies on financial deepening using variables such as broad money and market capitalization. The focus has been almost entirely on bank-based financial deepening measures while ignoring the possible impact of insurance companies on domestic investment. Other studies such as those of Odeniran and Udeaja [17]; Okpara [18]; and Ferreira, Tadeu, and Silva [19] failed to consider interest rates as a determinant of domestic investment. Finally, the previous studies neglected to consider the impact of financial deepening and infrastructural development on domestic investment in West Africa. Against this backdrop, this study aims to investigate the impact of financial deepening and sustainable energy supply on domestic investment while accounting for some macroeconomic variables, namely exchange rate, interest rate, credit to the private sector, and insurance services, in 16 West African countries. To this end, the panel ARDL method is applied, and the CS-ARDL method is also used as a robustness check over the period 1990–2020. Thus, this paper contributes to the existing literature in terms of scope and econometric method. Hence, the results are suitable for policy crafting in the examined bloc regarding financial deepening and sustainable economic growth.

Our study's empirical results highlight that financial deepening variables significantly impact domestic investment in West Africa. Additionally, sustainable energy supply significantly impacts domestic investment in West Africa. Therefore, there is a need to pursue policies that will deepen the efficient allocation of financial services for domestic investment in the region; the government of West African countries should strive to stabilize their capital market, thereby pursuing competitive market policies.

This study is organized into five sections. The first section is the introductory section while the second section presents the literature, and the third section is the methodology. This is followed by the empirical results and discussions of the findings. The last section covers the conclusion.

2. Literature Review

2.1. Theoretical Review

2.1.1. Theory of Financial Intermediation

According to Schumpeter's [20] theory of financial intermediation, financial intermediaries have a critical role to play in the process of growth by shifting financial resources from net savers to net borrowers, thereby affecting investment and, in turn, economic growth. According to the theory, financial intermediaries can eliminate information asymmetry and market inefficiencies by altering the risk characteristics of assets (Nzotta and Okereke [21]). Due to the fact that borrowers typically have a better understanding of their investment projects than do lenders, there are asymmetries in the loan markets.

Financial intermediaries, therefore, seem to at least somewhat offset the expenses associated with certain types of transaction costs that are caused by information breakdowns. According to Tobin [22], the concept of transaction costs includes costs associated with searches, monitoring, and auditing in addition to exchange or monetary transaction costs (Benston and Smith [23]). The idea that efficient financial intermediaries might increase overall economic efficiency is supported by Schumpeter's study [20]. Intermediation roles of the financial sector encourage creativity and the development of entrepreneurship, which are essential elements for economic progress, by pooling and adequately allocating these resources (Karimo and Ogbonna [24]).

2.1.2. Supply Leading Hypothesis

Schumpeter in 1911 developed this hypothesis, and it was later reinforced by other writers such as McKinnon, Shaw, and Gupta, among others. According to this hypothesis, financial progress leads to the expansion of economic activities. In a world of frictionless transaction, information, and monitoring costs, financial intermediaries are not required. No exchange will occur between economic agents if transaction, information, and monitoring costs are too high.

The financial sector was created in an effort to lower those costs and facilitate exchanges. According to the hypothesis, a developed financial sector offers vital products that lower transaction, monitoring, and information costs and also boost intermediation efficiency. It mobilizes savings, locates and finances successful company ventures, keeps an eye on managers' performance, makes trading and risk diversification easier, and promotes the trade of products and services.

2.2. Empirical Review

2.2.1. Financial Deepening and Economic Growth

It is commonly known that financial deepening has a significant role in boosting economic growth and productivity. Results on the relationship between financial deepening and economic growth, however, have been contradictory. According to Torruam et al. [25], financial deepening boosts the sector's competitive efficiency, which indirectly benefits the economy's non-financial sectors. The supply leading hypothesis is supported by research conducted by Christopoulos and Tsionas [26] that showed a uni-directional causal relationship between financial development and growth in developing nations. In developing economies, Odedokun [14], Ang and McKibbin [9], Frank and Eric [7], Ajide and Lawanson [8], and Onuonga [13] examined the effects of financial sector deepening and economic growth. However, the results of the studies show that there is a statistically significant positive relationship between the financial sector deepening and economic growth.

Ho et al. [27], Xu [28], and Ndikumana [10] reported a long-run equilibrium relationship between economic development and financial deepening, which was supported by Tonye and Andabai [13,29] and Mehrara and Ghamati [30], while Adamopoulos [31] found that a short-term 1% impact on economic growth is caused by financial deepening. However, in a study of the financial deepening and growth of Turkey's economy, Ardic and Damar [32] discovered a significant inverse relationship between the two variables. Meanwhile, according to John and Ibenta [33], Michael [34], and Nyamongo et al. [35], there was little to no impact on economic growth. According to Darrat [36], financial deepening is a necessary cause of the growth rate of any economy.

2.2.2. Financial Deepening and Domestic Investment

According to Onwumere et al. [15], an active financial sector can increase overall economic efficiency, generate and increase liquidity, foster capital accumulation, mobilize savings, and channel resources from traditional (non-growth) sectors to more modern, growth-inducing sectors as well as encourage businesses in these modern sectors of the economy. Levine [37] explains the impact of financial development from two angles: the view of financial services and the view of law and finance. When looking at the situation from the perspective of financial services, it emphasizes how crucial the financial system is to minimizing market imperfections and providing the private sector with essential services, which helps the economy perform better. By evaluating investment opportunities, exercising corporate governance, strengthening the management of risks, and lowering the cost of resource mobilization, financial systems improve the performance of the economy (Levine [38]). Financial development variables were found to significantly and favorably affect investment, according to King and Levine [39], Valderrama [40], and Deltuvaite and Sineviciene [12].

Misati and Nyamongo [41] looked into the impact of financial SSA development on investment while controlling it with political regime. According to the study, investment is adversely correlated with deposit interest rates and institutional characteristics but positively correlated with private sector credit and turnover ratio. According to Roger and George [42], the financial sector has a considerable impact on savings and subsequent investment in African nations. According to Agu [43], Nigeria's investment has slowed down due to higher lending rates, lower state spending, lower savings, political unrest, and poor infrastructure. Adu et al. [44] found a positive relationship between private sector credit and domestic investment, while finding a negative relationship when money supply was used as a proxy for financial development. By using the ARDL approach, Kargbo and Adamu [45] also discovered a positive relationship between financial development and economic growth in Sierra Leone.

Using a set of data from Nigeria, Osinubi and Amaghionyeodiwe [46] found no evidence of a relationship between indicators of capital market development and the growth rate of the economy between 1980 and 2000. Ndebbio [47] examined the relationship that exists among the deepening of the financial sector, economic growth, and development in sub-Saharan African countries. He came to the conclusion that the per capita growth rate of output is not positively impacted by real and nominal money supply or financial intermediation. In a cross-country analysis of the relationship among stock and investment effectiveness in African economies, Misati [41] showed that only North and Southern African countries are affected by investment efficiency. The results for sub-Saharan Africa, however, do not match this expectation. According to Ghura and Goodwin [48], lending to the private sector encourages private investment in Asia, Latin America, and SSA. Ho et al. [27] further revealed that financial deepening creativity is needed for investment in any nation. Le [11] in his study discovered that sociopolitical instability characterized by non-violent protests promotes investment, while violent uprisings hinder private investment. Similarly, Alhassan et al. [49] revealed a positive association between financial institutions and markets' development and economic progress in both upper–middle-income and lower–middle-income countries in Asia. Ferreira, Tadeu, and Silva [19] explored the determinants of private investment in Brazil. Using panel data and a fixed effects model, the result revealed a positive relationship between funding and investment.

The majority of the reviewed studies (such as Kargbo and Adamu [45] and others) considered a single country analysis, neglecting cross-country investigation such as in West African countries. Furthermore, the reviewed studies failed to consider the impact of the deepening of the insurance sector on domestic investment, which this study adequately considered.

2.2.3. Sustainable Energy Supply and Domestic Investment

The energy sector of any nation has a positive effect on businesses' efficiency, productivity, and effectiveness across a range of industries (Rehman et al. [50]). A wide range of productivity and services depend on infrastructure development, without which no significant economic activity can be carried out. Canning and Pedroni [51] asserted that increasing infrastructure spending which is important for maximum growth reduces the available funds for other unnecessary types of investment that may slow growth. According to Ntebo et al. [52], the expansion of the electricity infrastructure can support urban development and regional and national progress. According to Nketiah-Amponsah and Sarpong [53], an increase of 1% in transportation and electrical infrastructure leads to growth of 0.09 and 0.06%, respectively. Finally, Onabote et al. [54] found foreign direct investment infrastructure to significantly affect productivity in Nigeria.

3. Methodology

3.1. Model Specification

The supply leading hypothesis, which holds that the economy responds to real sector expansion aided by financial development, served as the foundation for this study. In order to determine whether financial deepening and sustainable energy supply influence domestic investment in West Africa, we classified the financial deepening variables as banking sector variables, namely credit to private sector/GDP, money supply/GDP, and interest rates/GDP; capital market variables, namely market capitalization/GDP and volume of trade/GDP; and insurance sector variables, namely insurance premiums/GDP, while sustainable energy supply was proxied with access to electricity (% of population). The dependent variable was domestic investment. This study made use of the autoregressive distributed lag model (PMG/MG-ARDL) method of estimations. Pesaran et al. [55] presented the PMG estimator in 1999, which involves pooling and averaging the coefficients across the cross-sectional units. On the other hand, the MG recommends assessing each unit independently and averaging the predicted coefficient across the cross-sectional units (Pesaran and Shin [56]). The ARDL model was employed since it is appropriate for our data collection because it allows a mix of stationary variables such as I(0) and I(1). In addition, it is suitable for studies with modest sample numbers. The 16 cross-sections (16 countries) and 31-year time series in this study are smaller than those in most panel studies, which ARDL models can adequately handle.

3.2. Model Specification

This study modeled domestic investment as a function of financial deepening and sustainable energy supply. The model specification was stated as follows:

$$\text{DOI} = f\ (\text{CPS, MS, INTR, MC, ISS, AE, ETD}) \tag{1}$$

Econometrically, it can be written as follows:

$$\Delta \text{DOI}_{\text{it}} = \beta 0 + \beta_1 \Delta \text{CPS}_{\text{it}} + \beta_2 \Delta \text{MS}_{\text{it}} + \beta_3 \Delta \text{INTR}_{\text{it}} + \beta_4 \Delta \text{MCGDP}_{\text{it}} + \beta_5 \Delta \text{ISS}_{\text{it}} + \beta_6 \Delta \text{AE}_{\text{it}} + \beta_7 \Delta \text{EXRA}_{\text{it}} + \varepsilon_{\text{it}} \tag{2}$$

where DOI = domestic investment (proxy with domestic investment is proxy by the total quantum of capital acquisition); CPS = credit to private sector to GDP; BMV = broad money to velocity (proxy with the ratio of M2 to nominal GDP); MCGDP = market capitalization (proxy with the ratio of listed shares to GDP); ISS = insurance services (proxy with the ratio of insurance services transacted to GDP); AE = sustainable energy supply (proxy with access to electricity (% of population)); INTR = interest rate (proxy with real interest rate is measured by rate of interest an investor, saver, or lender receives (or expects to receive) after allowing for inflation); EXRA = exchange rate (proxy with real exchange rate, which measures the price of foreign goods relative to the price of domestic goods); β1, β2, β3, β4, β5, β6, and β7 are the coefficients to be estimated; ε = error term. The subscripts i and t indicate country and time period, respectively.

4. Results

The summary data from the 16 West African economies are presented in Table 1.

Table 1. Descriptive statistics.

	(1)	(2)	(3)	(4)	(5)
Variables	**N**	**Mean**	**Std. Dev.**	**Min**	**Max**
Domestic investment (DOI)	496	20.33	10.93	−2.424	131.05
Credit to private sector (CPS)	496	13.70	11.78	0	73.19
Insurance services (ISS)	496	3.24	7.10	0	96.32
Market capitalization (MCGDP)	496	0.267	1.85	0	24.20
Broad money to velocity (BMV)	496	26.53	17.94	0	125.29
Interest rate (INT)	496	3.69	8.21	0	33.46
Exchange rate (EXRA)	496	745.48	1531.42	0	9829.92
Sustainable energy supply (AE)	496	27.09	23.40	0	94.16
Number of countries	16	16	16	16	16

Source: Authors' computation.

The descriptive statistics of the variables used in the study are presented in Table 1. The results indicate the total number of observations and the mean, standard deviation, minimum, and maximum values of all the variables for a panel of 16 West African countries over the period 1990 to 2020. The results show that the average DOI, CPS, ISS, BMV, MCGDP, INTR, EXRA, and AE values are 20.33, 13.70, 3.24, 0.267, 26.53, 3.69, 745.48, and 27.09, respectively. The standard deviations are 10.93, 11.78, 7.10, 1.85, 17.94, 8.21, 1531.422, and 23.40 for these variables, respectively. The minimum value of DOI is −2.424 and the maximum is 131.05. Furthermore, CPS has a minimum of 0 and a maximum of 73.19. ISS varies from 0 to 96.32, while MCG varies from 0 to 24.20 among the countries over the period considered. Additionally, INTR has a minimum of 0 and a maximum of 33.46, while in the same vein, the minimum and maximum values of EXRA are 0 and 9829.92, respectively. Meanwhile, BMV has a minimum of 0 and a maximum of 125.29, and the minimum and maximum values of AE are 0 and 94.16, respectively. This shows a significant variation in all the variables over the studied period. This enormous variation warrants investigation. Therefore, this current study evaluates the impact of financial deepening and sustainable energy supply on domestic investment in West Africa over the period of 1990 to 2020.

In a multiple regression model, multicollinearity (the interdependence of independent variables) causes biased estimations of the coefficient, which makes the regression result unreliable. In this investigation, a correlation test was performed to see if multicollinearity existed. Results as presented in Table 2, all of the correlation coefficients between the independent variables, according to the correlation analysis findings, are lower than 0.5. Moreover, the variance inflation factor (VIF) test was also employed to test the presence of multicollinearity. The rule of thumb is that when the VIF value is greater than five, there is a problem of multicollinearity; otherwise, there is no problem of multicollinearity. The result of the VIF test showed that the values of the VIF are 3.37, 1.05, 1.07, 3.14, 1.03, 1.08, and 1.49 for credit to the private sector, insurance services, market capitalization, broad money to velocity, interest rate, exchange rate, and sustainable energy supply, respectively, which are all lower than five. Therefore, there is no multicollinearity between them.

It is important to perform a unit root test to examine the order of integration of a series. Therefore, Im, Pesaran, and Shin [57] and Levin, Lin, and Chu [58] unit root tests were conducted in this study, and the results are presented in Table 3. The results of the IPS and LLC tests revealed that interest rates and insurance services are stationary at level. That is, they are integrated of order zero [I(0)], while domestic investment, credit to the private sector, money supply, market capitalization, access to electricity, and exchange rates are stationary at first difference, which means that they are integrated of order one—that is, I(1).

Table 2. Correlation.

Variables	DOI	ISS	CPS	MCK	BMV	INT	EXCR	AE	VIF
Domestic investment (DOI)	1.00								
Credit to private sector (CPS)	−0.09	1.00							3.37
Insurance services (ISS)	0.28	0.00	1.00						1.05
Market capitalization (MCGDP)	0.01	0.07	0.02	1.00					1.07
Broad money to velocity (BMV)	0.20	−0.01	0.81	0.01	1.00				3.14
Interest rate (INT)	−0.04	−0.05	−0.02	−0.00	0.03	1.00			1.03
Exchange rate (EXRA)	−0.01	0.17	−0.17	−0.03	−0.10	−0.03	1.00		1.08
Sustainable energy supply (AE)	0.29	0.01	0.51	0.21	0.48	0.08	−0.04	1.00	1.49

Table 3. Result of unit root (stationarity) test.

	IPS		LLC	
Statistics	**At Level t-Statistics**	**At First Difference t-Statistics**	**At Level t-Statistics**	**At First Difference t-Statistics**
Domestic investment (DOI)	−1.5271	−13.920 ***	−5.865	−19.563 ***
Credit to private sector (CPS)	0.207	−9.541 ***	−4.941	−14.892 ***
Broad money to velocity (BMV)	1.468	−11.049 ***	−3.326	−16.806 ***
Interest rate (INT)	−1.783 ***	−7.547 ***	−10.181 ***	−23.213 ***
Market capitalization (MCGDP)	−1.213	−6.331 ***	−4.740	−17.029 ***
Insurance services (ISS)	−1.725 **	−12.763 ***	−6.553	−18.308 ***
Sustainable energy supply (AE)	3.448	−13.734 ***	−2.691	−19.178 ***
Exchange rate (EXRA)	1.765	−9.576 ***	−0.854	−14.353 ***

Note: IPS and LLC refer to tests by Im, Pesaran, and Shin [57] and Levin, Lin, and Chu [58]), respectively. ** and *** denote significance at the 5% and 1% levels, respectively. Rejection of the null hypothesis (p-value < 5%) indicates the absence of unit root.

Interpretation of Results

By using the Hausman test, we could choose the best suited model between the pooled mean group and the mean group as well as between the pooled mean group and the dynamic fixed effect. The test in this study, however, revealed that the pooled mean group is the most suitable model because the results were not statistically significant. Thus, the pooled mean group estimator served as the foundation for our interpretation. The long-run assessment in Table 4 below indicates that credit to the private sector has a positive relationship with domestic investments, which is significant at the 1% level. Essentially, the coefficient value of credit to the private sector for domestic investment is positive (0.3090) and significant at the 1% level. Every unit rise in credit to the private sector leads to an increase of 0.3090 in domestic investment. This is consistent with the result of Adu et al. [44], which allows the continued existence of companies deprived of funding. This is also supported by the works of Adamopoulos [31]; Mehrara and Ghamati [30]; Sineviciene and Deltuvaite [12]; Ferreira, Tadeu, and Silva [19]; and Ghura and Goodwin [48] which averred that financial deepening is an important factor in the mobilization and allocation of savings for productive use of any nation. Similarly, the money supply is significant to domestic investment at the 1% level of significance with a coefficient value of 0.4607. This means a unit rise in money supply leads to an increase of 0.4607 in domestic investment. This is consistent with the work of Rafindadi and Yosuf [59] that found money supply to make a significant contribution to gross domestic product. However, insurance services and market capitalization are not significant to domestic investment. This is consistent with the studies of Osinubi and Amaghionyeodiwe [46] and Ndebbio [47] which opined that the capital market does not significantly impact domestic investment in West African countries. However, at the 1% level of significance, access to electricity displays a positive significant relationship with domestic investment with a coefficient value of 0.0828. This means a unit rise in access to electricity leads to an increase of 0.0828 in domestic investment. This is in agreement with the works of Ntebo et al. [52], Nketiah-Amponsah and Sarpong [53], and Onabote et al. [54] which supported that a sustainable energy supply improves the productivity and investment of any nation. Furthermore, interest rates and exchange rates are not significant to domestic investment. In addition, as indicated in the table, the coefficient of error correction term is −0.3490. Given the *t*-statistic of 0.0727, the value is statistically significant at 1%. Since it is negative and significant, it is implied that domestic investment responds to shocks from credit to the private sector, money supply, interest rates, insurance services, market capitalization, access to electricity, and exchange rates. This means that domestic investment is getting adjusted at a speed of 0.3490 from a state of disequilibrium in the short run to a state of equilibrium in the long run.

Table 4. Regression results of domestic investment (DOI) model.

	Dependent Variable: Domestic Investment		
Independent Variables	**Pooled Mean Group**	**Mean Group**	**Dynamic CCE (CS-ARDL)**
Long-run coefficients			
Credit to private sector (CPS)	0.3090 *** (0.0856)	0.2563 * (0.1530)	0.4855 (0.4584)
Broad money to velocity (BMV)	0.4607 *** (0.0847)	0.0289 (0.0996)	0.0225 (0.1880)
Insurance services (ISS)	−0.0092 (0.1173)	0.4305 *** (0.1174)	1.3886 (1.6494)
Market capitalization (MCGDP)	0.0247 (0.0985)	0.0413 (0.4551)	−155.34 (369.93)
Sustainable energy supply (AE)	0.0828 (0.0210)	0.1691 *** (0.0539)	0.2735 (0.1944)
Interest rate (INT)	0.0630 (0.1330)	−0.3539 *** (0.1276)	0.2857 (0.3554)
Exchange rate (EXRA)	0.00009 (0.0005)	0.00003 (0.0007)	0.0200 (0.0754)
Hausman rest	5.92 (0.5496)	1.75 (0.9725)	
Short−run coefficients			
Error correction	−0.3490 *** (0.0727)	−0.5677 *** (0.0419)	0.6876 *** (0.0622)
Credit to private sector (CPS)	−0.2308 (0.3370)	0.0784 (0.1434)	−0.6619 (0.6347)
Broad money to velocity (BMV)	−0.2667 *** (0.0762)	0.1195 ** (0.0569)	−0.1611 (0.0944)
Insurance services (ISS)	0.5026 (0.5264)	0.1629 ** (0.0684)	−0.3067 (0.5321)
Market capitalization (MCGDP)	−37.0848 (159.5608)	−0.1277 (0.3225)	150.8782 (93.5449)
Sustainable energy supply (AE)	0.1904 *** (0.0807)	−0.1233 (0.0821)	−0.3190 (0.1569)
Interest rate (INT)	−0.0289 (0.0558)	0.0639 (0.0553)	−0.1501 (0.1823)
Exchange rate (EXRA)	0.01294 (0.1801)	0.0052 (0.0026)	0.4109 (0.3406)
Cons	4.1265 *** (1.2052)	8.1048 *** (1.2395)	18.5470 *** (5.9515)

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors in parentheses. Source: Authors' computation (2022).

5. Conclusions

Using the cross-sectional autoregressive distributed lag model (CS-ARDL) panel estimator to analyze data from 1990 to 2020, which were sourced from the World Development Indicator database, we examined the nexus between financial deepening, sustainable energy supply, and domestic investment in West Africa. It was inferred from our studies that financial deepening variables significantly impact domestic investment in West Africa. Furthermore, sustainable energy supply significantly impacts domestic investment in West Africa. Some proxies were adopted, and the need for data transformation was the limitation of this study. However, the findings of this study are accurate, comprehensive, reliable, and therefore fit for policy formulation and implementation. Based on the conclusions, the study recommends that the management of banks should be encouraged to pursue policies that will deepen the efficient allocation of financial services for domestic investment in the region. The governments of West African countries should strive to stabilize their capital markets, thereby pursuing competitive market policies; this will improve the competitiveness of local firms by enhancing domestic investment output. Furthermore, the insurance regulatory agencies of West African countries should also implement policies and programs aimed at restoring customers' confidence, trust, and loyalty with a reflective effect in increased sales and insurance penetration. We also recommend that interest rates should be managed in a way that will encourage the use of financial services by the unbanked population.

Although the current study explores the nexus between sustainable energy supply, financial deepening, and domestic investment in 16 West African countries, it fails to account for demographic indicators, which serves as a limitation alongside the availability of the data. Thus, future studies could explore this theme while considering other macroeconomic variables not captured in the current study. Additionally, future studies can also explore this subject under an asymmetric framework.

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Examining the Interaction Effect of Control of Corruption and Income Level on Environmental Quality in Africa

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Abstract: The effects of corruption and income on environmental degradation is well established in the literature. However, little attention has been given to how the control of corruption affects the environmental quality at different levels of income. This study examines the interaction effect of the control of corruption and income on environmental quality in Africa over the period from 1996 to 2017. Using a Method of Moments Quantile Regression (MMQR) with fixed effects, the results revealed that both the control of corruption and income level increase CO_2 emissions while their interaction term reduces CO_2 emissions. This implies that the interaction effect of the control of corruption and income level mitigates carbon emissions. Particularly, the marginal effect of the control of corruption on CO_2 emissions decreases as income level increases. Furthermore, renewable energy consumption has a negative and significant effect on CO_2 emissions. The effect of foreign direct investment on CO_2 emissions is positive and significant, which validates the pollution haven hypothesis. These results are heterogeneous across the quantile distribution of CO_2 emissions. Based on these findings, our study suggests the need for the government and policymakers to stimulate income levels as a prerequisite for achieving sound and effective environmental policies in Africa.

Keywords: environmental quality; corruption; income level; renewable energy; Africa

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1. Introduction

Concerns about environmental sustainability are closely linked to the global stance against the vexed issue of global warming and climate change. The general consensus is that the rapid economic and social progress achieved in the past three decades, driven largely by fossil fuels, along with rapid growth in the human population is unsustainable. These concerns are exacerbated by the economic expansion with significant environmental disruptions, which occur at the national and international levels, exposing the entire world to danger [1]. Arguably, the increased attention given to the environmental question is also in accepting the fact that environmental sustainability remains one of the compelling cardinal targets of the United Nations Sustainable Development Goals (SDGs). Therefore, there exists the need for a proper interrogation of the environmental questions at all levels of governance, especially in Africa.

Based on the increasingly negative impact of climate change in Africa, the issue of environmental sustainability has become a top policy issue in recent times. The continent is most vulnerable to the effects of climate change under all climate scenarios above 1.5 °C, which is the global target. Even though, by comparison, Africa has a lesser contribution to global warming and other significant climate changes, the continent has been facing existential exponential collateral and environmental damages, leading to systemic risks in its economies, infrastructure investments, public health, water and food systems, agriculture, and livelihoods. All of these threaten to undo Africa's modest development gains and, therefore, slip into higher levels of extreme poverty [2]. To actively tackle the menace of environmental degradation and achieve a sustainable environment, the sub-Saharan African countries have signed and ratified the Paris Agreement and other related climate action consensuses towards reducing greenhouse gas and building alternative energy resources.

In addition to the over-dependence on fossil fuel energy to drive economic expansion, the African continent also faces the challenge of corruption in its efforts to achieve environmental sustainability. Corruption can be seen as the abuse of power, by the persons entrusted with it, for personal gains [3,4]. There are many forms of corruption, but the most common and worrisome form of corruption is financial corruption, which takes the form of bribes, kickbacks, inappropriate gifts, double-dealing, and other forms of dishonest financial dealings with Transparency International. The extant literature suggests that corruption influences the quality of the environment in two ways. First, it affects the environment by distorting the flow of investments and economic activities that may lead to improvement in the quality of the environment [3–5]. Second, corruption can destabilize the stringency of environmental laws and regulations, thereby exerting a negative influence on the environment [6–8].

While several studies [3,4,6,9] confirm that corruption aggravates CO_2 emissions and degrades the environment, little attention has been given to the effects of control of corruption on the quality of the environment. Meanwhile, unabated corruption may lead to the diversion or misappropriation of resources meant for promoting sustainable material consumption and combating environmental degradation. For instance, [10] found corruption in Tunisia to have been associated negatively with environmental quality measured by CO_2 emissions. Moreover, [11] divulged that the lower the corruption, the more energy efficiency there is for all income group economies. Since the control of corruption is expensive (requiring the setting up of agencies, procurement of modern equipment and gadgets, as well as personnel costs), countries with high levels of income are likely to achieve higher successes in the control of corruption.

Furthermore, as a continent of developing countries, Africa is seen as a haven for polluting industries due to the weak environmental laws, consistent with the pollution haven hypothesis which postulates that; developing economies keep their domestic environmental regulations laxer, thus offering the highly polluting multinational corporations the opportunity to move in their investments in form of foreign direct investment (FDI) [12–14]. The argument in support of FDI is that it enhances the transfer of technological innovation and consequently, provides the basis for the implementation of greener and cleaner modes of production [13]. In contrast, the economic literature argues that the FDI-induced environmental consequences due to increased CO_2 emissions outweigh the economic benefits associated with FDI inflows. To balance up, there is, therefore, a need for the African countries to quickly align to the global trend of increasing the share of renewable energy in the total energy mix. Renewable energy consumption is crucial in reducing CO_2 emissions and achieving green growth. In this regard, most African countries have started diversifying their energy portfolios by increasing the share of renewables in their total energy mix [1,15–18]. Empirically, several studies have confirmed the effect of renewable energy on reducing environmental degradation [19,20].

Given the position of the literature that the environment is always susceptible to continuous destruction when corruption becomes common in government and its agency structures, it becomes apparent that to reduce environmental degradation, institutions that relate to the process of environmental policymaking play an important role. Furthermore, the fight against corruption requires huge funding. Given the level of income in the African continent, it is still not empirically clear whether the fight against corruption can lead to effective environmental protection and sustainability in the continent.

Therefore, the main objective of the study is to examine the impact of the interaction of the control of corruption and income levels on environmental quality in Africa. The current study contributes to the literature by examining the determinants of environmental quality, measured by the level of CO_2 emissions in Africa. We show that the control of corruption is a significant determinant of CO_2 emissions in Africa, even when interacting with the level of income to account for the relevance of income in addressing the environmental question and achieving sustainable development. Our results also show that for developing countries, such as African countries, renewable energy consumption and foreign direct investment have a significant influence on the quality of the environment.

The rest of the study is organized as follows. Section 2 deals with a brief literature review. Section 3 focuses on the methodology. Section 4 presents the empirical results, and Section 5 concludes the paper and makes policy recommendations.

2. Literature Review

Theoretically, the relationship between economic growth and environmental degradation is better captured with the famous environmental Kuznets curve (EKC) hypothesis, which hypothesizes an inverse relationship between a country's level of pollution and its real GDP. However, the validity of the EKC hypothesis remains a disputable fact across countries, perhaps due to variation in the time frame, methodology, and country peculiarities [19,21–25]. In the case of Africa, several studies have presented conflicting submissions regarding the true nature of the relationship between CO_2 emissions (often used as a proxy for environmental pollution) and real income level, thus generating a crisis that does not support sound and formidable policy prescription and, consequently, opening the door for further studies [23,26]. Similarly, the study [27] validated the EKC for Nigeria by taking into account the role of international trade. Thus, the validity of the EKC remains a subject of heated debate in Nigeria.

The extant literature is active on the nexus between corruption and environmental sustainability [3–5,28,29]. The popular opinion is that corruption may stimulate environmental degradation in direct and indirect ways [5]. For instance, [3] applied a dynamic ARDL simulation technique to study the effects of social and economic factors on the environmental quality in Nigeria. While economic growth increased environmental degradation in Nigeria, corruption and internal conflict reduced environmental degradation through a decrease in investments and growth. The authors of [5] used system GMM on provincial panel data in China's industry from 2005 to 2015 to establish that corruption influences CO_2 emission through the distortion of environmental policy and by lowering the monitoring levels. Moreover, [9] used a panel quantile regression method to study how corruption affects CO_2 emissions and economic growth in Africa. The results revealed the following: (i) a higher level of corruption in Africa; (ii) corruption is negatively related to CO_2 emissions in lower emission countries; (iii) in higher emission countries, corruption is not a significant enough factor to explain changes in CO_2 emissions; and (iv) corruption is positively affected by CO_2 emissions. This positive effect supersedes the negative effect, and hence, the total effect of corruption is positive. Similarly, [4] studied the environmental sustainability impact of corruption using panel data on 16 southern African countries. Applying system GMM and DH Granger causality, the study divulged that corruption causes environmental quality in southern African countries. Wang et al. (2018), in a study, evaluated the nexus between economic growth and carbon emissions within the context of the environmental Kuznets curve hypothesis, covering the period from 1996 to 2017 for the BRICS countries. The results of the study showed that corruption control could reduce carbon emissions. Furthermore, Sinha et al. (2019), in their study involving BRICS and the Next Eleven countries, asserted that corruption dampens environmental quality. Likewise, [10] examined Tunisia's case of the effects of corruption on CO_2 emissions and energy consumption. Applying the ARDL modeling technique, the study presented that corruption is related negatively to environmental quality, which is perhaps measured by CO_2 emissions, while its effect on energy consumption is negative and statistically significant.

Regarding the nexus between FDI and CO_2 emission, [30] in a study on 55 Asia-Pacific countries observed that developing countries, such as most of the African countries, adopted convenient environmental regulations for various reasons, including the fact that economic growth is the major objective of these countries and not the quality of the environment. The study established that FDI causes a rise in CO_2 emissions and contributes to environmental deterioration. Corroboration of this assertion was the study of [31], which showed that FDI brings beneficial environmental impacts to developed countries, while it brings negative impacts to the environmental quality of poor or developing nations. The authors of [32], using green technology, FDI, and environmental regulation, found that environmental regulation has a significant effect on green technology innovation and that FDI causes green technology innovation to decrease. Ref. [33] applied PMG and the DH causality test to study the effect of ICGT and inflows of foreign direct investment on environmental degradation in some Asia-Pacific countries. The study found that foreign investment and ICT have a long-running negative impact on the environment. The authors of [12] examined the effect of foreign direct investment on CO_2 emissions in Pakistan from 1971 to 2014, within the context of the Pollution Haven Hypothesis. Using the ARDL and the ECM models, the results of the study confirmed the increasing effects of FDI on CO_2 emissions, thereby upholding the Pollution Haven Hypothesis. Applying the non-linear approach, [34] explored the relationship between foreign direct investment and environmental degradation in high-income, middle-income, and low-income countries. The results suggested that the environmental Kuznets curve exists, and foreign direct investment increases environmental degradation, also supporting the existence of the Pollution Haven Hypothesis. The authors of [30] in a study on the effect of inward FDI on environmental quality in China showed an inverse U-shape relationship between inward FDI and carbon emissions for the aggregate samples, while the provincial divisions presented heterogeneous results. These findings are confirmed by the studies of [13] which suggested that the entry of FDI into Latin American countries increases CO_2 emissions and consequently dampens the environmental quality.

Concerning the role of renewable energy use and environmental sustainability, the authors of [35], in a study on the nexus between renewable energy use and environmental protection of the Next Eleven developing economies, showed an inverse relationship between renewable energy and CO_2 emission. The authors of [36] confirmed the results for 25 selected African countries by establishing that renewable energy consumption decreases CO_2 emissions. Similarly, the studies [20,23] indicated that renewable energy consumption has a significant effect in reducing CO_2 emissions.

The review of the empirical literature shows that there are few studies and supporting data evaluating the consequences of corruption on environmental sustainability in the emerging economies of Africa, generally regarded as the most corrupt continent on the globe. Moreover, there are few or no studies focusing on the control of corruption's effect on the environment in Africa. Our study is the first, to the best of our knowledge, that focuses on the interactive effects of the control of corruption and income level on the environmental quality in Africa. This is particularly important because the fight against corruption is expensive, and therefore, countries with higher income levels may likely attain higher levels of environmental quality traceable to the pursuit of the control of corruption than countries with lower income levels. In addition, our study uses robust econometric procedures (Method of Moments Quantile Regression (MMQR) with fixed effects) to show how the interaction term with other control variables affects environmental quality across the quantile distribution. Finally, we used the Driscoll–Kraay standard errors based on the estimations of fixed-effects OLS and GLS random effect to control for serial correlation and cross-sectional dependence.

3. Materials and Methods

3.1. Data and Description

In this study, environmental quality was proxied by the level of per capita carbon dioxide (CO_2) emissions in metric tons. The control of corruption (CC) was measured as −2.5 for weak governance and +2.5 for strong governance. Per capita GDP (GDP) which is proxied for the level of income was measured at constant 2015 US Dollars divided by the total population. Renewable energy (REN) measured the percentage of renewables in total final energy consumption, while foreign direct investment (FDI) was measured as the direct investment equity inflows in current US Dollars. Furthermore, all variables used in this study were downloaded from the website of the World Bank via World Development Indicators (WDI), except the control of corruption which was downloaded from the Worldwide Governance Indicators. We selected the period of the study, i.e., 1996 to 2017, based on the data availability. The variables, their measurements, and sources are summarized in Table 1 below. The list of investigated countries are presented in Table A1 in the Appendix A.

Table 1. Description/measurement of variables and sources.

Variable	Description/Measurement	Source
Carbon dioxide emissions ($\ln CO_2$)	CO_2 emissions (metric tons per capita).	World Development Indicators (WDI)
Control of Corruption (CC)	−2.5 for weak governance and +2.5 for strong governance.	Worldwide Governance Indicators (WGI)
Economic Growth ($\ln GDP$)	Real GDP (constant 2015 US Dollars) per capita.	World Development Indicators (WDI)
Renewable Energy Consumption (REC)	Percentage of renewables in total final energy consumption.	World Development Indicators (WDI)
Foreign Direct Investment ($\ln FDI$)	Direct investment inflows measured in current USD.	World Development Indicators (WDI)

Source: Authors' computation.

3.2. Empirical Modelling

To achieve the objective of this study, we applied econometric methodological techniques. Based on the empirical works of [37,38], the functional model of the environmental quality with some modifications was specified as:

$$CO_2 = f(CC,\ GDP,\ CC * GDP,\ REN,\ FDI) \quad (1)$$

where CO_2 is the country's carbon dioxide emission, CC denotes the control of corruption, GDP is a real gross domestic product, REN is the renewable energy consumption, FDI represents foreign direct investment, and $CC * GDP$ is the interaction term of the control of corruption, and level of income. The econometric model of the functional relationship in Equation (1) was given as follows:

$$\ln CO_{2it} = \alpha_i + \rho_1 CC_{it} + \rho_2 \ln GDP_{it} + \rho_3 (CC_{it} \times \ln GDP_{it}) + \rho_4 \ln REN_{it} + \rho_5 lnFDI_{it} + \varepsilon_{it} \quad (2)$$

where ln represented the natural logarithms of the variables, except the control of corruption. Each country was represented by a time period. The main contribution of our paper was the argument that the level at which control of corruption influences environmental quality may be dependent on the level of income of a country; hence, we took the interaction term of the control of corruption and income level, i.e., $CC * \ln GDP$. The variables, REN and $\ln FDI$ were included in the model as control variables. α was the intercept, while ε was the residual term with zero mean and constant variance, σ^2, $\varepsilon_t \sim iid(0, \sigma^2)$.

3.3. Method of Moments Quantile Regression (MMQR)

Quantile regression analysis became important in the empirical modeling because of the shortcomings of the conditional mean regression approach. Basically, a conditional mean regression estimator uses a conditional mean, which is located in the middle of a distribution. This means that the conditional mean-based estimator only describes the incomplete distribution. To provide information on how the independent variables affect the entire conditional distribution, a quantile regression analysis is suggested by different scholars [39–42]. Applying a quantile regression in this paper, we followed the recent Method of Moments Quantile Regression (MMQR) with fixed effects, developed recently by the authors of [43]. This method allowed differencing out individual effects in the panel as it is usually performed in the estimation of the conditional mean and provides information on the effect of independent variables on the dependent variable using the entire conditional distribution. Moreover, the method controlled for heterogeneity, and as such, detected asymmetry associated with the series explored. Therefore, in a simple term, the MMQR can be specified as follows:

$$Y_{it} = \alpha_i + X_{it}'\beta + \sigma\left(\delta_i + Z_{it}'\gamma\right)U_{it} \tag{3}$$

where $(\alpha,\ \beta',\ \delta,\ \gamma')'$ are unknown parameters, $(\alpha_i, \delta_i), i = 1, \ldots, n$ of course, capture the individual i fixed effects, and Z' is defined as a k-vector of known differentiable transformations of the components of X_{it} with element l given by $Z_l = Z_l(X_{it})$ where $l = 1, \ldots, k$. The probability, $P\{\delta_i + Z_{it}'\gamma > 0\Big\} = 1$, and U_{it} represented an unobservable random variable that was palpably independent of X_{it}.

To satisfy the moment conditions, ref. [43] suggested that the density function, $F_U(\bullet)$ should be bounded away from 0, and hence, normalized, i.e., $E(U_{it}) = 0$ and $E(|U_{it}|) = 1$. Therefore, Equation (3) becomes:

$$Q_Y(\tau|X_{it}) = (\alpha_i + \delta_i q(\tau)) + X_{it}'\beta + Z_{it}'\gamma q(\tau) \tag{4}$$

where $q(\tau) = F_U^{-1}(\tau)$, and hence, $P(U < q(\tau)) = \tau$. The scaler parameter was given by $\alpha_i(\tau) \equiv \alpha_i + \delta_i q(\tau)$ and is indicative of the quantile-τ fixed effect for an individual, i. Unlike the ordinary least squares-fixed effects, the distributional effect of MMQR allowed varying impacts across the quantiles of the conditional distribution of Y, i.e., the dependent variable.

4. Results and Discussion

4.1. Preliminary Analysis

We begin the analysis by presenting the descriptive statistics of the variables explored in this study. From the descriptive statistics table (Table 2), it is clear that the mean of all the variables was large, except for the lnCO_2 emissions and CC. This suggested that the variables are not normally distributed, as can be seen by the Jarque–Bera statistics and their respective p-values. The standard deviation of the variables suggested that all of the variables were not too volatile, except renewable energy, which is highly volatile. Furthermore, the variables had positive kurtosis, which by approximations are close to the value of 3. The skewness of lnCO_2 and lnGDP were all positive while CC, REN, and lnFDI were negative, and they were all close to zero.

The correlation matrix of the variables provides that lnCO_2 had a negative and significant correlation with CC and REN. The correlation between lnCO_2 and lnGDP was positive and was also positive also with lnFDI. CC had a negative correlation with REN and lnFDI, while the correlation between CC and REN was positive. The correlation between lnGDP and REN was negative, while the correlation with lnFDP was positive. Moreover, REN had a negative correlation with lnFDI. These correlations were all statistically significant as shown via their respective probability values.

In Table 3, we present the results of the cross-sectional dependence. The results showed that in all the variables, the null hypothesis of no cross-sectional dependence was rejected. This implied that there is a cross-sectional dependence in all of the variables. Table 4 reports the results of the panel unit root tests. In this section, two-panel unit root tests were performed. First, the traditional unit root test proposed by [44] was applied while the second-panel unit root test applied was based on the second-generation unit root test advanced by [45], which controlled for cross-sectional dependence. The tests were conducted with the trend and intercept and the results were as follows: Based on the traditional panel unit root test of [44], the variables were stationary at levels, except for lnGDP, which was only stationary at the first difference. However, when cross-sectional dependence was controlled for, the results based on [44] showed that at levels, only $lnCO_2$, lnGDP, and lnFDI were stationary while CC and REN were only stationary at their first differences.

Table 2. Summary descriptive statistics.

Variable	$lnCO_2$	CC	lnGDP	REN	lnFDI
Mean	−0.853041	0.638209	6.902804	63.38086	19.49870
Median	−1.089915	0.600000	6.672230	77.37345	19.72185
Maximum	2.238980	2.130000	9.573770	98.34290	23.17240
Minimum	−4.115810	−1.220000	4.630820	0.059000	11.56060
Std.Dev.	1.425835	0.601351	1.057960	30.09306	1.893661
Skewness	0.306323	−0.186970	0.357867	−0.923091	−0.794093
Kurtosis	2.277278	2.860812	2.265845	2.415076	4.085796
Jarque-Bera	27.97715	4.961850	32.76421	116.8914	115.3568
Probability	0.000001	0.083666	0.000000	0.000000	0.000000
Observations	748	748	748	748	748
			CorrelationMatrix		
Variable	**$lnCO_2$**	**CC**	**lnGDP**	**REN**	**lnFDI**
$lnCO_2$	1.000000				
	——				
CC	−0.210956	1.000000			
	(0.0000)	——			
lnGDP	0.888235	−0.278047	1.000000		
	(0.0000)	(0.0000)	——		
REN	−0.823869	0.397265	−0.722741	1.000000	
	(0.0000)	(0.0000)	(0.0000)	——	
lnFDI	0.387732	−0.114827	0.506662	−0.366585	1.000000
	(0.0000)	(0.0017)	(0.0000)	(0.0000)	——

Table 3. Cross-sectional Dependence Test.

Variables	Breusch and Pagan LM Test	Pesaran CD Test	Pesaran LM
$lnCO_2$	4852.05 ***	30.826 ***	128.105 ***
p-value	(0.0000)	(0.0000)	(0.0000)
CC	2411.60 ***	−1.1039	55.248 ***
p-value	(0.0000)	(0.2696)	(0.0000)
lnGDP	8721.35 ***	91.125 ***	243.62 ***
p-value	(0.0000)	(0.0000)	(0.0000)
REN	4297.15 ***	39.980 ***	111.539 ***
p-value	(0.0000)	(0.0000)	(0.0000)
lnFDI	4129.8 ***	59.6977 ***	106.54 ***
p-value	(0.0000)	(0.0000)	(0.0000)

Note: *** reflects the statistical significance of values at a 1% level.

Having found the stationarity properties of the series, the study further tested the cointegrating properties of the series. As shown in Table 5, the Pedroni residual-based cointegration was applied. As we can see, the null hypothesis of no cointegration was rejected, suggesting that there was a valid cointegration among the variables employed. This was displayed by the statistical significance of the Panel PP-Statistic and Group PP-Statistic.

Table 4. Panel unit root results.

Variables	Im et al. (2003) [44] Trend & Intercept Model		Pesaran (2007) [45] Trend & Intercept Model	
	I(0)	I(1)	I(0)	I(1)
$lnCO_2$	−3.6243 ***	−13.513 ***	−2.447 ***	−3.734 ***
CC	−4.0836 ***	−13.847 ***	−2.025	−4.426 ***
lnGDP	−0.9446	−10.943 ***	−2.949 ***	−4.294 ***
REN	−2.7280 ***	−13.389 ***	−2.225	−4.329 ***
lnFDI	−7.355 ***	−15.488 ***	−3.660 ***	−5.372 ***

Note: Computed by the author. *** reflects the statistical significance of values at a 1% level. The lag length selected is 1.

Table 5. Pedroni residual co-integration test.

Alternative Hypothesis: common AR coefficients (within-dimension)				
	Statistic	*p*-value	Weighted Statistic	*p*-value
Panel v-Statistic	−1.45514	0.9272	−2.1001	0.9821
Panel rho-Statistic	3.3328	0.9996	3.6174	0.9999
Panel PP-Statistic	−2.6946 ***	0.0035	−1.8646 **	0.0311
Panel ADF-Statistic	1.1505	0.8750	−0.4518	0.3257
Alternative Hypothesis: individual AR coefficients (between-dimension)				
	Statistic	*p*-value		
Group rho-Statistic	5.5214	1.0000		
Group PP-Statistic	−3.2611 ***	0.0006		
Group ADF-Statistic	−0.7904	0.2146		

Note: *** and ** denote the statistical significance of values at 1% & 5% levels.

4.2. Results of MMQR and Discussion

In estimating the data for this study, we started by estimating the model without the interaction term. Results as presented in Table 6 were based on the MMQR estimation technique advanced by [43]. These results suggested that the control of corruption had a positive and significant effect on CO_2 emissions across the quantiles. Similarly, income level was positively related to CO_2 emissions, and this relationship was statistically significant across the quantiles. This meant that without the interaction term, both the control of corruption and income level exerted a positive and significant effect on CO_2 emissions. However, with the interaction term of the control of corruption and income level, the effect became negative and statistically significant across the conditional distribution of the quantile of CO_2 emissions as presented in Table 7. The plausible explanations for these results could be that at the low level of income of the country, the crusade against corruption may not translate into reducing CO_2 emissions. This is because fighting against corruption requires high level of income to improve environmental quality. Although increasing the level of income alone would stimulate CO_2 emissions through an increase in economic activity, which is accompanied by high-intensity of energy consumption and other factors that could trigger an upward trend of CO_2 emissions, such as a rising level of urbanization, population, investment, etc. Therefore, our finding was consistent with the earlier findings of [3,46,47].

In addition to the above discussion, the negative effect of the interaction term of the control of corruption and income level in Table 7 summarily suggested that a certain level of income is required for the control of corruption policies to reduce CO_2 emissions, and consequently, improve the quality of the environment. From Tables 5 and 6, the control of corruption exerted a positive and significant effect across the conditional quantiles of CO_2 emissions. This possibly implies that at a lower level of income, a country may not be able to implement effective policies to control corruption, as fighting corruption requires putting institutions in proper place, such as setting up of agencies, procurement of modern equipment, gadgets personnel costs, etc. However, when the control of corruption interacts with the income level, their effect on CO_2 emissions becomes negative and significant across the quantiles. The plausible explanation for this result is that as income is rising, countries tend to prioritize environmental cleanliness. In other words, at low-income levels, countries would be more concerned about increasing economic growth at the expense of the environment. This low-income level comes with insufficient tools to effectively control corruption. However, as income level increases, there is a change in policies from business as usual to more effective policies to control corruption and fight pollution. This paradigm shift is enhanced by the deployment of technologies that improve environmental quality. Moreover, with the high level of income, awareness of a sustainable environment and concerns for the urgent need to combat environmental pollution increase as governments and other stakeholders ensure that stringent environmental policies, as well as laws and regulations, stand tall, leading to a decline in corruption and progressive increase in environmental quality.

Table 6. Result of MMQR.

	Location	Scale	Quantiles								
Variable	Parameters	Parameters	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
CC	0.1165	0.0140	0.0944	0.101 **	0.107 ***	0.111 ***	0.117 ***	0.121 ***	0.127 ***	0.132 ***	0.139 **
	(0.0772)	(0.0244)	(0.0574)	(0.0461)	(0.0376)	(0.0327)	(0.0306)	(0.0323)	(0.0377)	(0.0447)	(0.0579)
ln *GDP*	0.1187 **	0.0083	0.106 ***	0.109 ***	0.113 ***	0.116 ***	0.119 ***	0.122 ***	0.125 ***	0.128 ***	0.132 ***
	(0.0479)	(0.0147)	(0.0367)	(0.0295)	(0.0241)	(0.0209)	(0.0196)	(0.0207)	(0.0241)	(0.0286)	(0.0370)
REN	−0.0251 ***	0.0014	−0.0273 ***	−0.0267 ***	−0.0261 ***	−0.0256 ***	−0.0251 ***	−0.0246 ***	−0.0241 ***	−0.0236 ***	−0.0229 ***
	(0.0044)	(0.0016)	(0.00296)	(0.00238)	(0.00194)	(0.00169)	(0.00158)	(0.00167)	(0.00195)	(0.00231)	(0.00299)
ln *FDI*	0.0222 *	−0.0078	0.0345 ***	0.0309 ***	0.0277 ***	0.0250 ***	0.0220 ***	0.0194 ***	0.0164 **	0.0137	0.00953
	(0.01126)	(0.0049)	(0.0115)	(0.00921)	(0.00754)	(0.00655)	(0.00613)	(0.00648)	(0.00755)	(0.00895)	(0.0116)
No. of Obs.	748	748	748	748	748	748	748	748	748	748	748

Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 7. Result of MMQR.

	Location	Scale	Quantiles								
Variable	Parameters	Parameters	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
CC	0.6399	0.1379 *	0.414	0.486 **	0.539 ***	0.600 ***	0.644 ***	0.688 ***	0.741 ***	0.789 ***	0.859 ***
	(0.429)	(0.075)	(0.299)	(0.235)	(0.194)	(0.161)	(0.152)	(0.158)	(0.184)	(0.217)	(0.278)
ln *GDP*	0.1824 **	0.0232	0.144 ***	0.156 ***	0.165 ***	0.176 ***	0.183 ***	0.190 ***	0.199 ***	0.207 ***	0.219 ***
	(0.0651)	(0.0199)	(0.0506)	(0.0397)	(0.0328)	(0.0273)	(0.0258)	(0.0268)	(0.0311)	(0.0368)	(0.0470)
CC × ln *GDP*	−0.0808	−0.0198	−0.0485	−0.0587 *	−0.0664 **	−0.0751 ***	−0.0814 ***	−0.0877 ***	−0.0954 ***	−0.102 ***	−0.112 ***
	(0.0639)	(0.0119)	(0.0433)	(0.0340)	(0.0281)	(0.0233)	(0.0220)	(0.0229)	(0.0266)	(0.0314)	(0.0402)
REN	−0.0247 ***	0.0014	−0.0269 ***	−0.0262 ***	−0.0257 ***	−0.0251 ***	−0.0246 ***	−0.0242 ***	−0.0237 ***	−0.0232 ***	−0.0225 ***
	(0.0043)	(0.0015)	(0.00314)	(0.00247)	(0.00204)	(0.00169)	(0.00160)	(0.00166)	(0.00193)	(0.00228)	(0.00292)
ln *FDI*	0.0226 **	−0.0082 *	0.0361 ***	0.0319 ***	0.0287 ***	0.0250 ***	0.0224 ***	0.0198 ***	0.0166 **	0.0138	0.00958
	(0.0105)	(0.0048)	(0.0123)	(0.00968)	(0.00800)	(0.00666)	(0.00628)	(0.00654)	(0.00757)	(0.00896)	(0.0115)
No. of Obs.	748	748	748	748	748	748	748	748	748	748	748

Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Furthermore, renewable energy had a negative and significant effect on CO_2 emissions across the quantiles in both the baseline model and interaction model. This implies that as the consumption of renewables is increasing, environmental quality is enhanced. The plausible reason for this result is consequent upon the fact that renewable energy is typically clean energy that has no combustible elements to deteriorate the environment. Unlike non-renewable energy, such as oil, coal, natural gas, etc., which are commonly used to generate electricity for industries and residential houses, renewables, such as hydropower, winds, solar, biomass, etc., have no environmental consequences, and their consumption dampens the level of greenhouse gases that are emitted into the atmosphere, thereby reducing climate change, air pollution, global warming, and other environmental challenges. This finding was consistent with [48] for EU countries, [37] for G7 nations, and [47].

In addition, the results revealed that foreign direct investment had a positive relationship with CO_2 emissions. The relationship is significant across the quantiles. The plausible economic explanation for the positive effect of FDI is that firms that are engaged in foreign direct investment inflows are always operating in environments that are conducive to making more revenues and profits. In other words, due to the high cost of environmental taxes in developed countries, firms would always like to operate where environmental taxes are not exorbitant or where environmental laws and regulations are not stringent. To this extent, firms would always like to operate in less-developed continents, such as the African continent, where they pay lesser environmental taxes and where environmental quality is not prioritized by the government of the day. In such an environment such as Africa, environmental laws and regulations are not stringent, and as such, the prevalence of corruption through bribery can also facilitate a minimum cost of environmental taxes compared with what such firms would have paid if they were operating in developed countries. Therefore, our finding is consistent with the pollution haven hypothesis firmed for Pakistan by [12], [30] for China, and [13] for the Latin American countries. Furthermore, our findings are related to the major finding of [49] that FDI inflows trigger environmental quality in developed nations because of their strong and effective environmental laws and regulation, while in the developing nations, the effect of FDI inflows is inimical to the environment.

Furthermore, from the estimations, it was clear that the coefficients of renewable and foreign direct investments are reducing across the quantile distribution of CO_2 emissions. In other words, the coefficients of the lower quantiles are higher but decrease across the quantiles. This implies that countries with a lower level of environmental degradation tend to experience a higher impact of renewable energy consumption and inflows of foreign investment. The finding was consistent with [37]. Although, in the case of the interaction term, the coefficients were increasing across the quantiles, suggesting that higher emission countries tend to experience the effect of the interaction term due to effective policies and commitment of the government to mitigate environmental degradation as recently demonstrated by [1].

4.3. Robustness Results

As we have mentioned in the methodology, one of the limitations of the MMRQ estimator is that it failed to control for the issue of cross-sectional dependence in the series. Therefore, it was very important to check the robustness of our results using some estimation techniques that could control for cross-sectional dependence. In this study, we applied the OLS-FE, GLS-RE, and pooled mean OLS—all with Driscoll–Kraay standard errors which control for cross-sectional dependence as demonstrated by [50]. The results of these techniques are displayed in Table 8 for the model without the interaction term and in Table 9 for the model with the interaction term. We found that the effects of the control of corruption, income level, and foreign direct investment are positive and significant while renewable energy consumption is negative. However, the effect of the interaction of the control of corruption and income turns out to dampen environmental degradation. These results, therefore, confirm the results of the MMQR that even in the presence of cross-sectional dependence, the results invariably survive.

Table 8. Results of conditional mean-based regressions for Model I.

	(1)	(2)	(3)
VARIABLES	**OLS-FE**	**GLS-RE**	**Pooled-OLS**
CC	0.116 ***	0.137 ***	0.318 ***
	(0.0257)	(0.0372)	(0.0381)
$\ln GDP$	0.119 ***	0.142 ***	0.883 ***
	(0.0213)	(0.0252)	(0.0242)
REN	−0.0251 ***	−0.0282 ***	−0.0207 ***
	(0.00182)	(0.00122)	(0.000443)
$\ln FDI$	0.0222 ***	0.0139	−0.0668 ***
	(0.00759)	(0.00855)	(0.00777)
Constant	−0.587 ***	−0.405 **	−4.540 ***
	(0.192)	(0.159)	(0.221)
Observations	748	748	748
R-squared	—-	—-	0.879
Number of groups	34	34	34

Note: *** $p < 0.01$, ** $p < 0.05$, Driscoll–Kraay standard errors in parentheses.

Table 9. Results of conditional mean-based regressions for Model 2.

	(1)	(2)	(3)
VARIABLES	**OLS-FE**	**GLS-RE**	**Pooled-OLS**
CC	0.640 ***	0.712 ***	1.111 ***
	(0.204)	(0.163)	(0.133)
$\ln GDP$	0.182 ***	0.210 ***	0.940 ***
	(0.0319)	(0.0283)	(0.0259)
$CC \times \ln GDP$	−0.0808 ***	−0.0880 ***	−0.109 ***
	(0.0280)	(0.0229)	(0.0167)
REN	−0.0247 ***	−0.0275 ***	−0.0207 ***
	(0.00172)	(0.00142)	(0.000460)
$\ln FDI$	0.0227 ***	0.0151 *	−0.0591 ***
	(0.00745)	(0.00848)	(0.00783)
Constant	−1.057 ***	−0.934 ***	−5.129 ***
	(0.300)	(0.275)	(0.271)
Observations	748	748	748
R-squared	—-	—-	0.881
Number of groups	34	34	34

Note: *** $p < 0.01$, * $p < 0.1$, Driscoll–Kraay standard errors in parentheses.

5. Conclusions

Given the intensive war against corruption in Africa over the years, there is a high expectation that such a move will help to achieve a structural transformation of the economies in Africa. In this study, we examined not only the effects of the control of corruption on environmental quality but also the extent to which the level of income of a country plays in influencing the impact of control of corruption on environmental quality in Africa. To achieve this objective, we applied the technique of MMQR with fixed effect, which controls for heterogeneity, and also OLS-FE, GLS-FE, and Pooled OLS with Driscoll–Kraay standard errors. These estimations controlled for cross-sectional dependence. Having found evidence in support of the integration of variables explored and their cointegration, the empirical results suggested that the effects of the control of corruption, income level, and foreign direct investment on environmental quality were positively significant, while renewable energy consumption dampened the quality of the environment. However, the effect of the interaction of the control of corruption and income level improved environmental quality in Africa. These results, therefore, suggested that income level plays a vital role in how the control of corruption crusade reduces environmental degradation. Moreover, the positive effect of inflows of foreign direct investment suggested that Africa is a dumping ground where high-intensive carbon-emitting firms operate because of environmental laws and regulations that are not stringent.

Following the results of this study, there are many policy recommendations. These recommendations will help the policymakers to draft environmental policies to achieve low-carbon economies in Africa. As shown by the results, income level forms the basis upon which the war against corruption can mitigate environmental degradation. Therefore, there is a need to stimulate income levels to influence an effective control of corruption. This can be achieved by stimulating consumption and investment in clean energy. Moreover, stimulating consumption and investment requires government and stakeholders to create an enabling environment to attract inflows of foreign investment in addition to domestic investment. Moreover, since renewable energy reduces CO_2 emissions, government policies need to target investment in the clean energy sector rather than in fossil fuels. To achieve this, subsidies, carbon tax, tax holidays, environmental taxes, etc. are suggested as operational instruments. The implication of this study further displays the need to strengthen the laws and regulations concerning the environment in Africa. In other words, since the African continent is a dumping ground for many highly carbon-intensive industries, there is a need to strengthen and implement effective environmental laws and regulations in Africa. Such environmental taxes should include taxes on pollution, taxes on resources, taxes on transport, and taxes on other activities that contribute to the upward trend of CO_2 emissions in Africa. Furthermore, a growing income level was found as one of the channels through which Africa increases the level of CO_2 and greenhouse gases. Therefore, to achieve the environmental sustainability target, there is a need for Africa to shift from carbon-intensive-led growth to a green growth path. This can be achieved by promoting a cleaner environment through clean energy consumption.

Finally, this study may have some practical limitations. Africa's economies are quite different from other continental economies such as Asia and South America. Therefore, the policy recommendations in this study might have a limited application in these countries. Therefore, we suggest that a similar study could be carried out in the continents mentioned to find out how their levels of income interact with the control of corruption to achieve environmental quality. Better still, future studies could use the World Bank classifications of countries' income levels and compare how income levels influence the impact of the control of corruption on environmental degradation in these categories of countries.

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Appendix A Aix A

Table A1. List of Countries.

-Algeria;
-Angola;
-Botswana;
-Burkina Faso;
-Cameroon;
-Congo;

Table A1. *Cont.*

-Congo DR; -Cote d'Ivoire; -Egypt; -Ethiopia; -Gabon; -Gambia; -Ghana; -Guinea; -Guinea-Bissau; -Kenya; -Libya; -Madagascar; -Malawi; -Mali; -Morocco; -Mozambique; -Namibia; -Nigeria; -Senegal; -Sierra Leone; -South Africa; -Sudan; -Tanzania; -Togo; -Tunisia; -Uganda; -Zambia; -Zimbabwe.

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Article

The Heterogeneous Effect of Economic Complexity and Export Quality on the Ecological Footprint: A Two-Step Club Convergence and Panel Quantile Regression Approach

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Abstract: This research aims to answer two fundamental questions of the present time: First, what is the impact of the increasing complexity of economic structures and the production of complex goods on the environment? Second, can increasing export quality lead to the improvement of the environment? Given that the relationship of the ecological footprint and its determinants has been revealed to be nonlinear, the use of the quantile approach is supported. This finding led us to the central hypothesis of this research: economic complexity and export quality first deteriorate the ecological footprint (i.e., in lower quantiles), and the middle and higher quantiles contribute to reducing or mitigating environmental damage. The effect of economic complexity and export quality on the ecological footprint was researched using a two-step approach. First, club convergence was applied to identify the countries that follow a similar convergence path. After this, panel quantile regression was used to determine the explanatory power of economic complexity and export quality on the ecological footprint of 98 countries from 1990 to 2014. The club convergence revealed four convergent groups. Panel quantile regression was used because the relationship between the ecological footprint and its explanatory variables was shown to be nonlinear for the group of countries identified by the club convergence approach. GDP, nonrenewable energy consumption, and the population damage the environment. Urbanisation contributes to reducing the ecological footprint. Export quality and trade openness reduce the ecological footprint, but not at all quantiles. The effect of trade openness mitigating the ecological footprint is lost at the 90th quantile. Export quality becomes a reducer of the ecological footprint in the 50th quantile or above, and in the higher quantiles, its contribution to reducing the footprint is vast. Economic complexity aggravates the ecological footprint in low quantiles (10th), becomes non-statistically significant in the 25th quantile, and reduces the ecological footprint in higher quantiles. Policymakers must identify the impact of the ecological footprint and consider the demand and supply side of economics.

Keywords: economic complexity; export quality; ecological footprint; club convergence; panel quantile regression

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1. Introduction

The motivation for this research was to assess if the generally desired evolution of economies toward more complex ones and the improvement of their exports are helping to mitigate the degradation of the environment (here measured as the ecological footprint). Indeed, the most pertinent issue facing societies today is the compatibility of economic growth with the maintenance of environmental quality. Environmental degradation caused by human activities due to rapid economic growth, increasing energy demand, industrialisation, and trade expansion has become a global issue. Hence, policymakers and governments have sought solutions to this problem. For this purpose, countries have held conferences and made agreements to take measures to combat environmental degradation (e.g., the Paris Climate Change Conference 2015; the United Nations). The novelty of this research is verifying how countries with similar ecological footprint pathways respond to economic variables, such as economic complexity and export quality. The club convergence approach was used to identify the countries that share similar patterns over time.

In addition to policymakers, researchers have become interested in this issue in recent decades. Numerous studies have analysed the relationship between economic activity, energy consumption as a driver of economic growth, CO_2 emissions, and environmental degradation [1–3]. Many studies have been performed in the context of the environmental Kuznets curve [4–8]. Kuznets's hypothesis states that much damage is done to the environment in the early stages of economic growth. Nevertheless, environmental damage is also reduced with rising incomes and greener technologies [9]. Although economic growth and energy consumption are important factors affecting the environment, these variables alone cannot explain environmental degradation [10]. Therefore, in addition to economic growth and energy consumption, some studies have examined other factors affecting the environment, such as financial development, population density, urbanisation, and energy intensity [9,11–16]. Recently, some studies have examined the impact of new indicators, such as the economic complexity index (ECI) and export quality (EQ), on CO_2 emissions [17–20].

In most previous studies, CO_2 emissions were considered as a proxy for environmental degradation [21]. However, economic activities affect different dimensions of the environment (such as the air, water, and land) that cannot be measured based on CO_2 emissions [22]. Therefore, a comprehensive new index called the ecological footprint (EFP) for environmental degradation has been introduced in the last few years. The EFP represents the total amount of natural resources (such as land and water required for human activities and the distribution of waste generated) produced and consumed by a community [23]. In other words, this index measures the biological capacity required to produce the goods and services consumed by each country's people and the capacity required to absorb the pollutants created by them [24]. Therefore, the EFP index interprets the degradation of the environment due to human activities better than the CO_2 emission index and is more comprehensive [25–29].

The ecological footprint (EFP) generally refers to the EFP of a society's consumption, including the EFP of production and net trade. The EFP of production measures the amount of biological consumption and carbon emissions from production processes in a given area. The EFP of trade also refers to the biological capacity in terms of imports and exports [22]. Recently, some studies have examined the impact of various factors (including the fertility rate, tourism, financial development, human capital, renewable energy consumption, and nonrenewable energy consumption) on the EFP in different countries [19,30–33]. However, despite researchers considering the EFP index as an environmental proxy, only a few studies have examined the impact of new indicators (ECI and EQ) on the EFP [34,35].

Today, the share of international trade in the global economy has impressively grown, such that the share of world trade in the gross domestic product (GDP) reached about 38% in 1990, about 59% in 2014, and 60% in 2019 [36]. Nevertheless, expanding trade and rapid economic growth will result in increased energy consumption [17,37]. Due to the importance of environmental issues, the expansion of trade, regardless of the export products' quality and their production technologies, causes irreparable environmental damage. Thus, expanding trade helps to preserve and improve the environment by improving the quality of export products resulting from production technologies [15,38]. The EQ is related to the characteristics of countries, such as the human capital, level of production efficiency, and research and development (R&D) activities [17,39]. In order for countries to achieve a high level of exportation, they should diversify their exports. The production of different types of goods requires a labour force with greater knowledge and more advanced production technology. Therefore, increasing the EQ improves the environment [20,40]. While the impact of trade openness on environmental degradation has been reviewed in many studies [17,37,41–43], the quality of the exports has not received much attention.

On the other hand, the quality and variety of export products require a complex production structure. The ability of a country to produce diverse and complex products with advanced technologies, higher knowledge, and more added value is called economic complexity (ECI). More complex economic structures are related to industrial and chemical products with higher energy consumption [22]. Researchers have differing views on the relationship between ECI and environmental quality, and some argue that a higher ECI increases environmental degradation [34,44].

On the other hand, another group states that more complex products are associated with higher knowledge and innovation that can provide advanced and environmentally friendly technology for the production process that increases resource efficiency and reduces environmental degradation [18,45,46]. In 2019, Lapatinas et al. [45] found that countries with higher ECIs were more willing to trade because of their international competitive advantage. Hence, they earn more income from businesses and have the financial resources to conduct R&D activities to protect the environment [47]. Therefore, examining the effect of ECI and EQ on environmental sustainability can have many policy implications.

As mentioned above, in previous environmental studies, the effects of new indicators, such as ECI and EQ, on the ecological footprint have been less investigated. Moreover, most of these studies have focused on CO_2 emissions. Therefore, this research contributes to the literature in diverse ways. In the first step, the club convergence approach is used to categorize countries (98 countries) based on convergence over time within the ecological footprint. After selecting the converging countries, we use the panel quantile regression (PQR) model in the next step to investigate the effect of explanatory variables on the EFP in different quantiles.

Therefore, in this study, we seek to answer these questions: What is the impact of the increasing complexity of economic structures and the production of complex goods on the environment? Furthermore, can increase the EQ lead to improving the environment? To answer these questions, we investigate the effect of ECI and EQ on the EFP for a panel of 48 countries selected by the club convergence method from 98 countries based on the EFP variable. The experimental findings of this study contribute to the development of the existing literature and have significant implications for the policies of complex economies with diversified export products to reduce environmental degradation. Moreover, they can help to develop new policies to use clean energy, reduce energy consumption, and achieve sustainable development.

The rest of this paper is structured as follows: Section 2 shows the literature review, Section 3 presents the data and models, Section 4 focuses on the empirical results and discusses them, and finally, the conclusions and policy implications are provided in Section 5.

2. Literature Review

In the literature, an increasing number of investigations consider new trade and economic development indicators to explain the EFP. Moreover, most studies have used CO_2 emissions as an ecological footprint indicator [35]. According to Fang et al. [17], the leading indicators used in the literature to explain environmental degradation or EFP are economic globalisation, export diversification, ECI, and EQ. The benchmark measure in our paper (the index of export product quality and economic complexity) belongs to this study group, as Fang et al. [17] mentioned.

Indeed, when we focused on the effect of EQ on CO_2 emissions or EFP, we found that some authors identified that EQ increases CO_2 emissions or EFP [17,19,48,49]. However, others also found that the EQ decreases environmental degradation by reducing CO_2 emissions or EFP [9,20]. Therefore, among the authors that found that the EQ increases CO_2 emissions, we can mention Fang et al. [17], who investigated the effects of the product quality of exports on CO_2 emissions per capita for 82 developing economies from 1970 to 2014. The authors found that the EQ increases CO_2 emissions. Furthermore, in a study of 63 developed and developing countries from 1971 to 2014, Doğan et al. [19] showed that EQ increases CO_2 emissions.

Other authors also found that export quality increases CO_2 emissions; for example, Wang et al. [48] investigated the effects of EQ and renewable energy for the top ten renewable energy countries and the top ten ECI countries from 1980 to 2014. The researchers found that for the top ten renewable energy countries, only renewable energy production contributes to reducing CO_2 emissions. However, in countries with a high level of ECI, EQ reduces greenhouse gas emissions. Kazemzadeh et al. [49] investigated the effects of EQ and energy efficiency on EFP in emerging countries from 1990 to 2014 using the quantile panel model. The authors found that EQ positively impacts EFP only in the 10th and 25th quantiles and is not significant at other levels, while energy efficiency in all quantile levels reduces EFP.

However, another group of authors also found that the EQ decreases CO_2 emissions; Murshed and Dao [20] investigated the impact of EQ on the economic growth–CO_2 emissions nexus in the context of selected South Asian economies, such as Bangladesh, India, Pakistan, Sri Lanka, and Nepal, from 1972 to 2014 using the FMOLS model. The authors indicated that the improvement in EQ led to lower levels of CO_2 emissions. In addition, Gozgor and Can [9] also showed that export product quality reduced CO_2 emissions in China from 1971 to 2010. Li et al. [50] also analysed the effect of trade openness, export diversification and renewable electricity production on CO_2 emissions in China from the period 1989–2019. Their experimental results showed that the diversification of export and renewable electricity production helps improve the environment, but the openness of trade and GDP increases CO_2 emissions.

Regarding the impact of ECI on environmental degradation, some authors found that the economy's complexity increases the CO_2 emissions or EFP [34,35,44], while others found a mitigation of CO_2 emissions or ecological footprint caused by ECI [18,45,46,51]. The authors found that the ECI increases CO_2 emissions or EFP. Neagu [44] studied the link between ECI and CO_2 emissions in 25 European Union countries using the cointegrating polynomial regression (CPR) model from 1995 to 2017. The author indicated a long-run relationship between ECI, energy intensity, and CO_2 emissions. Yilanci and Pata [34] investigated the Kuznets–Berri hypothesis of China during 1965–2016, using the role of ECI on the EFP. The authors used an autoregressive distributed lag (ARDL) model and a time-varying causality test. The authors illustrated that ECI has an increasing effect on the EFP. Kazemzadeh et al. [35] analysed the impact of ECI on the EFP for a panel of 25 countries from 1970 to 2016 using a panel quantile regression approach. The authors found that the ECI positively affects EFP in the 10th and 25th quantiles but not in the 75th and 90th quantiles. Rafei et al. [52] studied the effect of economic complexity, natural resources, renewable energy consumption, and foreign direct investment on the ecological footprint in the three groups of low, medium, and high institutional quality countries. Their experimental results showed that increasing economic complexity harms the environment. Shahzad et al. [53] examined the relationship between economic complexity and fossil energy consumption on the ecological footprint in the United States during the period 1965Q1–2017Q4 with a quantile autoregressive distributed lag (QARDL) approach. Their experimental results showed that the increase in economic complexity and the consumption of fossil energy cause an increase in the ecological footprint.

However, some authors found that the ECI mitigates environmental degradation or EFP. We can cite Can and Gozgor [51], who studied the impact of ECI on CO_2 emissions in France from 1964 to 214, using the dynamic ordinary least squares (DOLS) estimation. The authors discovered that the ECI decreases CO_2 emissions. Lapatinas et al. [45] investigated 88 developed and developing countries from 2002–2012 using the ARDL model method, the relationship between ECI and environmental performance. The authors found that at higher levels of ECI, environmental performance improved. Pata [18] examined the impact of ECI on both CO_2 emissions and EFP within the framework of the environmental Kuznets curve (EKC) hypothesis in the United States of America (USA) from 1980 to 2016. The author used a combined cointegration test and three different estimators. This study's main finding showed an inverted U-shaped EKC relationship between ECI and environmental pollution. In general, increasing ECI after a particular threshold helps reduce environmental degradation. Doğan et al. [46] analysed the effect of ECI, economic progress, renewable energy consumption, and population growth on CO_2 emissions in 28 Organisation for Economic Co-operation and Development (OECD) countries from 1990 to 2014.

Moreover, the authors used the augmented mean group (AMG) model. The authors found that the ECI and renewable energy might help mitigate environmental degradation. In a study, Kazemzadeh et al. [54] investigated the effects of ECI on the EFP in emerging countries from 2000 to 2016. The authors found that ECI negatively affected EFP in all quantiles except the 10th quantile. Ahmed et al. [53] examined the effect of economic complexity, democracy, and renewable energy technology funding on the ecological footprint in G7 countries from 1985–2017. Their experimental results showed that the effect of increasing economic complexity reduces the ecological footprint, and they found a U-shaped relationship between growth and pollution. Furthermore, their empirical results reported that the direction of causality is from ECI to ecological footprint.

As seen in previous studies, there is no consensus regarding the impact of EQ and ECI on CO_2 emissions and EFP. This inconsistency of results is related to different variables, groups of countries or regions, time series, and methods by the authors. Indeed, this inconsistency leads to more studies related to this topic of investigation. Therefore, our investigation complements the existing studies and deep knowledge about this topic of study. For this purpose, we first select the convergent countries from 98 countries using the club convergence. Afterwards, we examine the effect of ECI and EQ on the EFP using the panel quantile regression (PQR) model. The following section will present the data and method for this empirical investigation.

3. Data and Method

The model used in this research observes the generally good practices used in empirical research. Following the principle of parsimony, we included in our model only the variables of interest (economic complexity and exports quality), and those controls that the literature has identified as having explanatory power on ecological footprint degradation (i.e., GDP, the consumption of fossil fuels, urbanisation, population, and economic openness). This section is divided into two subsections. The first part contains the database/variables, and the second part shows the methodological approaches used in this experimental study.

3.1. Data

This section shows the data/variables used in this study. The data used in this study include the period 1990–2014. This study chose to use this data period because of data available for all countries in this panel. The study uses the following variables to investigate the effect of ECI and trade quality on EFP:

Table 1 describes the variables and their databases. The Results and Discussion section will provide more explanations and specifications of the variables, since, in this research, two models of club convergence and panel quantile regression were used. First, the club convergence model finds converging countries among 98 countries. Then, after selecting the convergent countries, this group of countries will be estimated using the panel quantile regression model. For this purpose, after determining the category of converging countries, we examine the characteristics of variables and tests related to those countries.

Table 1. Variable acronyms, definitions, sources, and QR Codes.

Abbreviation	Variables	Sources	QR Codes
EFPG	Ecological footprint (in global hectares)	Global Footprint Network (GFN) [55]	
ECI	Economic Complexity Index	Observatory of Economic Complexity (OEC) [55]	
GDP	Gross domestic product (GDP) (constant = USD 2010)	World Bank Data (WBD) [36]	
NONREC	Consumption of fossil fuels (e.g., oil, gas, and coal) in a million tonnes of oil equivalent	British Petroleum (BP) [56]	
EQ	Export Quality Index	International Monetary Fund (IMF) [57]	
URB	Urban population (% of the total population)	World Bank Data (WBD) [36]	
POP	Total Population	World Bank Data (WBD) [36]	
TO	Total economic openness = Import + Export (constant = USD 2010)	World Bank Data (WBD) [36]	

Notes: All data are annual over the period from 1990 to 2014.

3.2. Method Approach

The method is divided into two parts: the first part explains the methodology related to the club's convergence, and the second briefly deals with the quantile panel method. Indeed, to carry out this empirical investigation, the following methodological strategy will be used (see Figure 1 below).

3.2.1. The Club Convergence

The club convergence econometric method was created and introduced by Phillips and Sul [58]. This method, which the authors call the "log *t*-test", allows the classification of countries into convergence groups or clubs. This method has numerous advantages over other existing convergence measures. For example, it is based on a time-varying and nonlinear factor model with the potential for transitional heterogeneity [59]. Furthermore, according to the club convergence hypothesis, convergence can only be achieved in groups of countries (or regions) with some common characteristics.

In this study, to examine the club convergence of the ecological footprint in global hectares (EFPG), a panel dataset at the country level is used, which is represented by the variable X_{it}, $i = 1, \ldots, N$, $t = 1, \ldots, T$, where N and T refer to the number of countries and periods, respectively. X_{it} It is often decomposed into two components: Systematic g_{it} and transient a_{it} (Equation (1)).

$$X_{it} = g_{it} + a_{it} \quad (1)$$

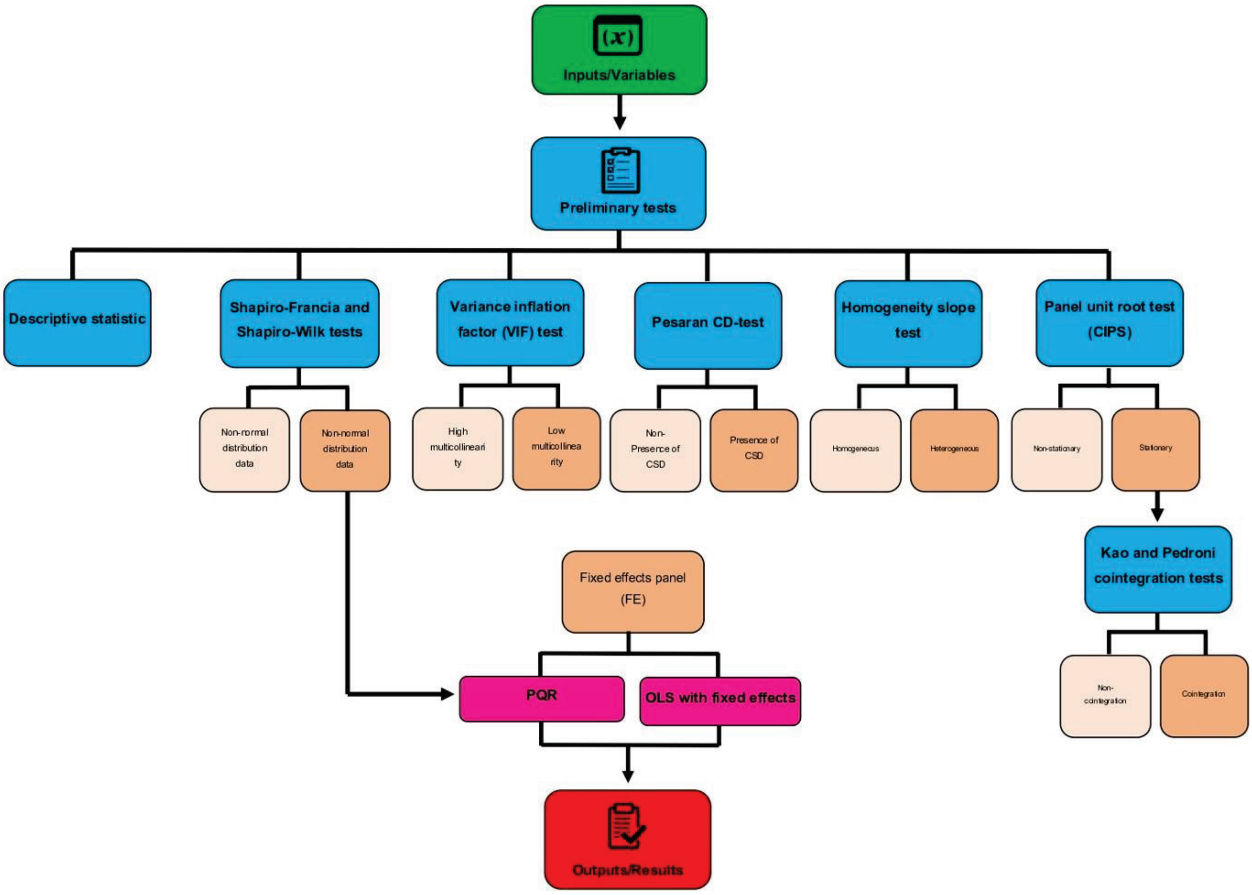

Figure 1. Methodology strategy. The authors created this figure.

The PS transforms Equation (1) so that the ordinary and distinct components in the panel are separated. Specifically, we decompose the X_{it} panel data as follows (Equation (2)):

$$X_{it} = \left(\frac{g_{it} + a_{it}}{\mu_t}\right)\mu_t = \delta_{it}\mu_t. \quad for\ all\ i, t \tag{2}$$

Thus, the variable X_{it} has two components, common, μ_t, and idiosyncratic, δ_{it}. Both are time-varying. This formula makes the convergence test possible by testing whether the δ_{it} factor converges. To achieve this, PS defines the relative transfer parameter, h_{it} (see Equation (3), below).

$$h_{it} = \frac{X_{it}}{\frac{1}{N}\sum_{i=1}^{N} X_{it}} = \frac{\delta_{it}}{\frac{1}{N}\sum_{i=1}^{N} \delta_{it}} \tag{3}$$

This transfer parameter shows the individual transfer path *i* concerning the panel average. This transfer path helps to obtain the cross-sectional variance of h_{it} (see Equation (4), below).

$$H_t = \frac{1}{N}\sum_{i=n}^{N}(h_{it} - 1)^2 \tag{4}$$

The PS *t*-test is based on the idea that if $if\ \delta_{it} \to \delta\ as\ t \to \infty\ then\ h_{it} \to 1$ and at the same time $H_t \to 0$, which guarantees convergence. PS shows that the transmission distance H_t has a finite shape (see Equation (5), below).

$$H_t \sim \frac{A}{L(t)^2 t^{2\alpha}} \quad as\ \ t \to \infty \tag{5}$$

where A is a positive component, $L(t)$ is a function that changes slowly and shows $\propto$ convergence speed. To test the Null convergence hypothesis (see Equation (6), below).

$$\begin{array}{c} H_0 : \delta_i = \delta \;\; and \quad \alpha \geq 0 \\ H_A : \delta_i \neq \delta \;\; for\, all\, i.\, or \;\; \propto < 0 \end{array} \tag{6}$$

We test this hypothesis with the regression model (see Equation (7), below).

$$\begin{array}{c} \log\left(\frac{H_1}{H_t}\right) - 2\log L(t) = a + b.\log(t) + \varepsilon_t \\ For = [rT].\,[rT] + 1,\; \ldots\ldots T \;\; with \;\; r > 0 \end{array} \tag{7}$$

Indeed, according to PS, $b = 2a$ and r represent the fraction of the sample that should be discarded for regression analysis. The result of this regression is sensitive to the sample fraction r. Monte Carlo experiments show that $r \in [0.2, 0.3]$ achieves good performance. It is recommended to set $r = 0.3$ for small or medium samples and $r = 0.2$ for large samples ($T \geq 100$). Using the usual t-statistic for t_b, if $t_b < -1.65$ the null convergence hypothesis is rejected.

The identification of clubs in a panel is performed using the robust clustering algorithm method presented by [58] and is as follows:

a. Sort countries based on their latest observations.
b. Forming a Core Club, perform a statistical calculation of the tk convergence test for successive log(t) regressions based on the highest individuals k ($2 \leq k \leq$ N) in the panel. Then, select the core size by maximizing tk with $tb > -1.65$.
c. Add one country to the main group each time and estimate the log(t) regression in Equation (5). The decision on whether a country/territory should join the core group is based on the $\hat{b} \leq 0$ criteria.
d. We repeat steps (b) and (c) for the remaining countries until we can no longer create a club, and each club has its convergence path. If the last group of the algorithm is not added, these countries form a divergent club.

3.2.2. The Panel Quantile Regression

The panel quantile regression (PQR) was introduced by Koenker and Bassett [60]. This model is based on a conditional quantitative function that minimizes the set of absolute error values in variables with asymmetric distributions. The advantage of quantile regression over ordinary least squares (OLS) is that it provides a comprehensive model by fitting multiple regression patterns to a dataset for different quantiles. This feature allows the inclusion of independent variables in all distribution parts, especially the initial and final quantiles. In addition, it does not face the limitations of conventional regression assumptions in estimating coefficients [61].

This model is a statistical method to calculate and plot different regression graphs and match different quantile points. While providing a complete and more comprehensive picture of the data, it allows the measuring of the relationship of independent variables with the desired quantiles of the dependent variable without the need for normal data even in the presence of outlier points. This regression is more powerful than the outlier data [62]. Quantile panel regression has been used in various fields (such as improving soil resources, economy, environment, climate, etc.) [29,63–69].

Therefore, this research applies the PQR method to evaluate the effect of ECI and EQ on the EFP. The mathematical formula of the PQR model is as follows in Equation (8).

$$\begin{array}{c} y_i = x_i b_{\theta i} + \mu_{\theta i}.\;\; 0 < \theta < 1 \\ Quant_{i\theta}(y_i/x_i) = x_i \beta_\theta, \end{array} \tag{8}$$

where x and y represent the vector of independent variables and the dependent variable, respectively; μ is a random error whose conditional quantile distribution is zero;

$Quant_{i\theta}(y_i/x_i)$ is the θth quantile of the explanatory variable; and the β_θ estimate shows the quantile regression θth and solves the Equation (9):

$$min \sum_{yi \geq x_i'\beta} \theta|y_t - x_i'\beta| + \sum_{yi < x_i'\beta} (1-\theta)|y_t - x_i'\beta| \quad (9)$$

As θ is equal to different values, different parameter estimations are obtained. The mean regression is a particular case of quantile regression under θ = 0.5 [70].

The model uses the logarithm form to remove the variables' possible heterogeneity (Equation (10)).

$$LEFPG_{it} = La + \beta_1 LPOP_{it} + \beta_2 LGDP_{it} + \beta_3 LECI_{it} + \beta_4 LNONREC_{IT} + \beta_5 LEQ_{it} + \beta_6 LURB_{it} \\ \beta_7 LTO_{it} + \delta_{it.} \quad (10)$$

where *EFPG* represents the ecological footprint measured in global hectares; *POP* is total population; *GDP* is Gross Domestic Product; *ECI* denotes economic complexity; *NONREC* is non-renewable energy consumption (which includes oil, gas, and coal) calculated in a million tonnes of oil equivalent; *EQ* is export quality; *URB* is urban population; and *TO* is trade openness.

Considering that the PQR model was used in this research to measure EFP, the quantile form of the equation is as follows (see Equation (11)):

$$Q_\tau(LEFPG_{it}) = (La)_\tau + \beta_{1\tau} LPOP_{i\tau} + \beta_{2\tau} LGDP_{i\tau} + \beta_{3\tau} LECI_{i\tau} + \beta_{4\tau} LNONREC_{i\tau} + \beta_5 LEQ_{it} \\ \beta_{6\tau} LURB_{i\tau} + \beta_{7\tau} LTO_{i\tau} + \delta_{i\tau} \quad (11)$$

In this regard, Q_r means the estimation of the PQR τth in the *EFP* and $(la)_r$ is the constant component. The coefficients $\beta_{1\tau}, \beta_{2\tau}, \beta_{3\tau}, \beta_{4\tau}, \beta_{5\tau}, \ \beta_{6\tau}, \ \beta_{7\tau}$ are the PQR parameters.

4. Empirical Results and Discussion

This section consists of two parts. In the first part, we check the convergence between countries using club convergence. Then, after selecting the convergent countries, we examine the effect of independent variables on the *EFP* using the PQR model.

4.1. Club Convergence Results

In this section, club convergence examines the convergence of the ecological footprint of 98 countries during the years 1990–2014. The results of this model are given in Table 2. Therefore, in Panel A, the results of the overall convergence for all countries indicate that given $\left(t_{\hat{b}} = -38.5298\right)$ is smaller than $t_{\hat{b}} < -1.651$ and $(\hat{b} = -0.4848)$ is smaller than $\hat{b} < 0$, the rejection of the null hypothesis demonstrates that there is a general convergence between all countries. Rejecting the null hypothesis for general convergence does not mean that there is no convergence in the subgroups. The result of the subgroup convergence test confirms the existence of seven subgroups and one non-convergent group. Of these seven groups, the first six are convergent among their group members, but the seventh group (China and Cyprus) is non-convergent. Convergence speed is measured by $\hat{b} = 2a$. As shown in Table 2 below, Panel A, Group 2, has the highest convergence speed.

However, in Panel B, we examine the integration of subgroups, showing that the integration of subgroups club 1 + 2, club 3 + 4, and club 4 + 5 are convergent. In addition, the integration rate in club 1 + 2 is faster than in other groups. Finally, in Panel C, we categorize the results of the final groups merging. The results of this section show four subgroups and one non-convergent group. All four subgroups are convergent. Finally, in this study, Group 2 in panel C, comprising 48 countries (e.g., Austria, Bolivia, Cambodia, Chile, Belgium, Cameroon, Colombia, Costa Rica, Denmark, Ecuador, Finland, Gabon, El Salvador, Greece, Guatemala, Guinea, Honduras, Hungary, Ireland, Israel, Jordan, Kenya, Mozambique, Lebanon, Mauritania, Morocco, New Zealand, Oman, the Netherlands, Panama, Norway, Peru, Paraguay, Poland, Portugal., Qatar, Romania, Senegal, Singapore, Spain, Sri Lanka, Sweden, Switzerland, Tanzania, Venezuela, Tunisia, and Zambia) is used to estimate the panel quantile regression model.

Table 2. Results of the Ecological Footprint based on club convergence (98 countries).

Panel A: Club convergence tests		$\hat{b}$ coef.	$t_{\hat{b}}$
Full sample convergence	Countries	−0.4848	−34.5298 **
1st club	India, the United States of America, Brazil, and Canada	0.230	4.281
2nd club	Argentina, Australia, Italy, Egypt, Malaysia, France, Germany, Ghana, Indonesia, Japan, Mexico, South Africa, the United Kingdom, and South Korea	0.245	5.327
3rd club	Austria, Belgium, Bolivia, Cambodia, Cameroon, Chile, Colombia, Denmark, Ecuador, Finland, Gabon, Greece, Guatemala, Tanzania, Guinea, Israel, Singapore, Jordan, Kenya, Lebanon, Morocco, Portugal, Mozambique, the Netherlands, Oman, Peru, Poland, Qatar, Romania, Sri Lanka, Sweden, Switzerland, Spain, Tunisia, Venezuela, and Zambia	0.180	4.116
4th club	Costa Rica, Cuba, Djibouti, El Salvador, Haiti, Honduras, Hungary, Ireland, Paraguay, Liberia, Niger, Madagascar, Mauritania, New Zealand, Norway, Panama, Senegal, Sierra Leone, Philippines, and Somalia	0.227	6.310
5th club	Albania, Bhutan, Bulgaria, Burundi, Fiji, Gambia, Jamaica, Luxembourg, Myanmar, Nicaragua, North Korea, and Zimbabwe	0.123	5.140
6th club	Barbados, Malta, and Tonga	0.039	0.750
7th club	China and Cyprus	−0.878	−59.077 ***
Panel B: Club merging analysis		$\hat{b}$ coef.	$t_{\hat{b}}$
New club I	Merging Club 1 + 2	0.0554	1.3645
New club II	Merging Club 2 + 3	−0.1523	−4.7723 **
New club III	Merging Club 3 + 4	−0.0168	−0.5046
New club IV	Merging Club 4 + 5	0.0458	1.6717
New club V	Merging Club 5 + 6	−0.1970	−15.015 ***
New club VI	Merging Club 6 + 7	−0.7617	−291.984 ***
Panel C: Final club classifications		$\hat{b}$ coef.	$t_{\hat{b}}$
Club 1	Argentina, Brazil, Australia, Egypt, Canada, France, India, Indonesia, South Korea, Italy, Japan, Malaysia, Mexico, Germany, the United States, South Africa, and the United Kingdom	0.055	1.365
Club 2	Austria, Norway, Bolivia, Costa Rica, Cambodia, Belgium, Cameroon, Colombia, New Zealand, Denmark, Ecuador, Tanzania, El Salvador, Finland, Chile, Spain, Gabon, Greece, Guatemala, Guinea, Honduras, Ireland, Israel, Jordan, Kenya, Lebanon, Mauritania, Morocco, Mozambique, the Netherlands, Hungary, Oman, Panama, Romania, Paraguay, Peru, Poland, Portugal, Sri Lanka, Qatar, Senegal, Sweden, Singapore, Switzerland, Tunisia, Venezuela, and Zambia	−0.017	−0.505
Club 3	Albania, Bhutan, Bulgaria, Burundi, Fiji, Gambia, Jamaica, Luxembourg, Nicaragua, Niger, North Korea, Zimbabwe, Cuba, Sierra Leone, Haiti, and Liberia	0.123	5.140
Club 4	Barbados, Djibouti, Malta, Madagascar, Myanmar, Philippines, Somalia, and Tonga	0.039	0.750
Not convergent Group 5	China and Cyprus	−0.878	−59.077 **

Notes: For testing the one-sided null hypothesis: b ≥ 0 against b < 0, we use the critical value: $t_{0.05} = -1.651$ in all cases; statistical significance at the (1%) and (5%) levels is denoted by *** and **, respectively, rejecting the null hypothesis of convergence.

After identifying the convergence between groups of countries, the PQR model is used to investigate the effect of *ECI* and *EQ* on the *EFP*.

4.2. Panel Quantile Regression Results

4.2.1. Pre-Estimation Tests

In this section, before performing the PQR model, we first examine the results of the preliminary testing, which include reading the normality (Royston [71]; Royston [72]), multicollinearity of the variables [73]; the existence of cross-sectional dependence [74]; the order of integration, i.e., unit roots [75]; and cointegration test [76,77]. Finally, the results of panel quantile regression estimation are given.

After selecting 48 countries based on the results of club convergence (see Table 2 above), we describe the statistics of the variables used in this study. In this context, Table 3 below shows the descriptive statistics of the variables.

Table 3. Descriptive statistics.

Variables	Descriptive Statistics				
	Obs.	**Mean**	**Std.-Dev.**	**Min.**	**Max.**
EFPG	1200	3.94×10^7	3.92×10^7	1216662	2.67×10^8
TO	1200	82.313	50.7916	23.98087	437.3267
EQ	1200	0.8165417	0.1739464	0.2	1.07
GDP	1200	1.59×10^{11}	2.25×10^{11}	2.06×10^9	1.47×10^{12}
ECI	1200	3.053186	1.019706	0.8217199	5.32899
NONREC	1200	1.83×10^7	2.56×10^7	25313.77	1.44×10^8
POP	1200	1.31×10^7	1.10×10^7	476278	5.00×10^7
URB	1200	62.74421	22.13819	15.546	100

Notes: Obs. is the number of observations in the model, Std.-Dev. is the standard deviation, Min and Max are the minimum and maximum, respectively.

After the descriptive statistics, panel quantile regression (PQR) was applied in this research. Therefore, the first test that should be checked is the normality of the data. Because the PQR method can be used when the data distribution is non-normal, in the normal distribution, there is no need to estimate with the PQR method, and the model can be estimated with OLS with fixed effects. In this research, two methods were used to check the data normality: (1) numerical method (see Table 4) and (2) graphical method (see Figure 2). In the numerical method, Shapiro–Francia [71] and Shapiro–Wilk [72] tests were applied to measure the normality. The results of the numerical method for both the Shapiro–Wilk and Shapiro–France tests show the non-normal distribution of the data. We also used skewness and kurtosis tests to check the normality of the data. If the skewness coefficient of the variable is equal to zero or its kurtosis coefficient is equal to three, the data normality is confirmed. According to Table 4, the skewness coefficient of all variables is non-zero, and their kurtosis coefficient is not close to 3. Therefore, it can be assured that it indicates the non-normal distribution of these variables. The results of both tests confirm the abnormal distribution of the variables.

Table 4. Normal distribution test.

Variables	Skewness	Kurtosis	Shapiro–Wilk Test		Shapiro–Francia Test		Obs
			Statistic		Statistic		
LEFPG	−0.2046549	3.554171	0.98945	***	0.98966	***	1200
LTO	0.8929333	4.984875	0.95518	***	0.95518	***	1200
LEQ	−1.535696	6.753622	0.86400	***	0.86422	***	1200
LGDP	−0.35884	2.747878	0.96742	***	0.96836	***	1200
LECI	−0.331808	2.672438	0.97726	***	0.97778	***	1200
LNONREC	−0.581245	2.368702	0.94329	***	0.94420	***	1200
LPOP	−0.377437	3.302496	0.97973	***	0.98030	***	1200
LURB	−1.152019	3.569148	0.88414	***	0.88518	***	1200

Notes: *** denotes statistical significance at a (1%) level.

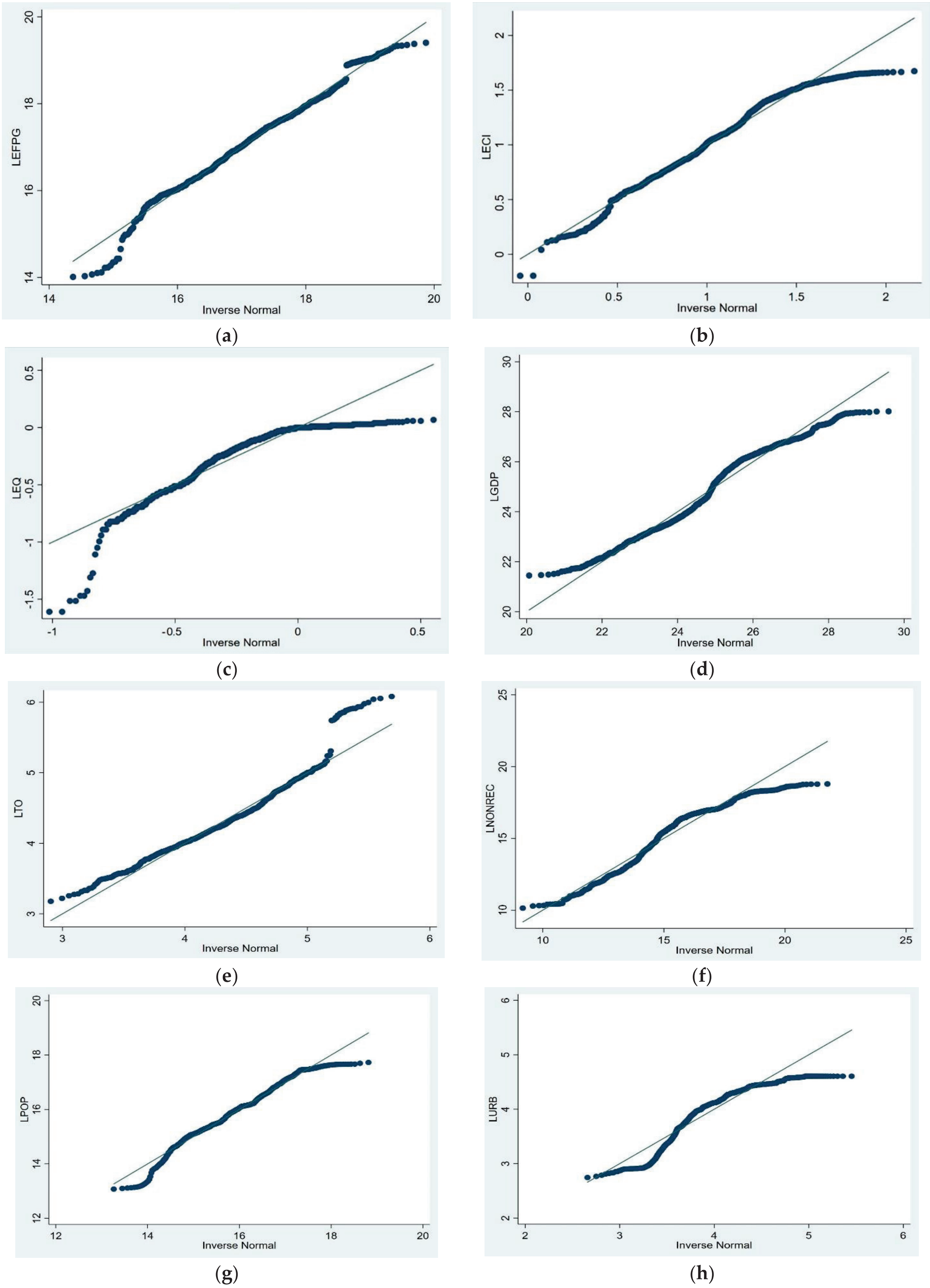

Figure 2. The normal Q-Q plot of LEFPG (**a**), LECI (**b**), LEQ (**c**), LGDP (**d**), LTO (**e**), LNONREC (**f**), LPOP (**g**), and LURB (**h**).

Another way to show the normal distribution of data is to plot a graph. The Q-Q test graph is the most common method (Figure 2). If the Q-Q diagram corresponds to the straight blue line in Figure 2, it indicates the normal distribution of the data. Otherwise, the data distribution is not normal. As seen in Figure 2, the Q-Q graphs of all variables deviate from the straight line, which confirms the non-normal distribution of the data, and the PQR method can be used to estimate the model.

The next step is to explore multicollinearity using the Variance Inflation Factor (VIF) [73,78,79]. As can be seen (Table 5), the highest VIF value is related to GDP (3.26), and the lowest is POP (1.46). The average VIF value is also 2.31. The low value of VIFs shows no severe multicollinearity problem in the model. Then, the Pesaran CD-test [74] was applied to check the existence of cross-sectional dependence. The null hypothesis is cross-sectional independence. The results of the CD-test reject the null hypothesis for all variables, and the existence of cross-sectional dependence is confirmed. Finally, we check the homogeneity slope (HS) using the Pesaran and Yamagata [80] test. The null hypothesis is the existence of a homogeneous slope. According to the rejection of the null hypothesis, the results confirm the existence of a heterogeneous slope. The results of all three tests are given in Table 5.

Table 5. VIF, CSD, and HS tests.

Variables	VIF-Test		Cross-Sectional Dependence (CSD-Test)		
	VIF	**Mean VIF**	**CD Test**	**Corr**	**Abs (Corr)**
EFPG	n.a.	2.31	79.34 ***	0.472	0.581
TO	1.54		58.91 ***	0.351	0.493
EQ	2.57		23.30 ***	0.139	0.387
GDP	3.26		155.50 ***	0.926	0.926
ECI	2.23		7.61 ***	0.045	0.393
NONREC	3.11		56.00 ***	0.339	0.649
POP	1.46		125.64 ***	0.748	0.957
URB	1.97		100.58 ***	0.634	0.825

Homogeneity Slope test		
Models	Delta	Adjusted Delta
Model I	26.075 ***	28.305 ***

Notes: *** denotes statistical significance at the (1%) levels; n.a. denotes not available.

The next test is to check the unit root for panel data. Considering the existence of cross-sectional dependence, Pesaran's panel unit root test (CIPS) [75] is applied in this research. The null hypothesis of this test shows the existence of a panel unit root. As can be seen in Table 6, the results show that EFPG, TO, GDP, ECI, and NONREC variables at the level cannot reject the null hypothesis based on a unit root. However, EQ and URB with lags 1 and 2 and POP with lag 2 reject the null hypothesis at a (5%) significance level. However, after transferring the variables to a logarithmic form and performing the panel unit root test, the results indicate the stationary of all variables with lags of 1 or 2.

After confirming the stationary of all the variables in the logarithmic form, it is necessary to evaluate the long-term relationship between the variables in the next step. For this purpose, the cointegration test was applied [4,81]. In this study, the Kao [76], Pedroni [77], and Westerlund [82] cointegration tests were used to examine the long-term relationship between variables [83–86]. The null hypothesis in these tests shows the absence of cointegration. As seen in Table 7, the cointegration test results for the Pedroni, Kao, and Westerlund tests indicate the null hypothesis rejection and the existence of a long-term relationship between EFP and explanatory variables.

Table 6. Panel unit root test (CIPS).

	CIPS			CIPS	
Variables	**Lags**	**(Zt-Bar)**	**Variables**	**Lags**	**(Zt-Bar)**
EFPG	0	−1.165	LEFPG	0	−3.483 ***
	1	1.093		1	−0.537
TO	0	−1.218	LTO	0	−1.874 **
	1	−2.462		1	−3.257 ***
EQ	0	−5.871 ***	LEQ	0	−5.020 ***
	1	−3.855 **		1	−2.824 ***
GDP	0	7.423	LGDP	0	−1.161
	1	4.503		1	−2.349 ***
ECI	0	2.807	LECI	0	−1.119
	1	4.079		1	−2.469 ***
NONREC	0	4.158	LNONREC	0	−2.041 ***
	1	4.055		1	−2.483 ***
POP	0	5.117	LPOP	0	−1.408 **
	1	−8.005 ***		1	−7.868 ***
URB	0	−3.110 ***	LURB	0	−6.790 ***
	1	−2.113 **		1	−6.002 ***

Notes: "L" variables in the natural logarithms, ***, and ** denote statistical significance at the (1%) and (5%) levels, respectively.

Table 7. Kao, Pedroni, and Westerlund's cointegration tests.

Kao Cointegration Test			**Pedroni Cointegration Test**		
Estimators	**t-Statistic**	**Prob.**	**Estimators**	**t-Statistic**	**Prob.**
ADF	−5.3062	0.0000 ***	Modified Phillips–Perron t	7.0314	0.0000 ***
Residual variance	0.00164		Phillips–Perron t	−11.9530	0.0000 ***
HAC variance	0.00135		Augmented Dickey-Fuller t	−10.6734	0.0000 ***
Westerlund panel cointegration test					
Statistic	Value	Z-value	Robust $p-$value		
Gt	−2.426	0.139	0.002	***	
Ga	−6.664	5.690	0.041	**	
Pt	−14.757	1.557	0.080	*	
Pa	−4.228	5.892	0.140		

Notes: ***, **, and * are used to denote statistical significance at the (1%), (5%), and (10%) levels, respectively.

4.2.2. Panel Quantile Regression Result and Discussion

After conducting the preliminary tests, it is time to estimate the PQR model. We applied 10th, 25th, 50th, 75th, and 90th quantiles for calculation. Therefore, before assessing the model, we first divide the countries based on EFP into six groups related to these quantiles (see Table 8) below.

Table 9 shows the results of PQR and OLS estimation with fixed effects. The OLS estimator with fixed effects is used to check the robustness of the model. The results of this model are compared with the 50th quantile.

A figure was created to summarise the effect of independent variables on the dependent ones (see Figure 3 below) to facilitate the visualisation of results found in Table 9 above.

After showing the summary of the effects, it is necessary to present the discussions and the possible explanations for the results found. As shown in Table 9, except in the 90th quantile, at other levels of quantiles, trade openness has a significant negative effect on the EFP, which means that increasing the volume of trade in these countries reduces the EFP. The results of Sbia et al. [87] confirm that trade openness improves the quality of the environment by transferring advanced and environmentally friendly technologies instead of using older technologies heavily dependent on fossil consumption. In a study of newly industrialised countries, Ahmed et al. [88] stated that open trade openness improves the quality of the environment. Aşıcı and Acar [89] also found in a study of 116 countries on the EFP that trade openness reduces environmental degradation. Zhang et al. [38], Baek et al. [90], and Frankel and Rose [91] confirmed the results. At the same time, some other studies reported opposite results. In a survey of the organisation of Islamic cooperation (OIC) countries, Ali et al. [92] said that open trade increases the EFP. Al-Mulali et al. [93] also found in a study of 58 developing and developed countries that open trade increases the EFP. In a survey of 98 countries, Le et al. [94] stated that trade openness increases particulate matter (PM_{10}) emissions.

Table 8. Country distribution of ecological footprint (gha).

Quantile	Country
quantile $<$ 10th	Gabon, Mauritania, Panama, and Costa Rica
10th $\leq$ quantile $<$ 25th	Zambia, El Salvador, Jordan, Honduras, Guinea, Cambodia, Senegal, and Lebanon
25th $\leq$ quantile $<$ 50th	Mozambique, Cameroon, Tunisia, Madagascar, Paraguay, Guatemala, Sri Lanka, New Zealand, Bolivia, Ireland, Ecuador, and Singapore
50th $\leq$ quantile $<$ 75th	Oman, Norway, Finland, Israel, Kenya, Hungary, Qatar, Switzerland, Morocco, Denmark, Portugal, and Tanzania
75th $\leq$ quantile $<$ 90th	Austria, Peru, Sweden, Chile, Greece, Romania, Belgium, and Venezuela
quantile $\geq$ 90th	Colombia, the Netherlands, Poland, and Spain

Notes: According to the level of EFP, we divided the panel of 48 countries into six grades.

Table 9. Estimation results from the PQR model and panel fixed effects.

Variables	Quantiles										OLS	
	10th		25th		50th		75th		90th		Fixed Effects	
LTO	−0.0790	***	−0.0950	***	−0.066	**	−0.0872	**	−0.0356		−0.1775	***
LEQ	0.0700		0.1074		−0.154	***	−1.0933	***	−1.6452	***	−0.4141	***
LGDP	0.2603	***	0.2875	***	0.2646	***	0.3675	***	0.3897	***	0.2619	***
LECI	0.2243	***	−0.005		−0.245	***	−0.1779	**	−0.1949	**	−0.1476	***
LNONREC	0.1306	***	0.1617	***	0.2441	***	0.2095	***	0.3059	***	0.2774	***
LPOP	0.5836	***	0.4787	***	0.3750	***	0.2670	***	0.1575	***	0.2899	***
LURB	−0.5802	*	−0.207	***	−0.342	***	−0.4041	***	−0.8012	***	−0.4779	**
Constant	−0.3712		−0.207	***	1.6245	***	1.6225	***	1.8114	***	1.4410	***
Pseudo R2	0.9312		0.8831		0.8802		0.8519		0.8689		0.8661	

Notes: ***, **, and * denote statistical significance at the (1%), (5%), and (10%) levels, respectively; "L" denotes variables in natural logarithms.

Export quality in the EFP's 50th, 75th, and 90th quantiles is negative and significant. The results show that this effect is greater at higher quantile levels, which means that the EFP decreases more with increasing export quality. Empirical results show that increasing the variety and quality of export products helps to improve the quality of the environment through increasing the ability to provide environmentally friendly technologies. Research findings by Doğan et al. [19] for 63 developed and developing countries confirm that trade quality reduces CO_2 emissions. Gozgor and Can [9] also confirm the research findings in a study for China, and they stated that trade quality decreases CO_2 emissions. Murshed and Dao [20] also found in a study of selected South Asian economies (e.g., Sri Lanka, Pakistan, Bangladesh, India, and Nepal) that improving export quality would reduce CO_2 emissions. Li et al. [50], in a study for China, found that by increasing export diversification, CO_2 emissions decrease, which helps to improve the quality of the environment.

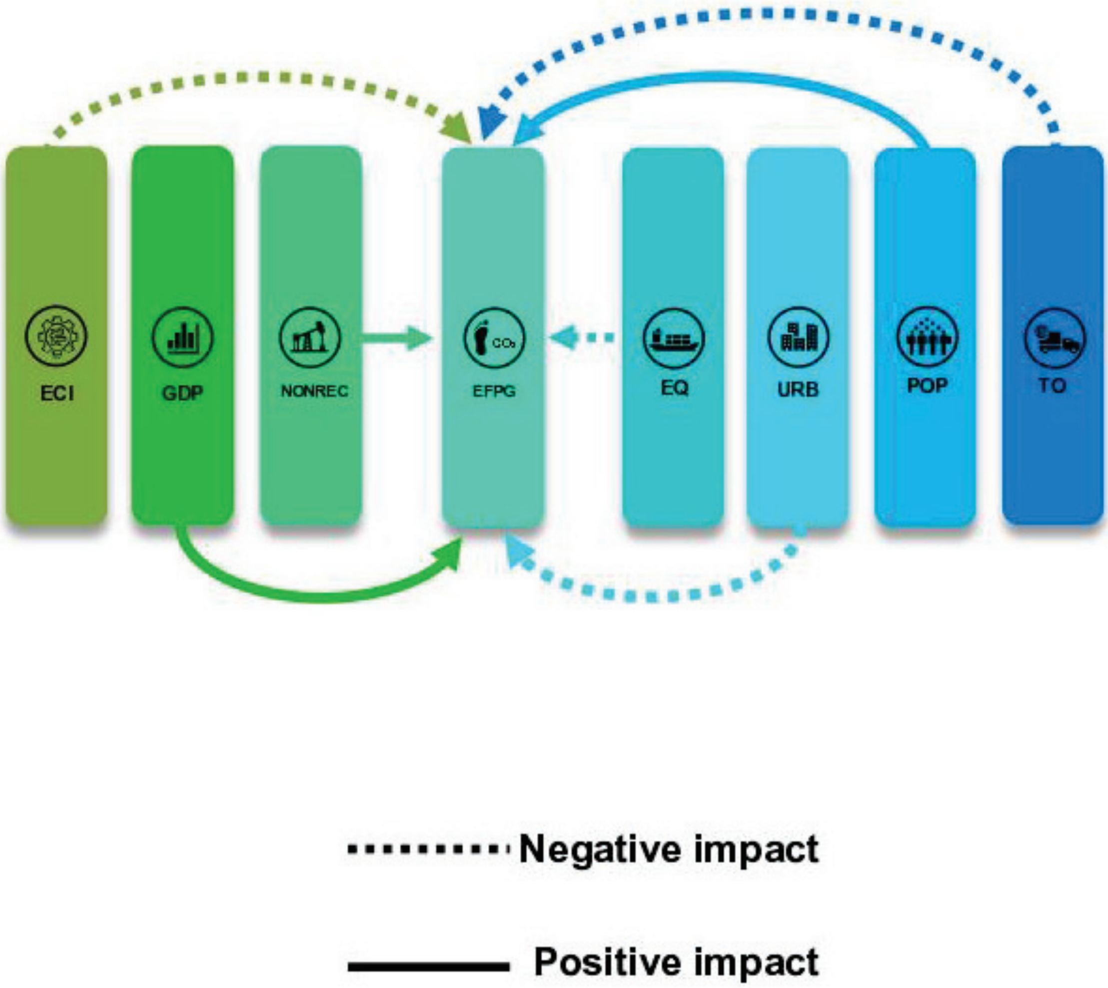

Figure 3. Summary of the effects. The authors created this figure.

In contrast, other studies have reported a positive relationship between export quality and environmental degradation. Wang et al. [48] studied the top ten renewable energy countries, and the top ten ECIs indicate that trade quality positively affects CO_2 emissions. The results of studies by Fang et al. [17] for 82 developing nations also show that export quality increases CO_2 emissions. Research findings for ten newly industrialised countries performed by Can et al. [95] indicate that export product diversification increases CO_2 emissions. The study by Shahzad et al. [96] for 63 developed and developing countries confirms that export product diversification reduces CO_2 emissions. The findings of Hu et al. [97] for 35 developed and 93 developing countries indicate that export product diversification negatively and positively impacts CO_2 emissions in developed and developing countries, respectively.

As expected, the effect of GDP on EFP is positive and significant in all quantiles. This effect is greater in higher quantiles. So that a (1%) increase in GDP in the 90th quantile causes a (0.3897%) increase in EFP. The study results of Hassan et al. [33] for Pakistan are consistent with this study's findings. They reported that economic growth increases the EFP. In a survey of five European Union (EU) countries (e.g., Spain, Germany, Italy, France, and the United Kingdom), Balsalobre-Lorente et al. [98] confirmed that economic growth would increase CO_2 emissions. Saud et al. [99], in a study for 59 Belt and Road Initiative (BRI) countries, confirmed that economic growth causes environmental degradation. Some other studies also confirm the research findings [32,37,100]. The results of Hanif [101] for sub-Saharan Africa showed an inverse U-shape relationship between economic growth and CO_2 emissions. Sarkodie's [102] study to investigate the effect of economic growth on environmental degradation in 17 African countries confirms the EKC hypothesis. In separate research, Haseeb et al. [103] and Alam et al. [104] demonstrate the EKC hypothesis.

The results of ECI on ecological footprint indicate that in the 10th quantile, ECI has a positive and significant effect on EFP. In contrast, the ECI on 50th, 75th, and 90th quantiles negatively and significantly affect EFP. It can be said that the low level of technology leads to the use of products with high energy consumption, which in turn leads to an increase in the EFP. In contrast, with the rise in ECI, newer and environmentally friendly technologies are being used. Moreover, this reduces the EFP. The empirical results indicate that economic complexity has asymmetric effects on the environment at the level of different quantiles. So, experimental results from a critical point of view show that production and economic structures significantly affect the environment. The findings of Kazemzadeh et al. [35] for 25 countries using the QPR model are consistent with the results of this study. They stated that low ECI increases environmental degradation, while the high quantile level of ECI helps to improve environmental quality. Findings from Doğan et al. [46] for 28 OECD countries show that ECI can help reduce environmental degradation. In a study for France, Can and Gozgor [51] confirmed that high levels of ECI reduce CO_2 emissions. Ahmed et al. [105], in a study of countries G7, found that increasing ECI causes a decrease in the ecological footprint.

In comparison, some other studies have reported a positive relationship between ECI and environmental degradation. The findings of Can et al. [95] for newly industrialized countries showed that ECI increases CO_2 emissions. The study results by Yilanci and Pata [34] for China indicate that ECI increases the ecological footprint. Doğan et al. [106], in a study of 55 countries, stated that the ECI of environmental degradation has increased in low and high-middle-income countries and has controlled CO_2 emissions in high-income countries. Rafei et al. [52], in a study of countries with different institutional qualities, discovered that increasing ECI significantly affects the ecological footprint. Shahzad et al. [53] found that increasing economic complexity increases the ecological footprint of the United States.

The results of Table 9 also show that urbanisation at all quantiles has a significant negative effect on the EFP, which is more significant at higher levels. So that (1%) increase in urbanisation causes a (0.8012%) increase in EFP. The findings of Lv and Xu [107] for 55 middle-income countries confirm the results of this study. They reported that urbanisation reduces CO_2 emissions. In a study of 19 emerging economies, Saidi and Mbarek [108] stated that urbanisation improves environmental quality. Sharma [109], in a survey of 69 countries, divided them into three sub-panel based on income level: high income, medium income, and low income found that in all three categories, urbanisation reduces CO_2 emissions.

In contrast, some other studies have identified urbanisation as one of the factors of environmental degradation. Parikh and Shukla's [110] results for 83 countries indicate that urbanisation increases CO_2 emissions. Findings by Wang et al. [111] for the Association of Southeast Asian Nations (ASEAN) countries confirm that urbanisation increases CO_2 emissions. Wang and Dong [112], in a study of 14 sub-Saharan Africa (SSA) countries during 1990–2014, stated that urbanisation increases the ecological footprint. In addition, the PQR results are shown graphically in Figure 4.

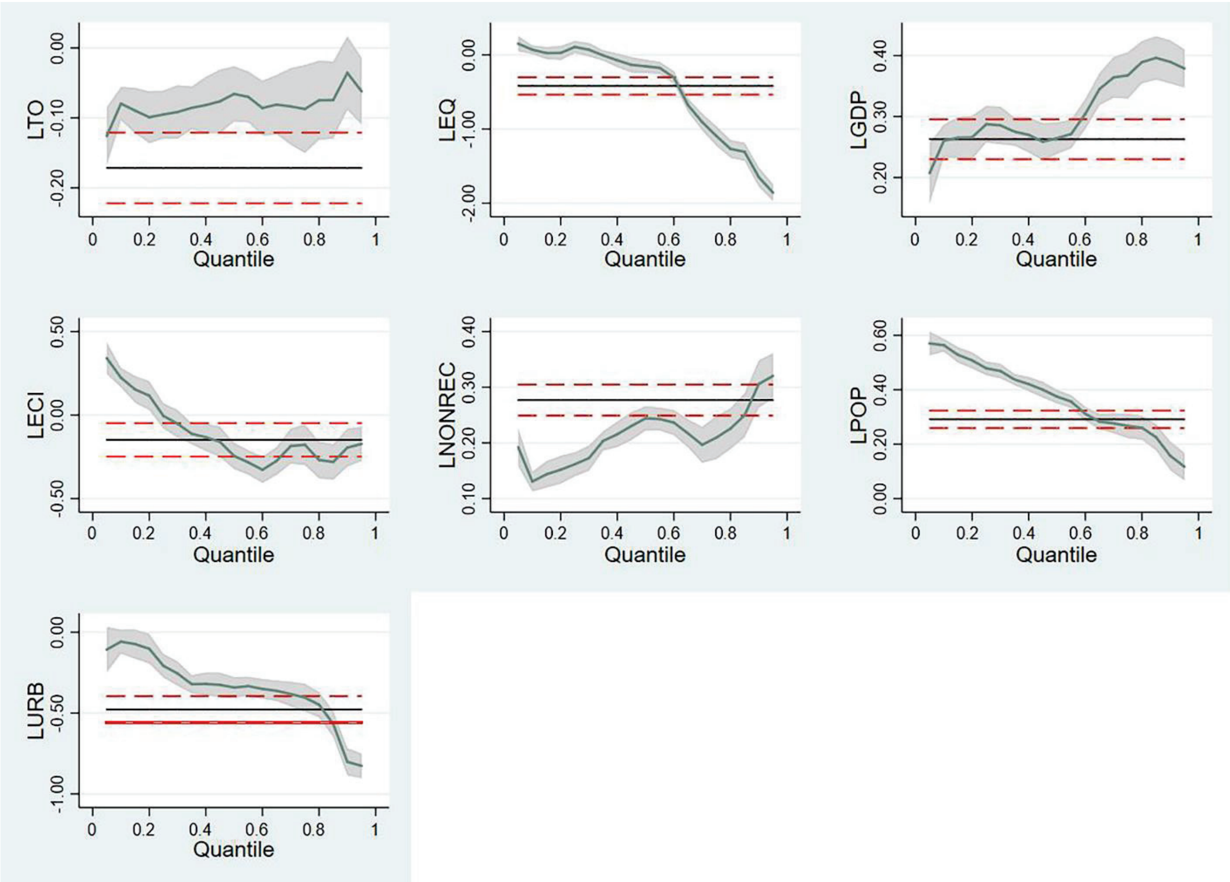

Figure 4. Quantile estimate: The red horizontal lines depict the conventional (95%) confidence intervals for the OLS coefficient.

4.2.3. Robustness Check

It is necessary to check the model's robustness [113] to gauge its validity. For this purpose, we used three methods: (i) the robust regression estimator (MM-Estimation), (ii) fully modified ordinary least squares (FMOLS), and (iii) the dynamic ordinary least squares (DOLS) to check the robustness of the main model. If the coefficients' direction and significance do not change, the model's results can be trusted. The results of the robustness check of the model are given in Table 10.

Table 10. Robustness check.

Variables	*DOLS*	*FMOLS*	*MM-Estimation*
LTO	−0.0344 **	−0.0221 **	−0.0627 ***
LEQ	−0.0163 ***	−0.0102 ***	−0.0265 **
LGDP	0.3548 ***	0.3278 ***	0.2796 ***
LECI	−0.2338 ***	−0.2660 ***	−0.1336 **
LNONREC	0.2264 ***	0.2406 ***	0.1341 ***
LPOP	0.2498 ***	0.1877 ***	0.5035 ***
LURB	−0.4917 ***	−0.4164 ***	−0.1509 ***
Constant			2.4329 ***
R^2	0.9250	0.9198	0.9384

Notes: *** and ** denote statistical significance at the (1%), and (5%) levels, respectively.

As can be seen in Table 10, the results of the model's robustness show that the effect of the variables (signs) and their significance on the ecological footprint are the same as in the original model. Therefore, the main model is reliable and can be used for analysis.

5. Conclusions and Policy Implications

A two-step approach was used to research the impact of economic complexity and export quality on ecological footprint. First, club convergence was applied to identify the countries that follow a similar convergence path. Second, the econometric technique of panel quantile regression was used to determine the explanatory power of two variables, economic complexity, and export quality on the ecological footprint.

Data cover the period from 1990 to 2014. Therefore, this option matches the period for which the variables are available for all countries in this panel. The club convergence method was used in 98 countries based on the ecological footprint variable. The research revealed four groups of convergent countries and one group that was not convergent. Therefore, from the 98 countries analysed, we chose to research the most numerous clubs (48 countries).

The panel quantile approach was used because of the linkage between the ecological footprint (explained variable), the trade openness, export quality index, GDP, economic complexity index, non-renewable energy consumption, the urban population as a percentage of the total population, and total population (explanatory variables) revealed to be nonlinear.

Gross Domestic Product, non-renewable energy consumption, and population damage the environment as they aggravate the ecological footprint, regardless of the quantity considered. Nevertheless, the environmental damage becomes less pronounced as we increase the quantiles. Urbanisation contributes to reducing the ecological footprint for all quantiles. It was found that export quality and trade openness lower the ecological footprint but not in all estimated quantiles. Trade openness losses the capacity to reduce footprint at the 90th quantile. Export quality becomes a reducer of footprint at quantile 50th or upper, and at upper quantiles, its contribution to reducing footprint is vast. Economic complexity reveals mixed results. Aggravate the ecological footprint in low quantile (10th), become not statistically significant at quantile 25th, and reduce the ecological footprint in upper quantiles.

The limitation of ecological footprint damage involves a wide range of policy actions. First, policymakers must recognize the effect of economic and social variables, such as consumption, on the ecological footprint. Therefore, policymakers must go further regarding the structure of their economies and promote less damaging consumption and production. Second, policymakers must promote energy policies encouraging the deployment of energy-efficient sources and accelerating the energy transition to renewable sources. These actions contribute to mitigating the ecological footprint damage. Finally, policymakers must implement measures to circumvent the population growth as it exerts an additional burden on the ecological footprint damage.

The tentative findings of this research are valuable for expanding the literature and have particular consequences for improving the policies of complex economies that have diversified export sectors and are confronted with the necessity to reduce environmental degradation. Moreover, these findings can help to develop new policies of using clean energy, reducing energy consumption, and achieving sustainable development.

The study also reveals that analysing countries with similar convergence processes can be a criterion for better identifying the factors that influence the ecological footprint. Thus, the next step should investigate the relationships between the variables in different convergence processes. However, the short period of data available imposes some limitations on our research. Therefore, further improvements in research can take advantage of econometric approaches that disentangle the total impact on its temporal dimensions, i.e., the short and long-term impacts. Furthermore, research should evolve to assess developing and developed countries' distinctions.

It should be stressed that the conclusions of this research are probably valid only for countries that share similar patterns of convergence in their ecological footprint. Moreover, the generalization of results could be poor in the presence of relationships that are not linear in their behaviours, as is the case of possible sudden changes in the environmental situation.

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Effect of Battery Electric Vehicles on Greenhouse Gas Emissions in 29 European Union Countries

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Abstract: This analysis explored the effect of battery electric vehicles (BEVs) on greenhouse gas emissions (GHGs) in a panel of twenty-nine countries from the European Union (EU) from 2010 to 2020. The method of moments quantile regression (MM-QR) was used, and the ordinary least squares with fixed effects (OLSfe) was used to verify the robustness of the results. The MM-QR support that in all three quantiles, economic growth causes a positive impact on GHGs. In the 50th and 75th quantiles, energy consumption causes a positive effect on GHGs. BEVs in the 25th, 50th, and 75th quantiles have a negative impact on GHGs. The OLSfe reveals that economic growth has a negative effect on GHGs, which contradicts the results from MM-QR. Energy consumption positively impacts GHGs. BEVs negatively impacts GHGs. Although the EU has supported a more sustainable transport system, accelerating the adoption of BEVs still requires effective political planning to achieve net-zero emissions. Thus, BEVs are an important technology to reduce GHGs to achieve the EU targets of decarbonising the energy sector. This research topic can open policy discussion between industry, government, and researchers, towards ensuring that BEVs provide a climate change mitigation pathway in the EU region.

Keywords: battery electric vehicles; greenhouse gas emissions; energy consumption; method of moments quantile regression; European Union

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1. Introduction

The arguments for climate protection have never been so convincing as now. Globally, climate change is endangering the lives of millions of people and threatening many aspects of the human economy [1]. The transport sector is expected to be a crucial part of the solution: a sector that can help reduce greenhouse gas (GHG) emissions, including carbon dioxide (CO_2) and non-CO_2 gases such as methane (CH_4), nitrous oxide (N_2O), partially fluorinated hydrocarbons (HFC), perfluorinated hydrocarbons (PFC), sulfur hexafluoride (SF6), and nitrogen trifluoride (NF3). To a greater or lesser extent, these gases are harmful to the environment as they trap heat in the atmosphere, causing global warming [2].

Climate change and the contemporary transportation system are inextricably linked in many ways. The Industrial Revolution innovations that brought in new forms of transportation are the same technologies that have led to the increasing GHGs in the atmosphere [3]. The need for fossil fuels such as coal and oil surged as machines replaced manual labour in the second half of the 18th century [3]. Powerful modern mobility, such as vehicles, steam-powered trains, and boats, were all powered by fossil fuels, which emit significant volumes of CO_2 into the atmosphere when combusted [4]. As recent evidence showed, CO_2 levels rose and resulted in a significant greenhouse effect [5]. Given the transport sector's potential, the hotly discussed transport-related environmental problem is how to fulfil the growing need for increased global connection and mobility sustainably. This study looks at the latest developments in the European Union (EU). In general, (GHG) emissions in the EU have been gradually declining in recent years, wherein 2019, the GHG emissions in the EU were down by (24%) compared with 1990 levels, representing an absolute reduction of 1182 million tonnes of CO_2-equivalents (see Figure 1 below).

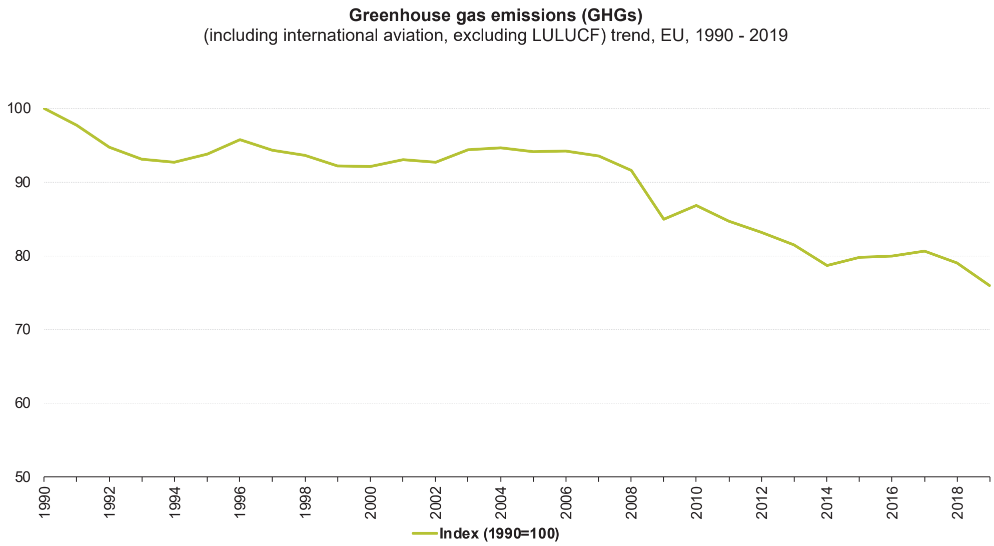

Figure 1. Greenhouse gas emissions in EU between 1990 and 2019. The authors created this figure with data from EEA [6].

As shown in Figure 1 above, from 1999 to 2008, the progression of GHGs emissions in the EU was unchanged. Moreover, in 2009, the GHGs emissions dropped due to the global financial and economic crisis and reduced industrial activity. However, the emissions increased in 2010 and decreased again from 2011 onward. Between 2015 to 2017, these emissions had slightly been increasing. In 2019, emissions decreased by (3.8%) (149 million tonnes of CO_2-equivalents) compared to 2018 levels [6].

In the EU, the energy-producing industries sector was the most significant contributor to the increase of GHG emissions, where the sector contributed with (28.0%), followed by fuel combustion by users (25.5%) and the transport sector (24.6%). Indeed, compared with 1990, the share of most sources decreased, transport increased from (14.8%) in 1990 to (24.6%) in 2018 (see Figure 2 below).

Indeed, the GHG emissions from the majority of sector decrease between 1990 to 2018 (e.g., Energy supply (−32%); Industry (−35%); Residential/commercial (−22%); Agriculture (−19%); and Waste (−42%)) with exception of the transport sector that registered an increase of (+19%). Moreover, the largest decrease in emissions in absolute terms occurred in energy supply and industry. However, agriculture, residential and commercial, and waste management have decreased GHG emissions since 1990 (see Figure 3 below).

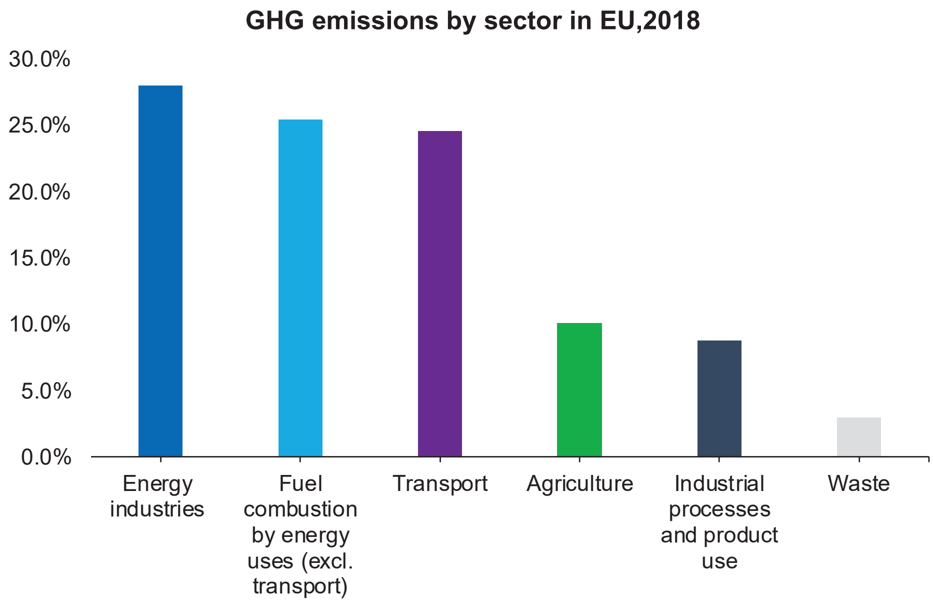

Figure 2. GHG emissions by sector in EU, 2018. The authors created this figure with data from Europa [7].

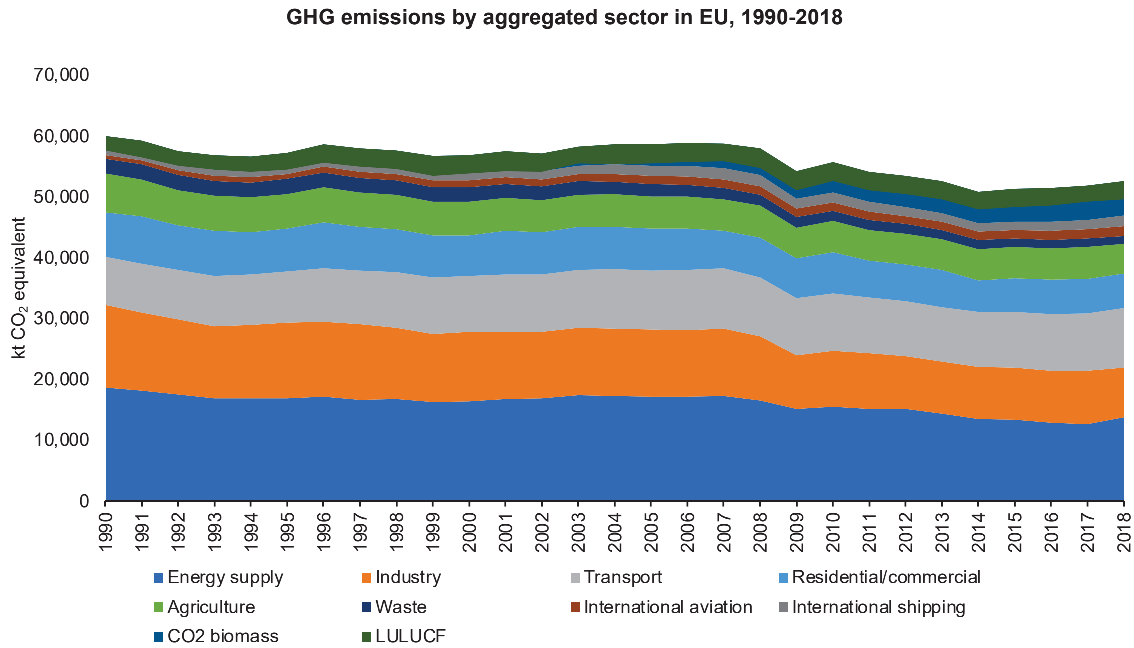

Figure 3. GHG emissions by aggregated sector in EU between 1990 and 2018. The authors created this figure with data from EEA [6].

Moreover, Figure 3 above also shows an increase in GHGs from biomass combustion (+182%), international aviation (+129%), and international shipping (+32%). Although net removals from land use, land-use change and forestry (LULUCF) increased over the period, the substantial increase in GHGs from biomass combustion highlights the rapidly growing use of biomass in replacing fossil fuel sources in the EU [6].

Although intervention is needed in all sectors to meet emission reduction targets, it is crucial to reduce the emissions, particularly from the transport sector in the EU, where the GHGs from this sector increased by (19%). Therefore, reducing transport related GHG emissions is projected to be especially difficult, but emerging technologies have the potential to make significant contributions to GHG mitigation in the sector (e.g., Hawkins et al. [8]; and Andersson and Börjesson [9]). Reducing vehicle energy and fuel carbon intensities offers the best potential for European countries to achieve significant reductions in GHG emissions from vehicular transportation (e.g., Xu et al. [10]; and Andersson and Börjesson, [9]).

The thermodynamics of traditional internal combustion engine vehicles (ICEVs) severely limit their energy efficiency potential, increasing the necessity for fossil fuel use in transportation (e.g., Hawkins et al. [8]: Helmers and Marx [11]; and Tagliaferri et al. [12]). Battery electric vehicles (BEVs) have recently been viewed as a viable alternative to ICEVs but have only recently inspired considerable public interest and acceptance (e.g., Ajanovic and Haas [13]). BEVs have a more efficient powertrain, require less maintenance, and generate no exhaust pollutants (e.g., Hawkins et al. [8] and Bekel and Pauliuk [14]). Because of these features, BEVs are viewed as a strong contender for reducing transportation related GHG and air pollutant emissions (Hawkins et al. [8]). However, mitigation efficacy may be limited by emissions from battery production and charging requirements (Andersson and Börjesson [9]).

In the EU, the BEVs are gradually penetrating the market. However, despite a steady increase in the number of new electric car registrations annually, from 734 units in 2010 to about 341,267 units in 2019, they still account for a market share of only (3.46%) of newly registered passenger vehicles (see Figure 4 below).

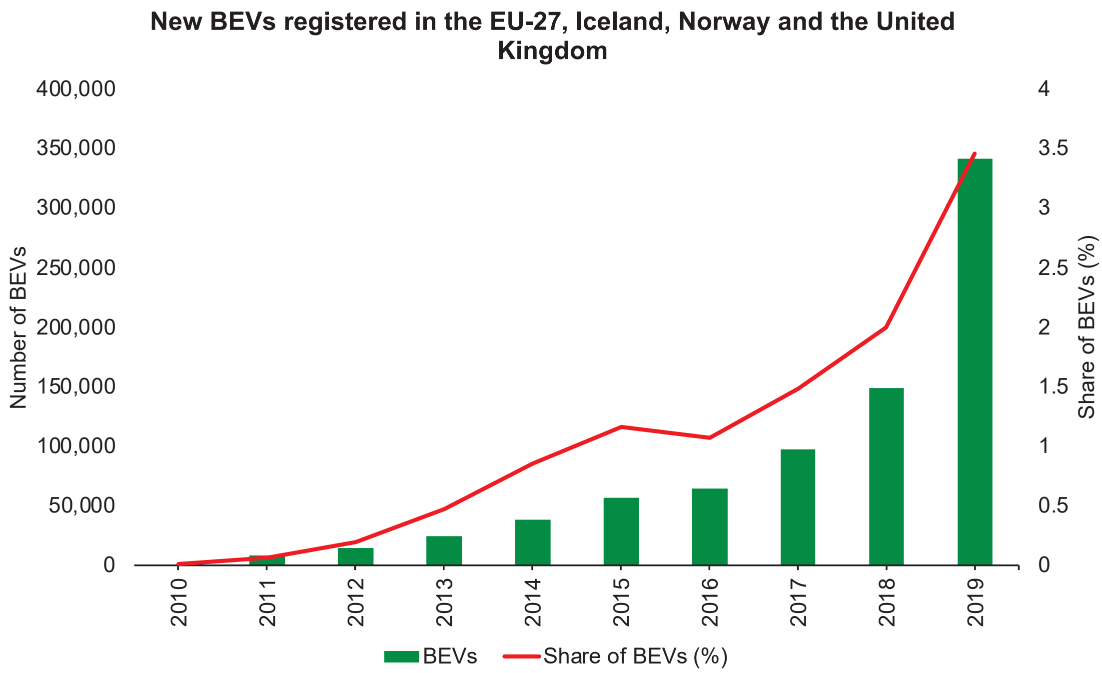

Figure 4. New BEVs registered in the EU-27, Iceland, Norway, and the United Kingdom, between 2010 and 2019. The authors created this figure with data from EEA [6].

Figure 4 above shows that the number of new BEVs registered in the EU is increasing. Indeed, more than half of all BEVs registrations were in Germany, Norway, the Netherlands, France, and the United Kingdom (see Figure 5 below).

In some countries, such as Cyprus, Estonia, Greece, Lithuania, Slovakia, and Slovenia, the proportion of BEVs in total vehicle registration remained below 200 units in 2019. On the other hand, there was a notable increase in new BEV registrations between 2018 and 2019 (129%), which can be partly explained by the inclusion of Norway in the data set in 2019, a country that registered around 60,000 BEVs that year [6].

Indeed, when we addressed the total number of BEVs in the fleet, we can observe that in 2010, the EU had 5785 vehicles and in 2020 reached a value of 1,125,485 (see Figure 6 below).

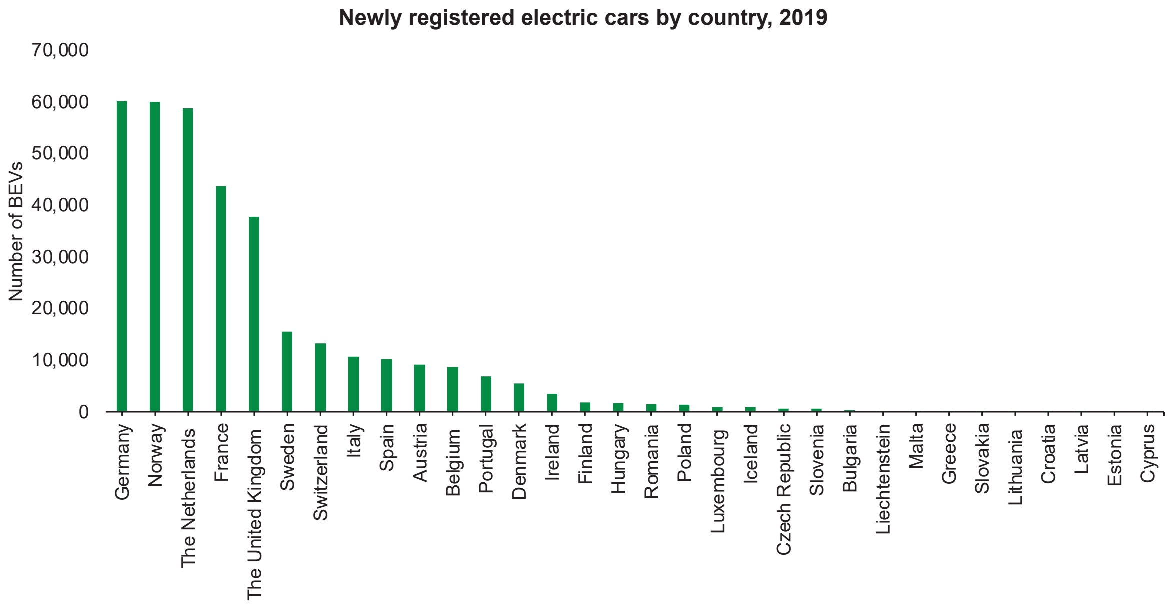

Figure 5. Newly registered BEVs in 2019 by country. The authors created this figure with data from EEA [6].

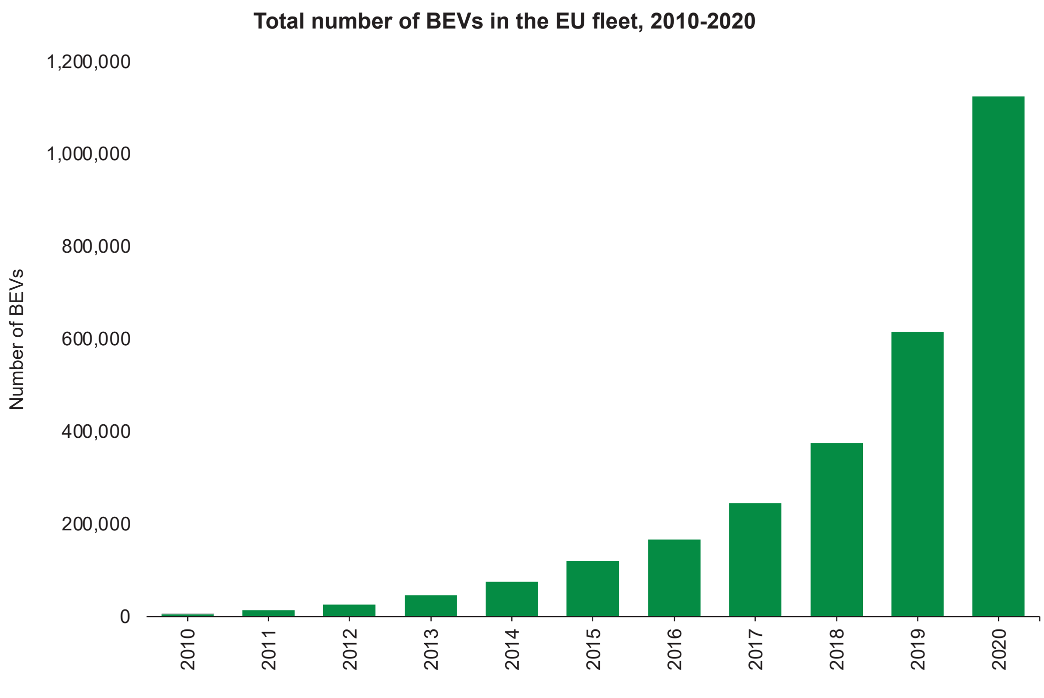

Figure 6. Total number of BEVs in the fleet of the European Union between 2010 and 2020. The authors created this figure with data from European Alternative Fuels Observatory (EAFO) [15].

However, when we address the total number of BEVs in the fleet of each country of the European region in 2020, we can observe that Norway, Germany, France, the United Kingdom, and the Netherlands are the top five countries with a significant number of BEVs in the European Union. In contrast, Liechtenstein, Cyprus, and Latvia have fewer BEVs in the fleet (see Figure 7 below).

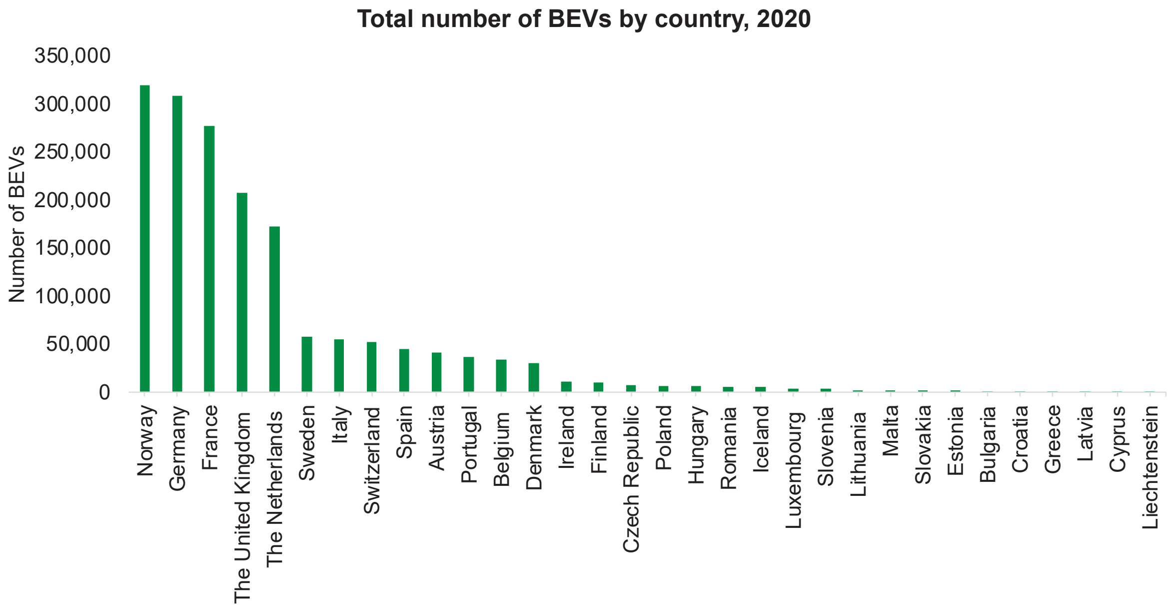

Figure 7. Total number of BEVs by country in 2020. The authors created this figure with data from European Alternative Fuels Observatory (EAFO) [15].

Moreover, in Norway, the number of BEVs in the fleet was 319,540 in 2020. In Germany, the number of BEVs in the fleet was 308,139. In France, the number of BEVs in the fleet was 277,001. In the United Kingdom, the number of BEVs in the fleet was 206,998. Moreover, in the Netherlands, the number of BEVs in the fleet was 172,534 in 2020. However, some countries in the European Union have a low number of BEVs in the fleet. For example, in Liechtenstein, the number of BEVs in the fleet was 222 in 2020. In Cyprus, this number was 251, while in Latvia, the number of BEVs in the fleet was 846.

Consequently, the increase in the number of BEVs in the EU's fleet could have several implications for the energy demand, the economy, and the environment, as significantly documented in the literature (e.g., Hooftman et al. [16]; Bekel and Pauliuk [14]; Xu et al. [10]; Andersson and Börjesson [9]; Gryparis et al. [17]; and Burchart-Korol et al. [18]). Moreover, other non-EU countries have explored the BEVs performance, resulting in lower GHG emissions, such as China [19], Australia and New Zealand [20], and their benefits to developing countries in decarbonising the transport sector [21]. As we already know, there exist several drives that lead to the increase of GHGs emissions. Energy, economic growth, globalisation, urbanisation, trade, and transportation, are widely explored in literature (e.g., Squib and Benhmad [22]; Koengkan et al. [23]; Leitão [24]; Ouédraogo et al. [25]; Balsalobre–Lorente et al. [26]; Shahbaz et al. [27]; Simionescu [28]; Leitão et al. [29]; Nwani [30]; Uzuner et al. [31]; Dogan and Inglesi-Lotz [32]; Ike et al. [33]; Badulescu et al. [34]; Panait et al. [35]; Koengkan et al. [36]; Destek et al. [37]; and Grossman and Kruger [38,39]). Thus, the main objective of this investigation is to explore the effect of BEVs on GHGs emissions in the EU using a macroeconomic approach.

It is highlighted that no literature approaches the effect of BEVs on GHGs using a macroeconomic and econometric approach. Indeed, this topic of investigation has been linked and studied by science, namely by engineering. In this context, numerous studies in technologies and engineering demonstrate that electric vehicles improve the environment and reduce greenhouse effects assessing the life cycle of electric cars, with a particular focus on the hybrid electric vehicle, the plug-in hybrid electric vehicle, and the battery-electric vehicle (e.g., Andersson and Börjesson [9]; Zhao et al. [40]; Vilchez and Jochem [41]; Xiong et al. [42]; and Ajanovic and Haas [13]).

In light of this, we can conclude that there is a gap in economic theory about the impact of electric vehicles and their components, namely the batteries of electric cars, on GHG emissions. In other words, econometric models have not been using this variable or proxy to understand if electric vehicles and their components help with air quality, reduce GHGs emissions, and improve the environment. These models can show us that the economic models should be rethought in combination with different study objects. For example, the adoption of these models can contribute to the analysis of the relationship between economic growth, final energy consumption, and BEV adoption. Moreover, the introduction of this variable as an explanatory factor of the Kuznets environmental curve has not received due attention from economists what become one of the most relevant contributions of this work. Therefore, this investigation takes a vital role regarding the effect of BEVs on GHG emissions in the literature. This investigation is the first to use macroeconomic data and an econometric approach to identify this effect in the EU. Then, the main novelty of this work focuses on establishing a relationship between how BEVs interact with three variables: energy, economy, and environment, in European countries. Emphasising also that the methodology applied here can be reapplied in other countries, resulting in different results between this interaction.

Well, faced with a lack of literature that approaches the effect of BEVs on GHG emissions in the European Union using a macroeconomic and econometric approach, we carry out the following question—**Can battery-electric vehicles mitigate the greenhouse gas emissions in the European Union?** This investigation will conduct an empirical analysis using macroeconomic panel data with twenty-nine countries, from the European Union, from 2010 to 2020, to answer this question. Therefore, this investigation will realise a macroeconomic analysis. For this research to be carried out, the method of moments quantile regression (MM-QR) and ordinary least squares (OLS) with fixed effects (to check the robustness of MM-QR' results) will be used. The use of MM-QR accounts for the possibility that the environmental impacts of BEVs may be heterogeneous across the spectrum of the conditional distribution of GHG emissions in Europe. Thus, although BEVs can reduce GHG emissions, these advantages cannot be realised at the same level in all countries.

Furthermore, because the carbon intensity of the energy used to charge BEVs significantly impacts the potential benefit and varies between European countries, the potential benefit will vary. For example, adopting BEVs can significantly save in countries where renewable energy accounts for a considerable portion of the energy mix. However, in countries where fossil fuels account for a substantial portion of the energy mix, emissions from charging BEVs may not be offset during the driving phase. As a result, the environmental benefits for some countries are likely to be minor.

This empirical investigation will contribute to the literature, introducing a new analysis related to the effect of BEVs on GHGs in the European Union. This topic of investigation is not explored by economists and opens new opportunities to study the relationship between electric cars and environmental degradation using an econometric and macroeconomic approach. Moreover, this investigation will contribute with the introduction of econometric models (e.g., MM-QR and OLS with fixed effects) that is not explored by literature on this topic. Furthermore, this empirical investigation will help governments and policymakers develop more initiatives to promote electric cars in the EU and policies to reduce the consumption of non-renewable energy sources, energy efficiency, and environmental degradation. Finally, this research topic can open a channel of policy discussion between industry, government, and researchers, as a crucial step towards ensuring that BEVs provide a climate change mitigation pathway in the region.

The remainder of this paper is divided into sections: a literature review in Section 2, data presentation and study methodology in Section 3, empirical results in Section 4, discussions of results in Section 5, conclusions and policy implications in Section 6, and limitations of the study in Section 7.

2. Literature Review

This section presents recent literature explaining the relationships between economic growth, non-renewable energy consumption, electric vehicles, and carbon dioxide emissions.

2.1. The Causality between Economic Growth and Carbon Dioxide Emissions

The links between economic growth and carbon dioxide emissions have been studied frequently by economists, especially since the 1990s with the overview of the environmental Kuznets curve [38,39]. In general, empirical studies find a U–shaped relationship between economic growth and polluting emissions. In the first stage of pre-industrialisation, countries are not aware of environmental issues, showing that economic growth is associated with high pollution levels. In the next step, in a phase of industrialisation, countries tend to reduce pollution emissions because they are aware of the environmental problems. This assumption is considered valid by the literature review.

More recently, new variables were introduced in the literature. Globalisation, renewable energies, corruption, economic complexity, urbanisation, tourism, democracy, and public health were introduced in the environmental Kuznets curve to assess their impact on air quality (e.g., Koengkan et al. [23]; Leitão [24]; Balsalobre–Lorente et al. [26]; Leitão et al. [29]; Nwani [30]; Uzuner et al. [31]; and Ike et al. [33]). Considering the presence of structural breaks for European Union countries, the empirical study of Ketenci [43] concluded that there are no found assumptions of EKC for the period 1974–1989, except for Sweden. Nevertheless, the EKC is valid for France, Germany, Greece, Italy, and Portugal when the author considers from 1960 to 2015 [43]. In this line, Panait et al. [35] studied EKC for EU countries between 1960 and 2014. The results showed that exports negatively affect pollution emissions, and imports positively impact CO_2 emissions. However, the authors do not find the expected signs for the correlation between income per capita, squared income per capita, and CO_2 emissions, i.e., according to their results, the variables of income per capita and squared income per capita present an opposite expected sign.

Recently, the ecological footprint was examined using the environmental Kuznets curve by Squib and Benhmad [22]. The authors used as sample 22 European countries, and their study validates the nonlinear relationship between economic growth and ecological footprint. Furthermore, they found that energy consumption encourages an environmental footprint. Similarly, the empirical research of Badulescu et al. [34] found EKC assumptions for EU countries.

Simionescu [28] tested the EKC for six Central and Eastern European countries, and the econometric results demonstrated a nonlinear relationship between renewable energy and carbon dioxide emissions. Besides, the relationship between economic growth and CO_2 emissions found an inverted N-shaped curve.

Then, the literature review applied to the EU countries is inconclusive regarding the environmental Kuznets curve. However, most empirical studies support a positive relationship between economic growth and climate change, showing a linear relationship between economic growth and carbon dioxide emission. Furthermore, there is a bidirectional relationship between growth and carbon dioxide emissions.

2.2. The Relationship between Energy Consumption and Carbon Dioxide Emissions

As in the previous relationship, the impact of non-renewable energy consumption is relatively abundant in the literature. Therefore, this item will try to present a non-exhaustive survey that justifies the introduction of energy consumption in the Kuznets environmental equation. Thus, as a rule, empirical studies find a positive association between energy consumption and carbon dioxide emissions, demonstrating that the intensity of non-renewable energy causes environmental damage. Indeed, it stimulates the climate change since this variable is associated with activity economy (e.g., Dogan and Inglesi-Lotz [32]; Ouédraogo et al. [25]; Shahbaz et al. [27]; Koengkan et al. [36]; and Destek et al. [37]). It is, thus, possible to observe a bidirectional relationship between the two variables when studies apply Granger causality or the more recent Dumitrescu and Hurlin technique.

The empirical study of Dogan and Inglesi-Lotz [32] evaluated the experience of European countries, and they found a nonlinear relationship between economic growth and pollution emissions. The variable of industry value-added also presents an inverted U curve. Moreover, the variables of energy structure, energy intensity, and population positively affect carbon emission, showing environmental damage. Similarly, Sharma et al. [44] evaluated the impact of energy consumption on the association between per capita income and CO_2 emissions and financial development and CO_2 emissions from 1976 to 2015, in Asian countries. The authors confirm that energy consumption leads to environmental pollution at the lower level of income; on the other hand, the impact of carbon emissions becomes weak at the higher level of income.

The environmental Kuznets curve applied to 11 African countries was investigated by Ouédraogo et al. [25]. Considering the causality results using Dumitrescu and Hurlin methodology, this empirical study showed bidirectional causality between CO_2 emission and economic growth. The same is valid for the relationship between carbon dioxide emissions and energy consumption and bidirectional causality between economic growth and energy use. Ardakani and Seyedaliakbar [45] investigated the relation between CO_2 emission, energy consumption, and GDP through multivariate linear regression in seven oil-rich countries in the MENA region to assess whether the environmental Kuznets curve can be confirmed or not. The authors confirmed EKC only in three countries (Oman, Qatar, and Saudi Arabia).

For instance, Shahbaz et al. [27] considered India's experience and tested the sustainable development goals considering a NADRL model (nonlinear autoregressive distributed lag). They concluded that India needs improvements in environmental aspects to obtain sustainable development because economic growth depends on non-renewable energy and imported crude oil.

The linkage between economic growth, energy, and carbon dioxide emissions applied to four Andean countries was investigated by Koengkan et al. [36]. They found bidirectional causality between growth and energy using an autoregressive panel regression. Thus, the economic activity needs energy intensity levels directly associated with energy demand theory. Moreover, the authors also found bidirectional causality between carbon dioxide emissions and economic growth. Therefore, energy consumption is directly related to environmental degradation.

Subsequently, Destek et al. [37] evaluated the EKC hypothesis using a dependent variable ecological footprint, considering 1980–2013. The authors used panel cointegration (FMOLS fully modified ordinary least squares) and DOLS (dynamic ordinary least squares). The results demonstrated that economic growth presents an inverted U-shaped ecological footprint. Furthermore, non-renewable energy positively affects the environmental footprint, and renewable energy and trade improve the environment.

2.3. The Link between Electric Vehicles and Carbon Dioxide Emissions

The transport sector, namely parts and components, contributes to the fragmentation or outsourcing process of the international economy [46], where vertical product differentiation predominates. On the other hand, the tertiarization of bilateral trade leads to economic growth. Besides, trade intensity and intra-industry trade reduce carbon dioxide emissions and climate change [47,48].

The transport sector's impact on carbon dioxide emissions and its relationship with the Kuznets environmental curve has been the object of study [49,50]. The study proposed by Ferreira et al. [49] applied to the case study for the BRICS countries (Brazil–Russia–India–China, and South Africa), using panel data for the transport sector, demonstrates that gas consumption and oil consumption have a positive effect on dioxide emissions of carbon.

The Malaysian experience was investigated by Go et al. [50] using the FMOLS (fully modified ordinary least squares), CCR (canonical cointegration regression), and DOLS (dynamic ordinary least squares) estimators. The authors used as dependent variable carbon dioxide emissions from the transport sector and as independent variables income per capita squared income per capita, corruption and oil consumption. The econometric results show that carbon dioxide emissions tend to increase with bribery and the assumptions of the environmental curve applied to the transport sector are not valid.

For the analysis of the eight leading countries in the global electric vehicle market (i.e., China, France, Germany, India, Japan, the Netherlands, Norway, and the UK), Xu et al. [51] used monthly data from 2009 to 2017, investigating the dynamic linkages between the stock of electric vehicles and carbon dioxide emissions. The authors used the quantile-on-quantile regression approach and obtained heterogeneous results between countries. However, overall, they find that electric vehicles negatively affect carbon dioxide emissions, and carbon dioxide emissions weakly and positively affect electric vehicles. Thus, there is a mixed directionality of causality between the two variables.

However, a meta-analysis on the relationship between electric vehicles and carbon dioxide emissions allows us to conclude that there is a gap in economic theory about the impact of electric cars and their components, namely the batteries of electric vehicles, on carbon dioxide emissions. In other words, econometric models have not been using this variable or proxy to understand if electric cars and their components help with air quality, reduce carbon dioxide emissions, and improve the environment. Indeed, very few studies have used econometric methods to explore the relation between electric vehicles and carbon emissions [51]. The introduction of this variable as an explanatory factor of the Kuznets environmental curve has not received due attention from economists. Still, as mentioned, there is an intuition that the batteries of electric vehicles can improve ecological issues. Intuitively we consider that electric cars improve and reduce climate change. This premise has been linked and studied by science, namely by engineering. In this context, numerous studies in technologies and engineering demonstrate that electric vehicles improve the environment and reduce greenhouse effects assessing the life cycle of electric cars, with a particular focus on the hybrid electric vehicle, the plug-in hybrid electric vehicle, and the battery-electric vehicle (e.g., Andersson and Börjesson [9]; Zhao et al. [40]; Vilchez and Jochem, [41]; Xiong et al. [42]; Ajanovic and Haas [13]).

The article by Ajanovic and Haas [13] draws some interesting conclusions, considering that electric vehicles contribute to the improvement of the environment, but emissions depend on the vehicle's production and use. Furthermore, the authors conclude that the environmental benefits depend on the use of renewable electricity. The study by Zhao et al. [40] looks at the impact of plug-in hybrid electric vehicles (PHEV) on the environment, concluding that the use of PHEV allows for a more sustainable environment, using tall batteries and, whenever necessary, replacing these batteries. In this line, Andersson and Börjesson [9] concluded that renewable fuels tend to reduce greenhouse effects in hybrid electric vehicles, plug-in hybrid electric vehicles, and battery-electric vehicles. Nevertheless, regardless of the use of renewable electricity, it is also essential to highlight the increase in the efficiency of electric vehicles. Considering different driving conditions, empirical data from Germany shows that battery-electric vehicles consume on average 67% less energy than internal combustion vehicles [52]. Indeed, technological innovation positively impacts energy efficiency [53].

The construction of explanatory scenarios for China, France, Germany, India, Japan, and the United States using electric cars was developed by Vilchez and Jochem [41]. The results show that electric vehicles can reduce greenhouse effects; however, the production must use clean energies.

A comparison between electric vehicle batteries (BEVs) and plug-in hybrid electric vehicle batteries (PHEVs) was proposed by Xiong et al. [42] for the Chinese case. In this study, the authors assess the greenhouse effects on the environment when comparing these types of vehicles. Like previous studies, the results showed that electric vehicle batteries (BEVs) decrease greenhouse effects and energy consumption.

The following section will be presented the data and method used to accomplish this empirical investigation.

3. Data and Method

This section will be divided into two parts. The first will approach the group of countries and data/variables used in this investigation, while the second will show the method.

3.1. Data and Hypotheses

This investigation uses annual data that was collected from 2010 to 2020, to twenty-nine European countries (e.g., **Austria**, **Belgium**, **Bulgaria**, **Croatia**, **Cyprus**, **Czechia**, **Denmark**, **Estonia**, **Finland**, **France**, **Germany**, **Greece**, **Hungary**, **Iceland**, **Ireland**, **Italy**, **Latvia**, **Lithuania**, **Luxembourg**, **Norway**, **Netherlands**, **Poland**, **Portugal**, **Romania**, **Slovakia**, **Slovenia**, **Spain**, **Sweden**, and **the United Kingdom**). This group of countries was selected because the BEVs gradually penetrated the European Union (EU) market. The region has registered an increase in new electric car registrations annually, from 700 units in 2010 to about 550,000 units in 2019. Nevertheless, they still account for a market share of only (3.5%) of newly registered passenger vehicles [15]. Moreover, as we are addressing a macroeconomic aspect, it is convenient to use all countries from the EU. Unfortunately, the European Alternative Fuels Observatory (EAFO) provides data from 2010 until 2020. The variables that were chosen to perform this investigation will be shown in Table 1 below.

Table 1. Variables' description and descriptive statistics.

Dependent Variables			
Variable	**Description**	**Time**	**Source**
GHGs	Greenhouse gas emissions per capita. This indicator includes carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and the so-called F-gases (hydrofluorocarbons, perfluorocarbons, nitrogen trifluoride (NF3), and sulphur hexafluoride (SF6).	2010–2020	Eurostat [54]
Independent variables			
GDP	GDP per capita based on purchasing power parity (PPP). This variable is converted to international dollars using purchasing power parity rates.	2010–2020	World Bank Open Database [55]
ENERGY	Final energy consumption in thousand tonnes of oil equivalent per capita. Final energy consumption covers the energy consumption of end-users, such as industry, transport, households, services, and agriculture.	2010–2020	Eurostat [56]
BEVs	The number of battery electric vehicles (BEVs) registered in the fleet.	2010–2020	European Alternative Fuels Observatory (EAFO) [15]

Variables	**Descriptive Statistics** Obs.	Mean	Std.-Dev.	Min.
LnGHGs	280	2.2281	0.3398	1.6486
LnGDP	290	10.5781	0.3738	9.7665
LnENERGY	290	3.9564	0.4332	2.1972
LnBEVs	290	5.1711	2.8874	0.0000

Notes: (Ln) denotes variables in the natural logarithms; Obs. denotes the number of observations in the model; Std.-Dev. denotes the Standard Deviation; Min. and Max. denote Minimum and Maximum, respectively; the command *sum* of Stata was used.

Next, we present the hypotheses formulated considering the literature review shown in this investigation.

Hypothesis 1 (H1). *The development of economic activity and economic growth presuppose high levels of carbon dioxide emissions.*

Considering the Kuznets environmental curve arguments, empirical studies usually find a positive association between economic growth and pollution emissions. In this context, Badulescu et al. [34], Panait et al. [35], Squib and Benhmad [22], and Simionescu [28] support the formulated hypothesis.

Hypothesis 2 (H2). *Non-renewable energies and their energy intensity stimulate greenhouse effects.*

Several studies such as Destek et al. [37], Koengkan et al. [36], Sharma et al. [44], Ardakani and Seyedaliakbar [43] found a statistically significant positive correlation between energy consumption and carbon dioxide emissions.

Hypothesis 3 was constructed based on empirical studies between the association of electric vehicles batteries and carbon dioxide emissions. However, as mentioned in the review from the literature and after having carried out a meta-analysis on the association of electric vehicle batteries and pollution levels, we observed that in economics science, there is little empirical evidence as far as we know. However, some studies, such as Andersson and Börjesson [9]; Zhao et al. [40]; Vilchez and Jochem, [41]; Xiong et al. [42]; Ajanovic and Haas [13], from the engineering areas allowed us to formulate the following hypothesis:

Hypothesis 3 (H3). *Electric vehicle batteries reduce climate change and improve air quality.*

In this context, the investigation will use the following variables **GHGs**, **GDP**, **ENERGY**, and **BEVs**. The variable **GHGs** is our dependent variable, while **GPD**, **ENERGY**, and **BEVs** are our independent variables. Moreover, the variables **GDP** and **ENERGY** are the control variables of our empirical model. Furthermore, it is worth remembering that the literature windily uses the variable **GHGs** as a dependent variable. The same occurs with the variables **GDP** and **ENERGY,** which also are windily used by literature as an independent variable to explain the increase of GHGs. However, only the variable **BEVs** was not approached by literature to explain the rise of GHGs in a macroeconomic and econometric context. At last, the variables in per capita values such as **GHGs**, **GDP,** and **ENERGY** were used to reduce the effects of population disparity. Therefore, after presenting the variables, it is also necessary to present the method used.

Then we present some theoretical foundations about the independent variables under study and carbon dioxide emissions.

Theoretically, the greenhouse gas emission–income nexus suggests that economic growth increases greenhouse gas emissions. This effect is due to the high consumption of energies intensive in carbon in countries' first stages of industrialisation [53]. This phenomenon leads to an inverted U-shaped EKC. In this line, the expected sign of the coefficient for economic growth is positive. Moreover, higher energy consumption leads to an increase in greenhouse gas emissions [27]. Thus, we expect the association between energy consumption and greenhouse gas emission to be positive. The current study is synthesised from the energy–growth–environmental degradation literature. However, incorporating the battery-electric vehicle variable into our empirical model distinguishes it from existing studies in the literature. The battery-electric vehicles are expected to increase environmental quality by mitigating greenhouse-gas emissions [42]. This study extends the EKC framework by using the functional relationship based on the growth-induced environmental degradation hypothesis with the inclusion of battery-electric vehicles to investigate the relationship between the variables mentioned above.

3.2. Method

This subsection presents the main methods used in this empirical investigation and the preliminary tests necessary to carry out.

3.2.1. Method of Moments Quantile Regression (MM-QR)

The recent and novel Method of Moments Quantile Regression (MM-QR) approach for panel fixed effects developed by Machado and Silva [57] is adopted to explore the impact of battery electric vehicles on greenhouse gas emissions for a panel of 28 OECD countries. Furthermore, unlike previous panel quantile regressions proposed by Canay [58], Lamarche [59], and Koenker [60] used the MM-QR with fixed effects technique. This approach captures the unobserved distributional heterogeneity across countries within a panel. Another merit of the MM-QR is that it assumes that covariate only affects the variable of interest through the channel of location and scale functions relative to a mere shifting location [61]. Thus, it is possible to investigate the conditional heterogenous covariance effects of the determinants of greenhouse gas emissions at different quantiles of its distribution for the countries under consideration.

Following the study of Machado and Silva [57], using data highlighted variables under review $\left\{(GHGs_{it}, X_{it}')'\right\}$ from a bloc of n countries $i = 1, 2, \ldots, n$ overtime periods $t = 1,\ 2, \ldots, T$, we conduct a location-scale model of the conditional quantiles $Q_{GHG}(\tau|X_{it})$ as given (see Equation (1) below).

$$GHGs_{it} = \alpha_i + X_{it}'\beta + \left(i + Z_{it}'\gamma\right)U_{it} \quad (1)$$

with $\Pr\left\{\delta_i + Z_{it}'\gamma > 0\right\} = 1$ and the unknown parameters $(\alpha_i,\ \delta_i), |\ i = 1, 2, \ldots, n$ measure the fixed effect for individual and Z is a known differentiable (with Pr = 1) transformation of the elements of X. U_{it} is the error term which is independently and identically distributed across i and t, uncorrelated with X_{it}. Model (1) can be extended. See Equation (2) below.

$$Q_{GHG}(\tau|X_{it}) = (\alpha_i + \delta_i q(\tau)) + X_{it}'\beta + Z_{it}'\gamma q(\tau) \quad (2)$$

where the scalar coefficient $\alpha_i(\tau) = \alpha_i + \delta_i q(\tau)$ denotes the quantile- τ fixed effect for an individual country. The distributional impact varies from the classical fixed effect, given that it is not location fixed. To this end, the distributional effect depicts the time-invariant traits that allow for other variables to have diverse effects on investigated countries (For the sake of brevity, see Machado and Silva [57] for more insight on the Method of the Moments Quantile Regression approach for panel fixed effects).

3.2.2. Ordinary Least Squares (OLS) with Fixed Effects

The OLS estimates the slope and intercepts for a set of observations and other estimates of mean response for the fixed predictors using the conditional mean function in this study (see Equation (3), below).

$$LnGHGs_{it} = \beta_0 + \beta_1 LnGDP_{it} + \beta_2 LnENERGY_{it} + \beta_3 LnBEVs_{it} + \varepsilon_{it} \quad (3)$$

where β_0 is the intercept, and β is the value of fixed covariates being fitted to predict the dependent variable $LnGHGs_{it}$, ε_i is the error term, and each variable enters regression for country i at year t. Thus, OLS modelling allows to describe the relationship between the covariates but cannot be extended to non-central locations in the case of shapeshifts. OLS is also heavily influenced by outliers [62,63].

Indeed, before realising the MM-QR and OLS with fixed effects, we must realise the preliminary tests. Therefore, we will evidence the preliminary tests used in this empirical investigation.

3.2.3. Preliminary Tests

As mentioned before, preliminary tests are necessary before the model estimations. Indeed, these tests are necessary to detect the proprieties of variables used in this empirical study and verify the existence of singularities, which is not considered and could lead to inconsistent and incorrect interpretations. To this end, some preliminary tests will be applied in the study, as shown in Table 2 below.

Then, this investigation will follow the following conceptual framework (see Figure 8), highlighting the methodological approach.

Table 2. Preliminary tests.

Test	Reference	Description
Shapiro-Wilk	Shapiro and Wilk [64]	It checks the normality of the panel model.
Skewness/Kurtosis	D'Agostino et al. [65]	Based on combining Skewness and Kurtosis amounts, it checks the normality.
Variance Inflation Factor (VIF)	Belsley et al. [66]	It measures multicollinearity in a regression analysis.
Cross-sectional dependence (CD)	Pesaran [67]	It recognises the presence of cross-sectional dependence in the model.
Panel Unit Root test (CIPS)	Pesaran [68]	It detects the presence of unit roots.
Westerlund panel cointegration	Westerlund [69]	It checks whether cointegration exists or not by determining whether error correction is present for individual model members and the panel as a whole.
Hausman	Hausman [70]	It verifies the random effects vs fixed effects; Identifies heterogeneity.

Notes: This table was created by the authors.

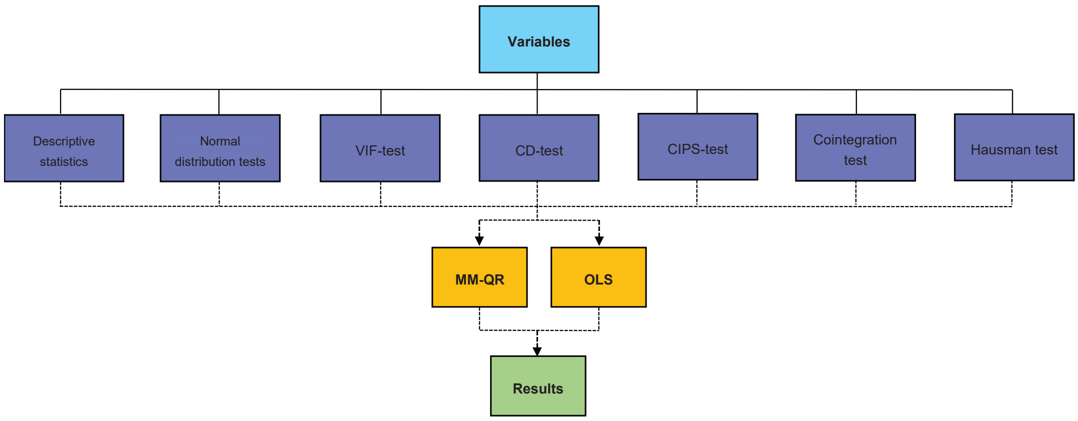

Figure 8. Conceptual framework. The authors created this figure.

The empirical analysis was carried out using the econometric software **Stata 17.0.** Moreover, this investigation will use the following Stata commands (e.g., *sum, sktest, swilk, vif, xtcd, multipurt, xtwest, hausman, xtqreg,* and *xtreg*). The next section will present the empirical results of this investigation.

4. Empirical Results

As mentioned before, this section is devoted to the empirical results of this study, which starts with the preliminary tests and then represents the model estimation results. The descriptive statistics of the variables were presented in the previous section. Next, the normality test was conducted to identify the distribution of the variables, which includes the Skewness/Kurtosis tests [65] and Shapiro–Wilk tests [64]. Table 3 below shows the results from the normal distribution tests.

Table 3. Normal distribution tests.

Variables	Obs.	Skewness	Kurtosis	Skewness/Kurtosis Tests	Shapiro-Wilk Test
				Prob > Chi2	Prob > z
LnGHGs	280	0.0003	0.8847	0.0034 **	0.0000 ***
LnGDP	290	0.0034	0.2217	0.0100 **	0.0000 ***
LnENERGY	290	0.0000	0.0016	0.0000 ***	0.0000 ***
LnBEVs	290	0.3782	0.0008	0.0048 **	0.0002 ***

Notes: ***, **, denote statistically significant at (1%), and (5%) level; (Ln) denotes variables in the natural logarithms; the commands *sktest* and *swilk* of Stata were used.

The results of the normal distribution tests revealed that **LnBEVs** is highly skewed. In addition, the combined skewness–kurtosis test proposed by D'Agostino et al. [65] showed that the null hypothesis of the normal distribution could be rejected for the data from this group of countries during this specific period. Moreover, testing normality applying the Shapiro–Wilk test, the null hypothesis of normal distribution for all variables in the model can be rejected; hence, all model variables are not normally distributed.

In the next step, it is essential to test and measure multicollinearity between variables in the model; therefore, the variance inflation factor (VIF) test [66] was calculated. Table 4 shows the model's VIF-test result. The mean VIF of 2.19 represents low multicollinearity among the model variables, as the rule of thumb suggests a mean VIF value of 6 or lower to proceed with the model estimation [71].

Table 4. VIF-test.

Variables	VIF	1/VIF	Mean VIF
	LnGHGs		
LnGDP	2.88	0.3466	
LnENERGY	2.28	0.4385	2.19
LnBEVs	1.41	0.7081	

Notes: (Ln) denotes variables in the natural logarithms; the command *vif* of Stata was used.

Applying the Pesaran CD-test developed by Pesaran [67] to identify the presence of cross-sectional dependence (CSD) in the panel data (Table 5) shows the existence of cross-section dependence in all variables of the model. Furthermore, this test indicates that the countries selected in this study represent the same characteristics and shocks [23].

Table 5. Pesaran CD-test.

Variables	CD-Test	*p*-Value
LnGHGs	19.69	0.000 ***
LnGDP	49.15	0.000 ***
LnENEGY	54.45	0.000 ***
LnBEVs	54.45	0.000 ***

Notes: *** denotes statistically significant at (1%) level; (Ln) denotes variables in the natural logarithms; the command *xtcd* of Stata was used.

Verifying the order of integration of the variables in the model is essential in deciding whether to proceed with the cointegration test. Hence, the panel unit root tests were applied, such as the CIPS-test developed by Pesaran [68]. Table 6 below shows the results from the unit root tests. For example, the panel unit root test (CIPS) indicates that the variables **LnGDP** and **LnENERGY** without and with the trend are stationary or I(1). On the contrary, the variables **LnGHGs** and **LnBEVs,** without and with the trend, are between the I(0) and I(1) order of integration.

Table 6. Unit Root test.

Variables	Panel Unit Root Test (CIPS) (Zt-Bar)		
	Without Trend		With Trend
	Lags	Adjusted t	Adjusted t
LnGHGs	1	−1.210	−2.516 ***
LnGDP	1	−3.900 ***	−3.158 ***
LnENERGY	1	−0.143 **	−3.296 ***
LnBEVs	1	−1.009	−1.661 **

Notes: ***, ** denote statistically significant at (1%) and (5%) levels; (Ln) denotes variables in the natural logarithms; the command *multipurt* of Stata was used.

The existence of I(1) variables in the model suggests the necessity of verifying the presence of cointegration between these variables. In doing so, the Westerlund panel cointegration test [69] is applied in this study. Table 7 below represents the Westerlund panel cointegration test results. This test is for checking the presence of cointegration between **LnGDP** and **LnENERGY**.

Table 7. Westerlund panel cointegration test.

Variables LnGDP and LnENERGY			
Statistic	**Value**	**Z-Value**	***p*-Value**
Gt	0.216	11.951	1.000
Ga	0.427	7.488	1.000
Pt	1.156	9.004	1.000
Pa	0.490	5.726	1.000

Notes: The command *xtwest* with option *constant* of Stata was used. H_0: No cointegration; H_1 Gt and Ga test the cointegration for each country individually, and Pt and Pa test the cointegration of the panel.

The results of the Westerlund panel cointegration tests revealed that the null hypothesis of no cointegration could not be rejected. All panel statistics, such as Gt and Ga, test cointegration for each country individually, and Pt and Pa that test the cointegration of the panel also do not reject the null hypothesis. The Hausman test compares the model's random effects (RE) and fixed effects (FE). The null hypothesis of this test suggests that the difference in coefficients is not systematic, where the random effects are the most suitable estimator [23]. The results of this test are presented in Table 8 below, which indicates that the null hypothesis cannot be accepted, confirming the presence of fixed effects in the model.

Table 8. Hausman test.

Dependent variable LnGHGs				
Variables	**(b) Fixed**	**(B) Random**	**(b-B) Difference**	**Sqrt(diag(V_b-V-B)) S.E.**
LnGDP	−0.0961	−0.0536	−0.0424	0.0136
LnENERGY	0.8986	0.7997	0.0989	0.0278
LnBEVs	−0.0123	−0.0138	0.0014	0.0004
Chi2 (3)		15.73 ***		

Notes: *** denotes statistically significant at the (1%) level; (Ln) denote variables in natural logarithms; the Stata command *hausman* (with the options, sigmaless) was used.

The model can be estimated with the quantile regression and the OLS model with fixed effects at the final stage. Table 9 represents the results of quantile regression and OLS with fixed effects of the model. Estimating the model with the quantile regression indicates that in all three quantiles, the variable **LnGDP** causes a positive impact on **LnGHGs**. This variable is statistically significant at a (1%) level with quantile regression. According to previous studies (e.g., Koengkan et al. [23]; Nwani [30]; and Uzuner et al. [31]), this result shows that economic activity is direct with environmental damage and climate change.

Table 9. Estimation results from Quantile regression and OLS with fixed effects.

Independent Variables	**Dependent Variable (LnGHGs)**			
	Quantiles			**OLS**
	25th	**50th**	**75th**	**Fixed Effects**
LnGDP	0.6948 ***	0.6516 ***	0.4148 ***	−0.0961 *
LnENERGY	0.1665	0.2178 ***	0.2323 ***	0.8986 ***
LnBEVs	−0.0339 ***	−0.0490 ***	−0.0348 ***	−0.0123 ***
Constant	−4.1859 **	−3.2541 ***	−0.5458	8.1558 ***
Obs	280	280	280	280
Pseudo R^2	0.3087	0.3526	0.3506	0.3705

Notes: ***, **, * denote statistically significant at (1%), (5%), and (10%) levels; (Ln) denotes variables in the natural logarithms; the command *xtqreg* with option reps (350) and *xtreg* with option fe of Stata was used.

In the 50th and 75th quantiles, the variable **LnENERGY** also causes a positive effect on the dependent variable, and the variable is statistically significant at a (1%) level. Hence, both economic development and energy consumption increase the emissions of GHGs in EU countries. However, the variable **LnBEVs** in the 25th, 50th, and 75th quantiles result in a negative impact on the variable **LnGHGs**, meaning that the battery electric vehicles are capable of mitigating GHGs emissions. Our results are according to the conclusions of engineering studies. Thus, as concluded by Andersson and Börjesson [9], Zhao et al. [40], electric batteries aim to reduce CO_2 emissions.

Moreover, the estimation results applying the OLS model with fixed effects indicated that the variable **LnGDP** has a negative impact on the variable **LnGHGs**; therefore, it is possible to conclude that economic development mitigates the emissions of GHGs. This finding contradicts the results from the quantile regression. The variable **LnENERGY** causes a positive impact on the variable **LnGHGs**, indicating that energy consumption contributes to an increase in GHGs emissions. In contrast, the variable **LnBEVs** causes negative effects, which are in line with the results from the quantile regression. This result indicates that BEVs are capable of mitigating the emissions of GHGs.

Figure 9 illustrates the graphical results of the quantile regression. The shaded areas are (95%) confidence bands for the quantile regression estimations. The vertical axis represents the elasticities of the explanatory variables. The horizontal lines depict the conventional (95%) confidence intervals for the OLS coefficients.

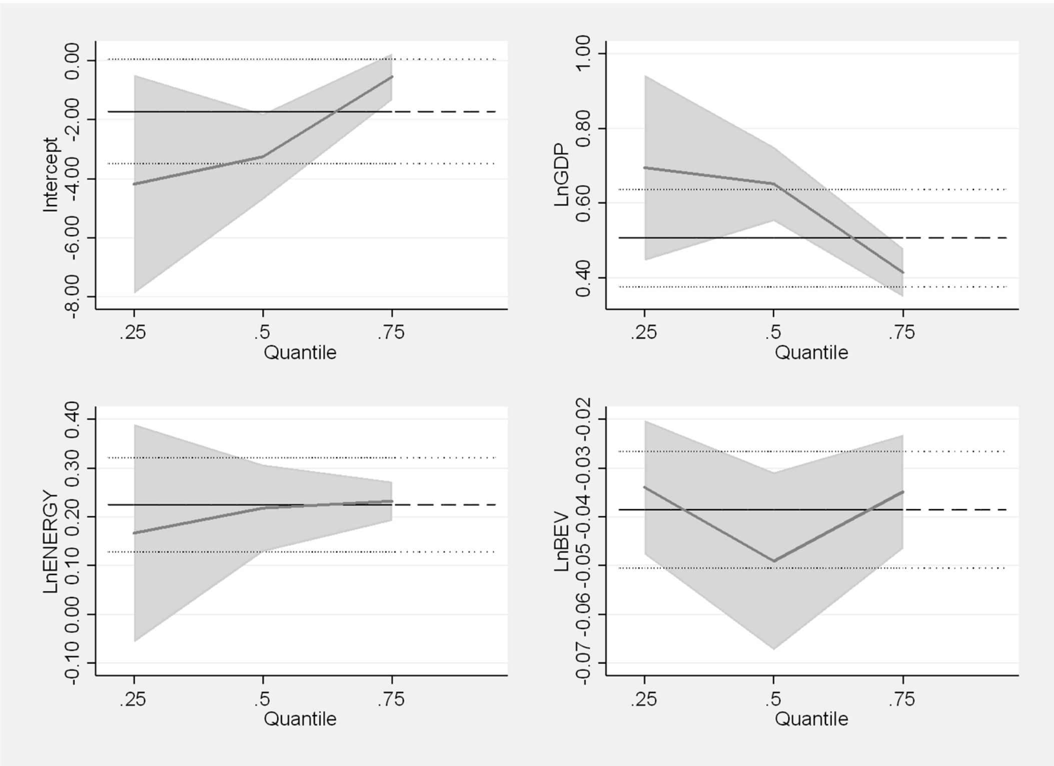

Figure 9. Quantile estimate: Shaded areas are (95%) confidence bands for the quantile regression estimates. The vertical axis shows the elasticities of the explanatory variables. The horizontal lines depict the conventional (95%) confidence intervals for the OLS coefficient.

Moreover, Figure 10 below summarises the impact of independent variables on dependent ones. This figure was based on results from Table 9.

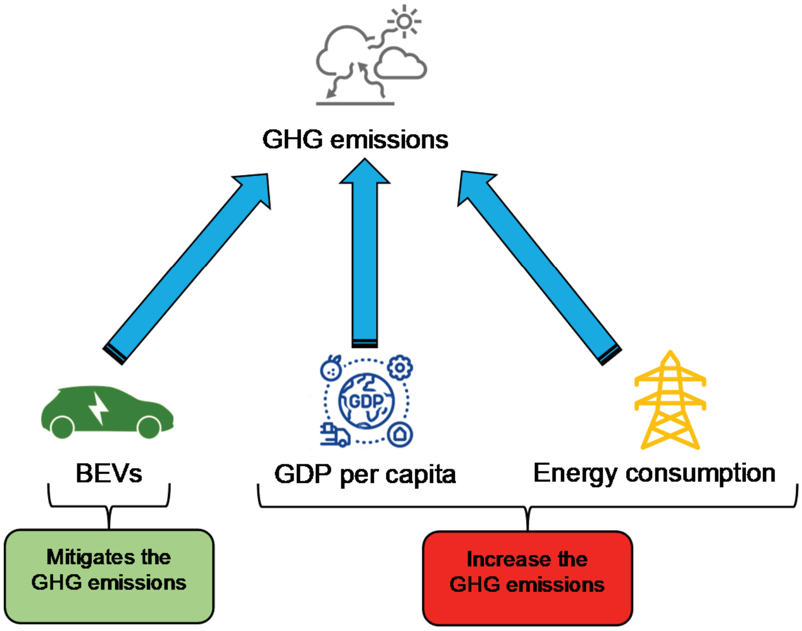

Figure 10. Summary of the variable's effect. The authors created this figure.

This section approached the empirical results, starting with the preliminary tests, and presenting the main model regression results. The following section will present the discussions and presented the possible explanations for the results that were found.

5. Discussions

In this section, we will address the discussions of results that were found in this empirical investigation. As shown in Section 4, the economic growth and the final energy consumption increase the GHG emissions, while the BEVs mitigate them. In light of this finding, we arose the following questions: What are the possible explanations for the results found? Are these results in accordance with the literature? The positive impact of economic growth on GHG emissions in the European region was confirmed by several authors in the literature (e.g., Mendonça et al. [72]; Nawaz et al. [73]). For example, Mendonça et al. [72] studied the impact of GDP, population, and renewable energy generation in CO_2 emissions in 50 countries (including the EU countries) for the period between 1990 and 2015. The authors found that an increase of (1%) in the GDP generates (0.27%) in CO_2 emissions in all study countries. According to the authors, this result was found because most study countries depend on energy from fossil fuels to grow.

This vision is shared by Nawaz et al. [73]. According to the authors, modern production techniques make industrial production more attractive and effective in developing and advanced nations. Consequently, it increases the utilisation of non-renewable energy sources. Indeed, this increase substantially influences per capita GDP and improves the quality of life by increasing the provision of goods. Indeed, the efforts to increase per capita GDP through increasing production impact negatively the environment.

Indeed, the evidence that European countries depend on non-renewable energy to grow, as mentioned by Mendonça et al. [72], makes perfect sense. For example, in 1990, (71%) of the final energy consumption came from non-renewable energy sources, while renewable energy sources had a share of (4.33%) in the energy mix in the European region. However, in 2019, this scenario changed, where fossil fuels had a share of (69.4%) in the energy mix, while renewable energy had a share of (15.8%) (see Figure 11 below).

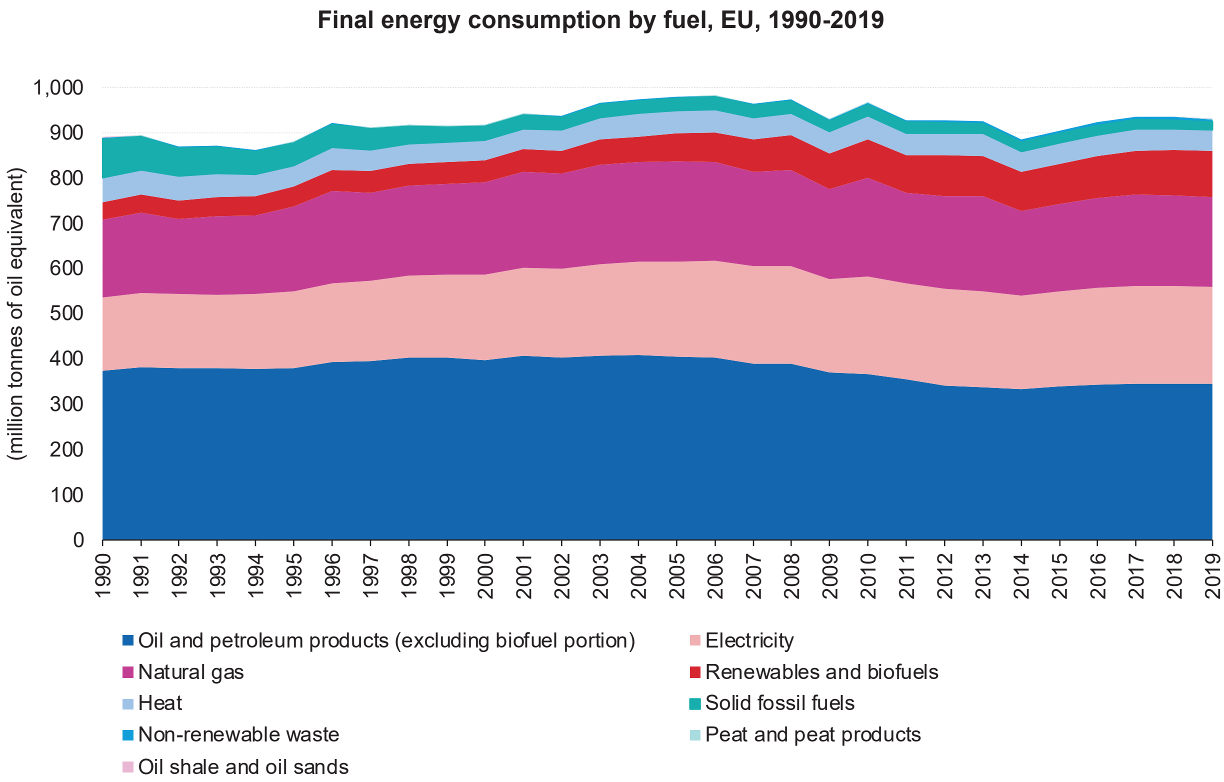

Figure 11. Final energy consumption by fuel in EU between 1990 and 2019. The authors created this figure with data from European Environment Agency [74].

However, the mix of fuels and their share in final energy consumption varies in different EU countries due to the natural resources available, the industry in each country, and national resources in energy systems. Thus, for example, we can include the share of solid fossil fuels, crude oil, petroleum products, and natural gas in final energy consumption below (50%) (e.g., Estonia (9.1%); Sweden (28.7%); Finland (39.4%); and France (48.25%)) (see Figure 12 below).

Moreover, it should be noted in the figure above, France and Sweden were also the countries with the highest contribution of nuclear heat to the final energy consumption, where both countries contributed with (42.3%) and (32.8%), respectively. In Sweden and Latvia, renewable energies accounted for just short of (40%) of their final energy consumption in 2019 (39.6% and 38.9%, respectively), with Finland closely following at (34.6%). The lowest participation of renewable energy was registered in Malta (5.4%), the Netherlands (6.0%), and Luxembourg (6.5%).

Therefore, the capacity of energy consumption to increase GHG emissions in the European countries is associated with economic activity, as mentioned above. Several authors found this evidence (e.g., Ouédraogo et al. [25]; Shahbaz et al. [27]; Mendonça et al. [72]; Dogan and Inglesi-Lotz [32]; Nawaz et al. [73]; Koengkan et al. [36]; and Destek et al. [37]). Indeed, the increase in economic activity leads to increased energy consumption from non-renewable energy sources. Moreover, the evidence that economic growth increases the final energy consumption in the European countries was found by us (see Table 10 below).

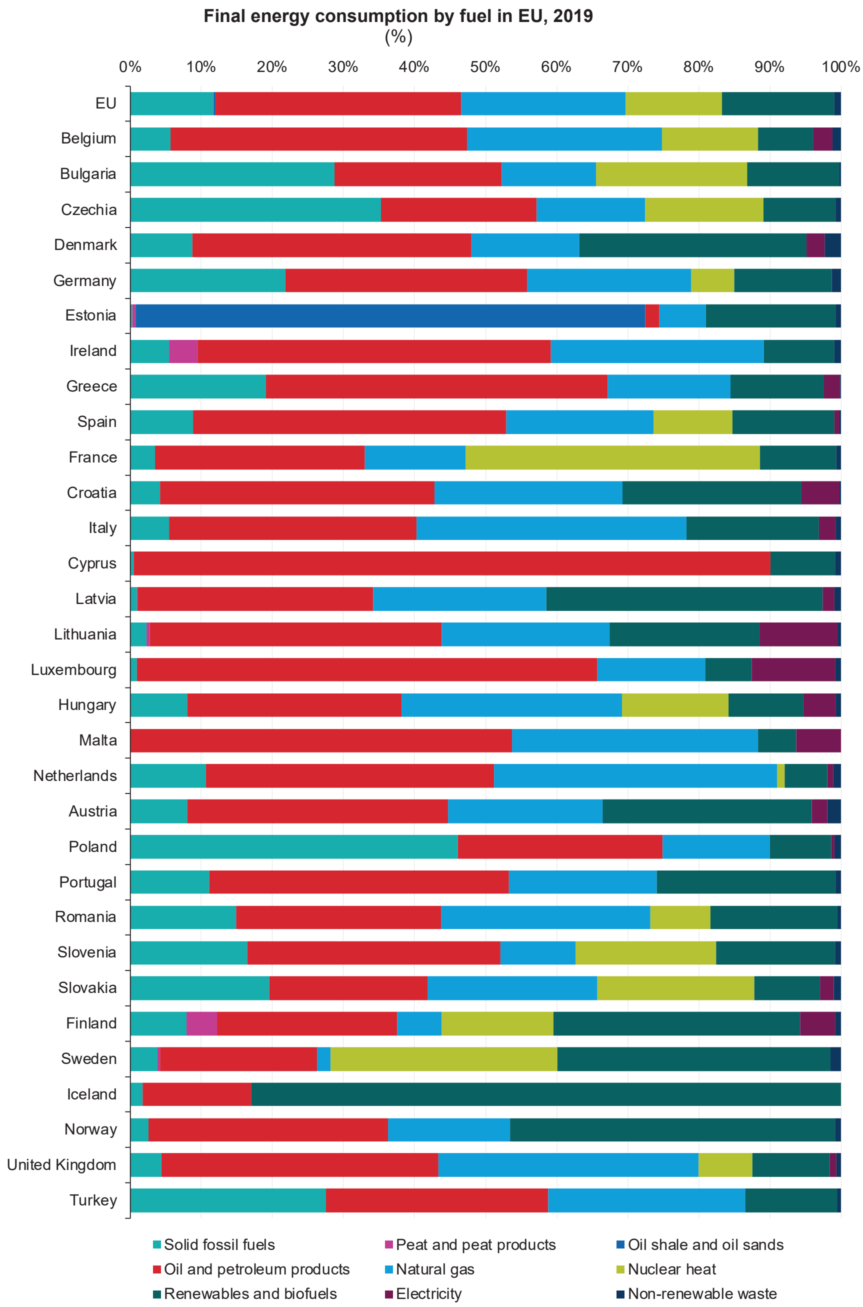

Figure 12. Final energy consumption by fuel in EU countries in 2019. The authors created this figure with data from European Environment Agency [74].

Table 10. Estimation results from Quantile regression and OLS with fixed effects.

Independent Variables	Dependent Variable (LnENERGY)			
	Quantiles			OLS
	25th	50th	75th	Fixed Effects
LnGDP	0.8047 ***	0.9423 ***	1.0445 ***	0.4667 ***
LnBEV	−0.0034	−0.0264 ***	−0.0341 ***	−0.0154 ***
Constant	−14.0654 ***	−15.2045 ***	−16.1439 ***	−10.2377 ***
Obs	290	290	290	290
Pseudo R^2	0.3208	0.3995	0.4618	0.5827

Notes: *** denotes statistically significant at (1%) level; (Ln) denotes variables in the natural logarithms; the command *xtqreg* with option *reps (350)* and *xtreg, fe* of Stata were used.

Therefore, as shown in Table 10 above, in the quantile model regression, the economic growth in 25th, 50th, and 75th quantiles increase the final energy consumption, while the BEVs decrease the consumption in all quantiles. Moreover, these results also were confirmed by the OLS model with fixed effects, where an increase of (1%) in economic growth increased (0.46%) of the final energy consumption.

That is our object of study regarding the impact of BEVs on GHG emissions. As we already know, the impact of BEVs on GHG emissions is not explored by macroeconomic literature. However, this topic of study has been linked and studied in the literature, namely by engineering (as mentioned before in Section 2). Therefore, the evidence that the BEVs mitigate environmental degradation was found by several authors (e.g., Andersson and Börjesson [9]; Zhao et al. [40]; Vilchez and Jochem, [41]; Xiong et al. [42]; and Ajanovic and Haas [13]). For example, Ajanovic and Haas [13] found that electric vehicles improve the environment, but emissions depend on the vehicle's production and use. Furthermore, the authors conclude that the environmental benefits depend on the use of renewable electricity. Vilchez and Jochem [41] share this idea. The authors studied scenarios for China, France, Germany, India, Japan, and the United States. Therefore, electric cars can mitigate the GHGs' effects production must use clean energies.

Moreover, Xiong et al. [42] that studied the Chinese case complement the vision of Vilchez and Jochem [41] and Ajanovic and Haas [13]. According to the authors, the BEVs decrease greenhouse effects and energy consumption. This point of view that BEVs can reduce energy consumption is supported by European Environment Agency [74]. According to the agency, the average mass of BEVs increased from 1200 kg in 2010 to 1700 kg in 2019, while average energy consumption decreased from 264 Wh/km to 150 Wh/km, indicating that BEVs have become more efficient. Indeed, the reduction of energy by BEVs was predicted by Nielsen and Jørgensen [75], where according to the authors, the consumption of energy from BEVs will be 0.10 (kWh/km) between 2016 and 2030 (see Figure 13 below).

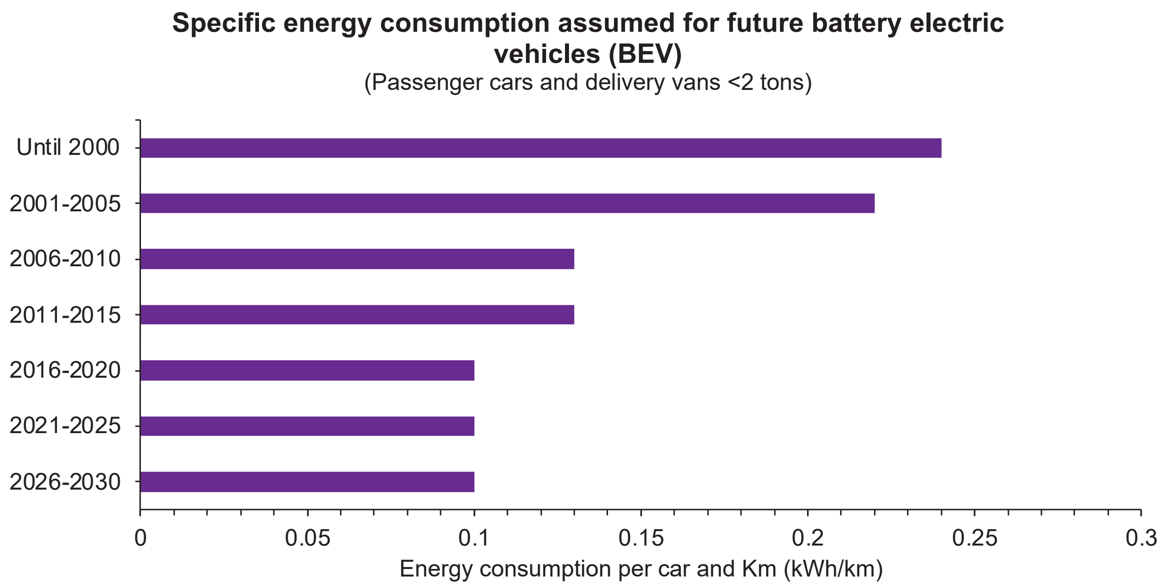

Figure 13. Specific energy consumption is assumed for future battery electric vehicles (BEVs). The authors created this figure with data from Nielsen and Jørgensen [75].

Indeed, to confirm the capacity of BEVs to reduce energy consumption, we realise a model regression (see Table 10 above), and the results confirmed the visions of Xiong et al. [40] and the European Environment Agency [74], although the result is minimal. Therefore, the BEVs can decrease energy consumption and, consequently, environmental degradation. However, the reduction in the energy consumption caused by BEVs is not enough to mitigate the GHGs in the European region due to the low participation of BEVs in the fleet. For this reason, that final energy consumption is still able to increase GHG emissions.

This field of research is in an exploratory stage of development. Nevertheless, this investigation contributes to the literature with a macroeconomic analysis of the impact of BEVs on GHGs. However, more studies are necessary to deepen the knowledge about the research topic. Therefore, macroeconomic studies should be directed to identify the relationship between BEVs, renewable energy consumption, and GHG emissions. Thus, we can confirm the possible explanation of Vilchez and Jochem [41] and Ajanovic and Haas [13] that the capacity of BEVs to decrease GHG emissions is related to the consumption of energy. In the next section, we will present this study's conclusions and policy implications.

6. Conclusions and Policy Implications

This analysis explored the effect of BEVs on GHG emissions in a panel of twenty-nine countries from the EU from 2010 to 2020. This study is kick-off regarding the impact of BEVs on GHGs and other aspects such as energy consumption in a macroeconomic and econometric aspect. Indeed, this investigation is in the early stages of maturation and will supply a solid foundation for second-generation research regarding this topic.

The MM-QR was used as the main model, while the OLS with fixed effects was used to verify the robustness of the results. The results from the preliminary tests indicated **(i)** the variables are not normally distributed, **(ii)** low multicollinearity between the variables, **(iii)** presence of cross-section dependence, **(iv)** variables **LnGDP** and **LnENERGY,** without and with the trend, are stationary or I (1), **(v)** the variables **LnGHGs** and **LnBEVs,** without and with the trend, are borderline I (0) and I (1) order of integration, **(vi)** non-presence of cointegration between the variables **LnGDP** and **LnENERGY**, and **(vii)** presence of fixed effects in the model.

The results from the MM-QR indicates that in all three quantiles, the variable **LnGDP** causes a positive impact on **LnGHGs**. In the 50th and 75th quantiles, the variable **LnENERGY** also causes a positive effect on the dependent variable. Hence, both economic development and energy consumption increase the emissions of GHGs in European Union countries. However, the variable **LnBEVs** in the 25th, 50th, and 75th quantiles results in a negative impact on the variable **LnGHGs**, meaning that the battery electric vehicles are capable of mitigating GHGs emissions. Moreover, the results from the OLS with fixed effects indicated that the variable **LnGDP** has a negative impact on the variable **LnGHGs**; therefore, it is possible to conclude that economic development mitigates the emissions of GHGs. This finding contradicts the results from the quantile regression. The variable **LnENERGY** causes a positive impact on the variable LnGHGs, indicating that energy consumption contributes to an increase in GHGs emissions. In contrast, the variable **LnBEVs** causes negative impacts, which are in line with the results from the quantile regression.

The capacity of economic growth and the final energy consumption to increase the GHGs could be related to the dependence of European countries on energy consumption from non-renewable energy sources to growth. Therefore, economic activity will positively impact energy consumption and negatively affect the environment. This explanation is widely supported and explored by literature and it was proved in this empirical investigation that economic growth increases the final energy consumption in the EU. Now, the capacity of BEVs to mitigate the GHGs could be related to the low energy consumption of electric cars and consequently decrease the energy consumption. Another possible explanation could be the consumption of energy from renewable energy sources by electric vehicles. Thus, the empirical founds of this investigation answered our central question but led us to new questions, such as **Do BEVs can increase the consumption of renewable energy, as mentioned by Vilchez and Jochem** [41] **and Ajanovic and Haas** [13])? **As the manufacturers say, is the production chain of BEVs (100%) sustainable and clean?** These questions need to be answered to understand how the BEVs interact with energy, the economy, and the environment.

In the face of this discovery, another question arises. **What are the possible policy implications of this study?** This research is motivated not only by the BEVs impacts on emissions but also by the policy implications for the EU to increase the commercialisation of BEV vehicles and decrease the GHGs emissions. Therefore, we recommend the potential policy measures supporting the insertion of BEVs focus on: **(i)** an intense market penetration; **(ii)** investments in network and private charging infrastructure; **(iii)** specific and efficient emission regulations; **(iv)** technological development (e.g., fast charging; longevity of batteries); **(v)** additional financial incentives (e.g., feed-in tariffs; fiscal incentives; battery costs); **(vi)** integration between energy supply and transport sector; **(vii)** domestic policies considering geographical issues; and **(viii)** consumer acceptance of BEVs. Moreover, although the EU has supported a more sustainable transport system, accelerating the adoption of BEVs still requires effective political planning in the short, medium, and long term to net-zero pledges emissions. Thus, to achieve the EU targets of decarbonising the energy sector, the BEV has been considered an important technology to reduce GHG emissions. Finally, this research topic can open a channel of policy discussion between industry, government, and researchers, as a crucial step towards ensuring that BEVs provide a climate change mitigation pathway in the region.

7. Limitations of the Study

This investigation is not free of limitations during the process of investigation. The study modelled GHG emissions against major economic determinants, including the BEVs, GDP per capita, and energy consumption. While these variables are a significant contributor to GHG emissions, including renewable energy policies, incentive policies for electric cars, and globalisation index could bring more robustness to the model. However, as we have data until 2018 for the variable globalisation index at KOF Globalisation Index, and until 2019 for the variables renewable energy policies and incentive policies for electric cars at International Energy Agency (IEA)-Policy database, this investigation did not include these variables. Another limitation of this investigation is the lack of macroeconomic data on the ecological footprint of all production chains of electric cars. If this data were available, this investigation could realise a robustness verification to confirm if electric cars decrease the GHG emissions in the EU.

Moreover, another limitation of this study is the impossibility of including dummies in the model. This restriction is due to the short period that this investigation has used. However, these dummies could represent shocks or outliers in the EU countries (e.g., economic, financial, political, social crises, economic growth, etc.). Therefore, these dummies could also bring more robustness to the model. Indeed, these limitations mentioned above are normal in an investigation in the early stages of maturation. Then, as mentioned in the conclusions section, it is necessary to develop second-generation research regarding this topic to overcome these limitations. Despite the limitations mentioned above, the study allows us to draw meaningful conclusions in terms of economic and energy policy. In this context, government policy should encourage electric batteries to reduce greenhouse effects and improve air quality. On the other hand, the European economy must continue implementing green growth practices.

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Industry Leaders' Perceptions of Residential Wood Pellet Technology Diffusion in the Northeastern U.S.

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Abstract: Within a shifting climate of renewable energy options, technology innovations in the energy sector are vital in combating fossil-fuel-driven climate change and economic growth. To enter this market dominated by fossil fuels, renewable energy innovations need to overcome significant barriers related to cost, relative advantages compared to fossil fuels, and policy incentive programs. A better understanding of the innovation diffusion of new technologies in establishing the renewable energy industry can aid policy makers in designing and implementing other renewable energy support programs and improving adoption rates within existing programs. This study assessed industry leaders' perceptions through semi-structured interviews. We explored the innovation diffusion process of wood pellet residential heating technology, as well as policy needs and barriers within this industry that are hindering successful long-term diffusion and sustainability. We show that while there is high potential to the wood pellet industry in terms of local resources and overall advantages to fossil fuels, it can be difficult to achieve sustainable economic growth with current cost barriers and further policy programs and incentives are needed in addition to improved communication to reduce adoption barriers for wood pellet technology.

Keywords: wood pellets; diffusion of innovation; forest products business; energy policy; qualitative interviews; industry leaders; wood economy; residential heating technology

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1. Introduction

Renewable energy, including types made from forest products, plays a critical role in sustaining the social and economic well-being of societies while combating fossil-fuel-driven climate change [1–3]. While innovations in the heating, transportation, and electricity sectors have allowed renewable energy sources to become more convenient and economically affordable for consumers, there are still significant barriers in place preventing the widespread diffusion of many renewable energy and forest product innovations [4–6]. The slow growth of the residential wood pellet industry in New England provides a valuable case study.

Despite initial development of automated wood pellet heating supply and demand, the diffusion of this technology within the region has not reached the tipping point in the product life cycle from take-off to growth. These take-off periods vary by individual innovation, with take-off periods lasting more than ten years not being uncommon [7]. The concept of innovation diffusion is a critical foundation for establishing continued support for innovative forest products and technology, including various forms of renewable energy. Innovation diffusion is the process by which an innovation is communicated through channels among the members of a social system over time and eventually adopted and integrated as the norm within that system [7]. To enter a fossil-fuel-dominated market, a new renewable energy product often needs to overcome barriers such as high initial cost and low consumer awareness [8,9]. Policy support is critical in such a risky and uncertain diffusion process of new innovations [10,11]. Many policy support programs are designed to help new renewable energy products reach a stage of self-sustainment that infers continual supply and demand growth for the product. Without policy support, however, producers paving the path for innovative technologies often have significant financial hurdles to overcome, which can lead to lower participation in the technology and reduced likelihood that the product will reach self-sustainment.

A number of studies have examined different innovations from various perspectives, including customer characteristics and their responses to innovation, developing market entry strategies, and modeling of innovation processes [4,5,7,12,13]. However, little research has been conducted from the perspective of change agents or the managers of an innovation seeking to establish its industry and create economic growth. In this case study, our focus are leaders of equipment firms, bulk delivery companies, and pellet mills within the forest products sector. As they work at the forefront to promote a renewable energy innovation and specialized forest products industry, managers' experiences and perceptions could provide rich accounts of and insights into the opportunities and challenges faced in other real-world renewable energy diffusion processes.

This case study focused on the perspectives of wood pellet industry producers in order to provide in-depth perspectives on the diffusion of a renewable energy product innovation: residential wood pellet heating technology. We specifically hone in on residential use of this renewable innovation. An assessment of the diffusion of this technology can help to identify the influence of barriers to renewable energy products industry success, such as a decline in competing alternative prices or limited policy incentives, while also identifying patterns of consumer adoption from the industry leaders attempting to diffuse this technology into a highly competitive energy market. The two central objectives of this study were (1) to assess the innovation diffusion process of wood pellet heating technology from the perspective of industry leaders and (2) to identify barriers to consumer adoption and industry needs to achieve successful diffusion, long-term product sustainability, and, ultimately, a market for residential wood pellets and related heating technology. Studies exploring the diffusion process often focus on the preferences of consumers from the perspectives of consumers, or they focus on production from the perspective of producers [2,14]. We focus specifically on insights regarding the challenges of market development from industry leaders seeking to build a robust market for automated wood pellet heating systems. Specifically, we focused on analyzing industry leader perceptions of relative advantages, disadvantages, external influences, and incentive programs related to the wood pellet industry using the diffusion of innovation theoretical framework. Our discussion focuses on recommendations that can support the development and growth of the residential wood pellet market and may have broader implications for emerging markets of other renewable energy products.

2. Case Study Context

The northeastern region of the United States consumes 86% of the 4.4 billion gallons per year of fuel oil burned nationwide, primarily for space and water heating [15]. Peak oil prices in 2009 spurred greater policy interest in a wood–heat transition. Wood-based fuel helps fulfill heating needs, is a readily available resource in northern New England, and is associated with the strong wood-based economic identity of the region. The region has a longstanding history of burning wood, with firewood being a longstanding rural community staple. In Maine specifically, half of residents have indicated that they plan to use wood as a primary or secondary heating source in the future [16]. However, in New England over 55% of homes continue to be heated with oil [2].

With the recent decline in the paper and pulp industry in the United States over the last several decades, studies have begun to show the potential of wood-based alternatives to heating oil (such as wood pellets) in resurging declining forest industry economies [17]. Northern New England's vast forested lands are sources of economic vitality. The timber and wood products industries provide a quarter of the timber resources—$33 billion and 178,000 jobs' worth—for the entire nation [18,19]. However, the closure of several major pulp and paper mills in the region has resulted in a severe decline in low-grade wood markets, posing threats to the livelihoods of the region's rural communities and logging infrastructure [19,20]. Developing a more robust wood heating sector could contribute significantly to regional social, economic, and environmental well-being.

Around the time of the 2009 spike in oil prices, wood pellet heating technology—specifically automated, high-efficiency boiler systems—were being introduced to northern New England as a wood heating innovation and an alternative to heating oil at a higher rate than ever before [2]. The scale of these heating systems ranged from residential homes to smaller-scale community or commercial applications like apartments, schools, and municipal buildings. At the time this innovation was introduced to the market oil prices were reaching over $100 per barrel. A stark decline in oil prices beginning in mid-2014 added uncertainty to the diffusion process and raised concern about total market failure for wood pellet heating systems. The nominal price of crude oil had fallen to $30 per barrel by the end of 2015 and had stabilized in the range of $40 to $50 per barrel through 2017, eventually reaching a peak of just over $70 per barrel prior to the COVID-19 pandemic [21,22]. In general, lower oil prices reduced the competitiveness of renewable energy sources by enhancing the relative economic costs to purchase renewable energy products [23]. As oil prices fell, wood pellet heating equipment firms in northern New England reported stagnant sales growth. Wood energy subsidies have taken place exclusively at the state level, while tax preferences and subsidies that shift incoming oil reserves into economic profitability happen at the national level [24].

Compared to pellet stoves or convertible boilers that fit on existing fossil fuel heating systems, new residential pellet heating systems feature an automated pellet feeding system, can heat the entire home, allow homeowners to control the temperature from a thermostat, and are self-cleaning. Professionals deliver pellets in bulk to homeowners, saving those homeowners time and effort. States in this region (Maine, New Hampshire, Vermont, and New York) have established varying policies to increase adoption of wood heating systems as a way of reducing their dependence on fossil fuels. All four states have developed subsidy programs that offset the initial purchase cost of wood heating systems for consumers. All states require proven fossil fuel energy reductions to qualify, and New York has additional offsite outdoor wood pellet storage requirements. In addition to state-level subsidy programs, some banks in the region offer loan programs that allow residents to purchase wood heating systems with low interest rate loans. Furthermore, non-profit organizations such as the Northern Forest Center launched community-based education and incentive programs to promote clustered demand in selected communities. Pellet manufacturers, bulk delivery companies, and equipment firms established informal and opportunistic networks to supply automated pellet heating throughout the region [25]. Cost in comparison to the price of oil heating units remains a significant barrier towards the adoption of this technology, a barrier that can only be alleviated through further development of more cost-efficient automated wood pellet boilers or through policy incentive programs. As the cost of advanced wood pellet heating units starts at $10000 USD and can be in excess of $20,000 USD, the current existing state-level incentive programs are often insufficient in competing with the price of oil heating units [14]. Recent federal policy developments, such as the Wood and Pellet Heater Investment Tax Credit, will prove critical in incentivizing homeowners to move away from oil heating.

3. Theoretical Framework

The theory of diffusion of innovations has been widely adopted in renewable energy research [4,5,26–29]. The innovation diffusion process can be characterized by how extensively and quickly an innovation spreads through the market [30]. The rate of adoption describes the relative speed with which an innovation is adopted by members of a social system [7]. It is often measured by the length of time required for a certain percentage of members to adopt an innovation. Plotted on a cumulative frequency basis over time, adoption rates often result in an S-shaped curve similarly described by the Bass Diffusion Model, a simple equation that describes the process of how new products are adopted in a population [12,31]. The curve is marked by two distinct turning points: take-off, the sudden spike in sales that follows an initial low-sales period, and slowdown, the sudden leveling in sales that follows a period of rapid growth [12,31].

Critical mass is a key component of diffusion of innovation theory, and it occurs when enough individuals in a system have adopted an innovation that further adoption occurs due to saturation rather than to innovator action [7]. Reaching a critical mass could mean that sales of a new product reach a level sufficient to reduce the distribution costs for suppliers and the initial cost for customers [29]. More individuals in the social system may consider the innovation common and ordinary, which could lead to further adoption [7]. It is essential for an innovation to move from the take-off to the growth stage in order to achieve sustainability. Four strategies for getting to critical mass have been identified: (1) targeting highly respected individuals in a system's hierarchy for initial adoption of the innovation, (2) shaping individuals' perceptions of the innovation to imply that the adoption is inevitable or that critical mass will soon occur, (3) introducing the innovation to intact groups in the system whose members are likely to be relatively more innovative, and (4) providing incentives for early adoption [7]. Within the New England region, poor networking has been identified as a barrier for innovation adoption, especially in the realm of forest products where it has been found that those harvesting wood-based resources often have poor lines of communication with public research and education institutions [4].

Relative advantage, particularly consumer perceptions of these advantages, is often described as one of the strongest predictors of an innovation's rate of adoption [7,32–34]. Relative advantage is characterized as economic profitability, social prestige, the saving of time and effort, and the immediacy of reward. However, there is rarely universal agreement about the relative advantage of an innovation based on objective and systematic comparison. The actual or perceived characteristics of an innovation may change in the diffusion process. For example, large demand may reduce the initial cost to adopt and increase the amount of innovation diffusion [7,29,31]. Large numbers of adopters may reduce the level of consumer uncertainty regarding switching from heating oil to wood pellets and increase the likelihood that individuals will perceive the advantage of the innovation [29]. One key advantage that exists for wood pellet technology is the existence of infrastructure in the region to utilize the vast biomass resources which can be transformed to wood pellets. Loggers are looking for more ways to utilize these resources which are often wasted in the woods [4,5]. One key aspect of the relative advantage of an innovation is its ability to be tested by potential adopters [7,35]. High efficiency wood pellet boiler systems are not typically a product that consumers can test, due to their complexity and the cost associated with installation. Increasing the number of adopters is often thought to be the best way to give potential future adopters a trial by proxy through the testimony of members of their social group.

4. Materials and Methods

Our case study examined the high-efficiency wood pellet heating industry in northern New England. Data were collected through semi-structured interviews from 2016 to 2017. Before data collection, four scoping interviews were conducted with staff from a non-profit organization that was active in promoting automated pellet heating technology diffusion (Figure 1). Using these scoping interviews, as well as searching wood pellet industry association membership directories, and other online sources, we identified businesses in the region that were directly involved in wood pellet production for residential use, ranging from wood pellet manufacturers to residential heating equipment installers. A total of 21 wood pellet industry leaders and other stakeholders (e.g., state industry association leaders and residential technology business owners) were specifically identified as being the primary relevant industry leaders surrounding wood pellets in northern New England. Eighteen of the twenty-one invited participants agreed to be interviewed. One invited participant from an equipment firm refused to participate due to lack of interest, while two invited participants from pellet mills did not respond. Our response rate of 86% led to a final group of 18 participants, who represented active pellet mills, automated pellet boiler equipment firms, bulk delivery service providers, and installers in Maine, New Hampshire, and Vermont. We identified data saturation by open coding the interviews in the order in which they were conducted and evaluating the number of new codes generated by each new interview. In total we identified 1023 codes from the 18 in-depth interviews, which we narrowed into thematic categories based on innovation diffusion theory.

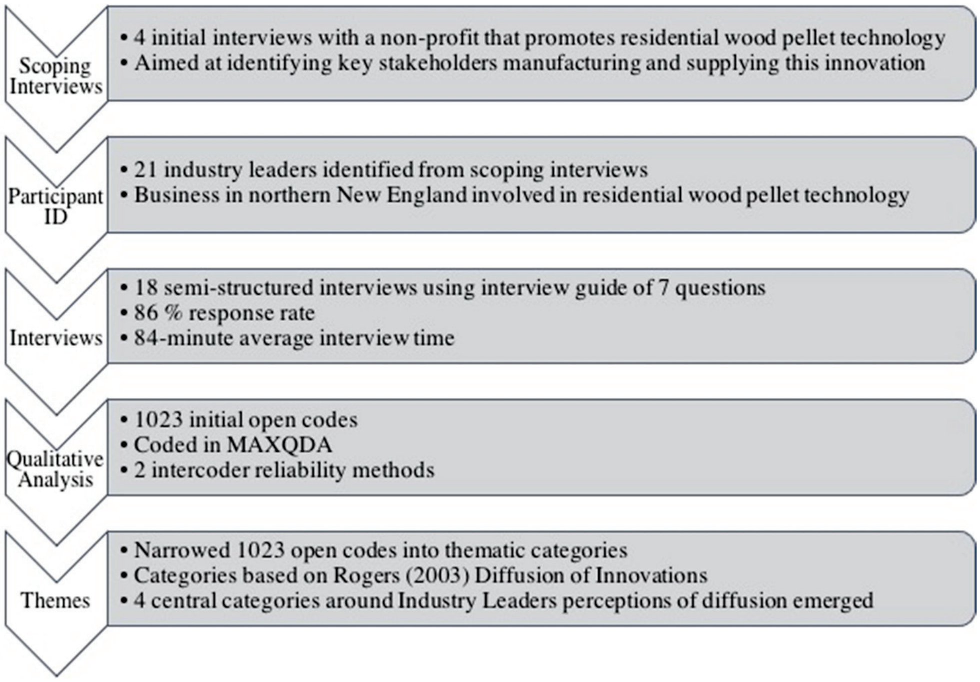

Figure 1. Research methods approach taken for qualitative interview procedure.

All interviews were conducted at company sites where participants worked. Interviews lasted anywhere from 48 to 89 min with a mean length of 84 min. Questions, based on interview guides, addressed study objectives and included: (1) In your experience, is the demand for wood pellets increasing or decreasing, and why?; (2) What in your opinion is the future for automated wood pellet boiler systems?; (3) Would you consider automated wood pellet boiler technology mature?; (4) Do you share customer satisfaction, decision-making, or relevant technological information with others in your industry?; (5) What may be the biggest challenge facing the industry, and what are the goals for your company in the upcoming five years?; (6) How do oil prices influence your business?; (7) What is your vision for the wood pellet and boiler equipment industry? The exact wording and order of these questions changed based on the flow of the interviews.

All transcripts were first open-coded in MAXQDA version 12 (VERBI GmbH, Berlin, Germany), resulting in a total of 1023 initial codes. These codes were further analyzed and narrowed in several rounds of merging and organizing codes based on study objectives and components of the diffusion of innovations theory. Coded transcript segments were then reviewed based on specific thematic categories to check whether the coding was true to the participants' original meaning in the context of the question. Several themes regarding the diffusion process of automated pellet heating and the influence of barriers arose in the process. We compared participants' perspectives on each theme and findings against the diffusion of innovation theory. We conducted two intercoder reliability checks. First, we had a second coder review all transcripts for coding and themes related to the diffusion of innovation theory. Second, the themes were reviewed and confirmed by four additional members of the research team which included academics and practitioners. To complete the analysis, we organized the themes by research objective and organized into a logical hierarchy based on both concept and frequency. Quotations from the transcripts were then selected to present participants' thoughts in their own wording for the results section.

5. Results

5.1. Description of Interviewees

A total of 18 individuals were interviewed, including managers from two automated pellet boiler equipment firms, one equipment and bulk delivery company, four bulk delivery companies, and six pellet mills, as well as a leader from a regional pellet industry trade association and a consultant working extensively in the pellet and automated pellet heating industry. The sample captured data from 13 of the 16 known companies within the study region, representing more than 80% coverage of the industry. All participants were males between the ages of 30 and 69 years. Participants had a wide range of tenure in the pellet heating industry, ranging from one year to over two decades. All companies and organizations represented in the study were physically located in Maine, New Hampshire, or Vermont.

5.2. The Complex Question of Innovation Diffusion Take-Off

Most industry leaders noted the slow growth in automated pellet heating demand since 2010, with an emphasis on the struggle in achieving critical mass against the standard residential oil burner most commonly used in the region. There was a spectrum of beliefs held by participants regarding how likely their product was to completely diffuse within the renewable energy market. Participants' views on the stage of diffusion were informed by their different assessments of the eventual future number of adopters. These assessments, in turn, were influenced by how participants viewed perceptions of the relative advantages of the automated pellet heating industry, perceptions of achieving critical mass, and other external factors influencing adoption such as incentives and oil prices. We conceptualize the key themes from our interviews with industry leaders on their perceptions of the diffusion of wood pellet residential technology in New England (Figure 2).

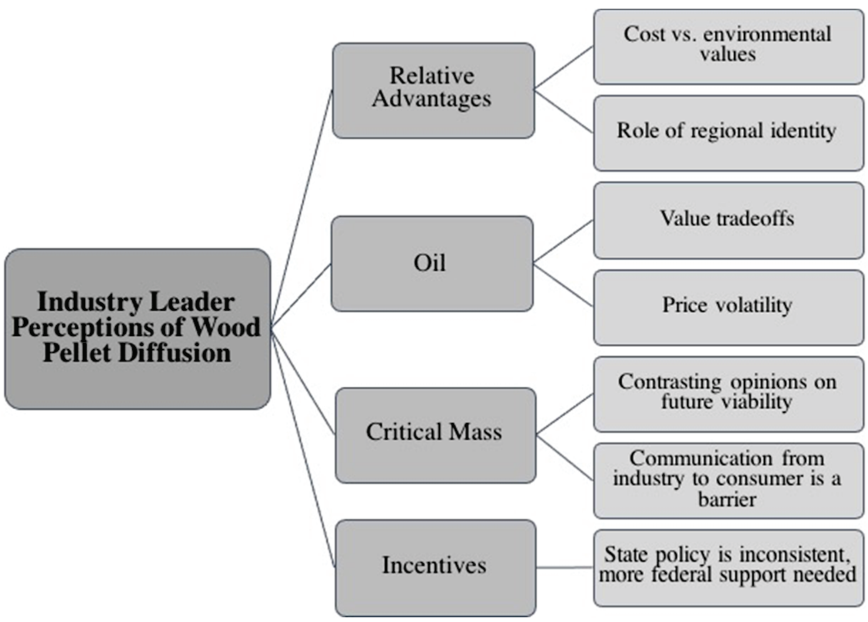

Figure 2. Conceptual model of coded thematic categories that emerged from interviews.

5.2.1. Perceptions of Relative Advantages

Compared to pellet stoves or other traditional wood combustion equipment, participants agreed that automated pellet heating was more efficient, easier to use, more tolerant of pellet quality, more convenient, renewable, required less maintenance, and was overall "a simple piece of equipment that really can work for everyone." Participants found that many individuals in the region were familiar with burning cordwood or pellets and had a genuine enjoyment of wood heat compared to oil. Automated pellet heating technology in turn was an upgrade from traditional wood heat and appealed to such a market, while also having specific benefits over the standard oil heater. Industry leaders noted:

> *"They tell me how much they love their wood stove or pellet stove. But they never once told me how much they love their oil boiler. So, I think it's just natural."*

> *"Once people have their pellet stove in or pellet boiler in, they love that heat. Wood heat is a lot different than oil heat."*

> *"From my experience, most people don't want oil. So, if you don't want oil in your house, it's not a hard pitch. The simplicity of the operation, the ease of the ash removal, the bulk delivery–it's wood heat for everybody."*

Automated pellet heating has relative advantages over traditional wood combustion equipment and is compatible with some individuals' preferences, such as the convenience of the pellet heating systems for aging customers.

> *"People who have burned traditional firewood their whole lives love wood heat. So, they're looking to not have to cut firewood because it's very labor-intensive and hard work, and they're aging out of being able to do that, and so the pellets are a great alternative to still have that wood heat but not the work."*

These industry leaders also noted conflicting perceptions regarding the influence that local or regional identity played in the adoption process. Some interviewees indicated that pellets or pellet systems had a relative advantage over oil due to the regional wood-based economy.

> *"So, you really still need a consumer who wants wood heat, likes wood heat, believes it's better, wants to support a local economy. That's their Northern Forest . . . They know it's a lumber mill in town. They know it's supporting their region."*

> *"It's renewable. It keeps the dollars in our local economy, and it really gets rid of heating oil. That's one thing I really love about what we do is we literally take that oil out of the network, and it's gone. This house is oil free now totally. A lot of people are keen on that."*

While supporting a local economy was likely important to most consumers, interviewee responses indicate an uncertainty regarding whether or not consumers associate the purchase of wood pellet products with supporting local industries and whether or not industry leaders are communicating this relative advantage to consumers.

One disadvantage of automated pellet heating cited was the high equipment cost. With current demand level, this cost is unlikely to drop in the near future. When oil prices were high, such a disadvantage could be mitigated by the stability of pellet cost and overall savings on fuel price, as one interviewee noted:

> *"You can justify a high capital cost, and these boiler systems cost two to three times what a conventional oil or gas does, by the fact that you are going to save a lot of money on your fuel bill."*

> *"The drawbacks are, number one, the low price of heating oil right now. But, we all know that's not going to be forever. It's too sporadic and, what's the word, volatile. So, if there was some type of education program out there that would help people see, just because the price of heating oil is low today doesn't mean it's going to be low next year. And pellet prices have been relatively stable for years and years and years."*

With the oil price decline, the savings were not "there the way they were a few years ago, so the financial cost/benefit is . . . the calculation is very different today." This factor may explain the sales dip after the oil price decline. However, how the reduction in payback influenced the diffusion of automated pellet heating was unclear, particularly since the trajectory of oil prices was uncertain. One noted:

"Ninety-five out of 100 consumers make their decision based on pure economics, not is this going to reduce greenhouse gasses? Is this better for the environment? Will my dollars stay local?"

In contrast, others stated:

"Nobody really wants to burn it [oil]. We just have to give them reasons not to. And some people you can push without the financial picture being perfect for them. Some people won't. They don't like it. But, they're not willing to pay to move away from it yet. But, that's okay. They will once—there are people like that, when oil goes back up, they're going to pick up the phone."

"Once it [oil prices] stabilized, I think we go back to our normal mindset of, "I don't want to burn oil." The conception that it's not cheap is still there. It may be cheap at the moment. Nobody goes—I don't think any consumers go, "Well, we're going to have cheap oil for the next ten years." They might not see that it's going to spike to five dollars a gallon again."

These opposing observations led to different predictions about the eventual number of adopters (i.e., market size) based on the perceived relative advantage of the innovation. However, once again, disagreement arose about consumer perceptions towards oil pricing. Aforementioned participants indicated a concern that consumers perceive oil as being generally cheaper, while others relayed that consumers understand the volatility of oil markets at this point.

Some participants were concerned that residential automated pellet heating would remain a niche market and suggested switching attention to other commercial-scale markets for wood heating technology such as schools, governmental buildings, and hospitals. Others thought there was still large demand for automated pellet heating and that the market just required time to get there. There was also concern about current wood pellet industries in New England competing with markets outside of the Northeast region. An industry consultant indicated the following in response to a question about whether New England had a competitive advantage:

"Not so much within this region. It's more within other regions of the country that have lower power businesses. The Southern Appalachian states have access to cheap power. And they do ship product into this region . . . They have lower wood costs, lower electricity, lower labor costs. They have the disadvantage of a 500- or 600-mile trek to get to where the market is, so they kind of balance out."

These findings demonstrated the difficulty in clarifying the relative advantage of an innovation and predicting cumulative adoption rates. The role of environmental values on consumer behavior to adopt wood pellet heating innovations was stated a few times, such as the eagerness to switch away from oil heating. Few interviewees, however, directly mentioned climate change as a relevant factor in consumer decisions on whether or not to purchase wood pellet boilers. Some participants expressed concerns regarding how environmentally friendly their technology was perceived to be.

"The states are continuing to push ahead for the most part with clean energy policy objectives and priorities. But, as you know, there is a whole sector of the environmental community out there that does not view this [wood pellet burning] as being renewable or clean."

External disturbances, such as declines in oil price, might make certain disadvantages more salient to potential adopters and change agents. If change agents stopped their promotional efforts due to these external disturbances, it could in turn slow the diffusion of innovation in the future.

5.2.2. Perceptions of Achieving Critical Mass: Can This Innovation Take Off?

Many participants expressed doubt regarding the future viability of wood pellet heating systems. Other participants maintained a determined optimism regarding the industry, suggesting that there is hope in the future and expressing frustration in the current lack of innovation diffusion. Some indicated an awareness of the concept of critical mass and what is needed to achieve it.

> *"The infrastructure in the state is set up for heating oil. I mean, there's heating oil delivery trucks and dealers everywhere you look. You drive down the road, and you'll meet five delivery trucks from five different companies. Well, here in southern Maine, there's only really two legitimate wood pellet delivery companies, and there isn't even enough–there aren't enough customers really to support those two. So, we need a lot more infrastructure and need a lot more people to convert to pellet heat to make it economically feasible and sustainable."*

> *"We want to make pellet heating–pellet central heating, pellet boilers–common and ordinary. Once it becomes common and ordinary, people will feel comfortable adopting the technology."*

Many participants were actively working with customers on the adoption of wood pellet systems in urban areas such as Portland, Maine. Others expressed doubts that there existed a viable urban market for wood pellet systems.

> *"Another thing is these are systems that are generally going to be used in a rural area, and they're not cost-effective compared to natural gas. So, any urban area that has natural gas is not going to install a wood pellet boiler."*

Some participants had more stated optimism regarding the growing market for residential wood pellet heating technology.

> *"The market's definitely not saturated. I don't think we have to worry about that for a long time still. I think it's mostly–we have not–the one thing we've not done well as an industry is to promote bulk delivery. But, those of us who are out there are pretty well established now."*

5.2.3. Incentives or Lack Thereof

A consistent theme among participants was the need for improved policy incentives for the wood pellet heating industry in order to achieve innovation diffusion. Some participants noted differences between the practices of states in the Northeast, identifying the advantages of some states' renewable energy incentives (albeit confusing bill requirements and recommendations) and the disadvantages of other states' incentives or lack thereof.

> *"It helps to have additional financial incentives for sure. So, those are state policies that provide added funding for these systems. That's probably the most important one [incentives]. And then the other is more like don't have policies that get in the way of these and being installed and working well. The state of New York has some really restrictive requirements around getting its incentive, like they require that you store the pellets outdoors, which adds to the cost and not everyone wants to store their pellets outdoors."*

> *"So, there's certainly advantages to buying Maine wood products in these businesses [due to incentives]. Now, Vermont just passed a bill that, by 2030, 35 percent of all public buildings have to be fueled by wood, either chips or pellets. So, they're looking ahead."*

Maine and Vermont were consistently identified by participants as having more effective incentive programs than New York (cited frequently) or New Hampshire (cited infrequently). Participants linked incentive programs, such as rebate policies, with consumer decision-making.

> *"It's [rebate policies] probably the only reason anybody is selling any of those systems right now with very few exceptions, is because there are rebates available to offset the capital, some portion of the capital costs."*

Along with comparing these programs across states, participants expressed what future needs and concerns should be addressed regarding renewable energy incentives. Some identified other policy changes that could greatly aid the diffusion of wood pellet heating innovation:

> *"I see the customer will [adopt] if oil and energy prices are high enough to definitely make some big gains, right? I'm talking very kind of incremental gains. But, to have a big transitional way, I think it has to happen primarily at the policy level. And that can be carbon taxes or taxes on fossil fuels or bigger subsidies on products like this."*

Several participants observed that policy incentives coming from the state level need federal support. These interviews were collected prior to the development of the Wood and Pellet Heater Investment Tax Credit which begins in 2021 but expires in 2023.

> *"These states will grow weary of providing subsidies. And they'll want to put their money in other areas that are showing greater promise or potential for real market growth and development. That's a problem."*

> *"The states are delivering all the rebate incentives for stoves and boilers, but nothing is happening at the federal level. And then, even at the state level, it is nothing like they do with these other energy technologies."*

Interviewees consistently agreed that improved policy incentives or subsidies would improve market conditions and the future viability of their renewable innovation, and some indicated that improved incentives would be vital for continued innovation and diffusion.

> *"You get better at supply chain when you have more demand for your produce and services. That's what forces innovation and delivery of services. It creates competition, price competition. It gets more companies into the market. Good ones get better and bad ones don't survive. Those dynamics really aren't in play right now. So, all the factors that push a sector to get better are not at play to the same extent that they were a few years ago because of the market."*

5.2.4. The Role of Oil Prices

Not surprisingly, industry leaders reported being impacted by the oil price decline that began in 2014; however, they differed in their perceptions of how long the impact would last and what the future market conditions would be like as a result. All participants reported decreased sales following the decline of oil prices in 2014. Participants from bulk delivery companies commented on a similar trajectory of booming business when oil prices were high and reduced sales after the oil price decline. The two bulk delivery companies that entered the market earlier recovered more quickly from the oil price decline. One pellet delivery company commented, *"Last year, there was a lot more burning oil. This year, some came back on the pellets."* Another bulk delivery company manager reported, *"We've had probably the best first quarter sales year I've ever had. Part of that is just becoming established, and the equipment is starting to become more common and ordinary."* It was more challenging for companies who entered the bulk delivery market more recently. One participant described winter 2015 as being *"disastrous."* He added that winter 2016 brought marginally better sales but the business was still not profitable.

While oil price declines proved to be tough competition for the wood pellet industry, some producers indicated that overall weather and climate have a more direct impact on market viability than the stability or current status of oil prices. Most pellet mill managers attributed the weak wood pellet market from 2015 to 2017 to warm winter weather. A participant mentioned that the weather cut the market in half.

> *"Well, the number one factor that affected the softness of the market status is weather. I think low oil prices is going to have a 10% impact, where the weather has a 90% impact on the market."*

Oil price falls accelerated the economic impacts brought by winter weather and formed a perfect sequence of events for pellet sales and manufacturers.

The equipment firms and bulk delivery companies were key change agents in promoting automated pellet heating technologies. However, the oil price decline impeded their ability to continuously promote the diffusion through marketing and education, seek policy support, improve products, and attract and maintain investment. The findings suggest that the oil price decline impacted the diffusion of automated pellet heating technology first by directly influencing the industry players who were key change agents. The following quotes from stakeholders within the industry expressed such concerns:

> *"And right now, there's nothing, basically almost zero education or–and for instance, in our business, we can't even break even–we're not making a profit, we're losing money and business right now. So, there's zero dollars for advertisement."*

> *"When you have a stagnant and soft market, the resources of any company and then even the interest at the political level, it's just not there."*

> *"From the investment we made, what's our return? Right now, I don't think there's much return on any of them. I think the growth is going to be limited until that changes."*

While this concern was stated throughout interviews, many participants also countered that they believed consumers remember past oil price fluctuations and understand the natural volatility of the oil market.

> *"Once it [oil prices] stabilized, I think we go back to our normal mindset of, "I don't want to burn oil." The conception that it's not cheap is still there. It may be cheap at the moment. Nobody goes 'well we're going to have cheap oil for 10 years now'."*

6. Discussion

This case study examined the ongoing innovation diffusion process of automated pelleting heating technology in the northeastern U.S. from the perspective of the region's industry leaders. While there was agreement that this technology was undergoing a slow diffusion process, industry leaders had differing perceptions of the potential of automated wood pellet heating technology to achieve critical mass or simply establish a more sustainable and consistent market. Critical mass has been established within the diffusions of innovations literature to be key to achieving sustainable take-off of an innovation [7]. Some producers believed that achieving critical mass was possible in the near future due to the abundant wood supply in the Northeast and to the particular values that consumers held regarding using wood products or combatting climate change by reducing oil consumption. Others indicated that achieving critical mass would not be feasible due to the technology's high entrance cost for both producers and consumers, with the current affordability of oil heating being a major barrier for consumers to switch. Skjevrak and Sopha [36] echo this finding that affordability is one of the largest barriers for potential early adopters of wood pellet technology. They also found that reliability of the technology was a major barrier, a finding not reflected by our industry leaders. Some industry leaders, however, felt that the affordability of oil was less important than the role of climate and weather on winter conditions and the need for heat. There was also a conveyed sense by the industry leaders that consumers held a general understanding of the volatility of oil prices and market fluctuations, and that it is not a permanently cheap fuel source.

Interview participants highlighted that consumers appreciated the perception of the wood burning experience as a relative advantage versus burning oil. The technological innovation of automated pellet heating is also compatible with consumer identity preferences in the region for wood heating based on regional wood supply and a desire to support local rural economies, which ties back into regional and place-based identities. The economic benefits of automated pellet heating rely mostly on long-term payback through stable pellet fuel prices. The oil price decline significantly reduced such payback. Participants disagreed on how the advantages of the technology and its compatibility with regional values influenced individual decision-making regarding the innovation. Some believed economic considerations dominated individual decisions while others maintained that preferences for wood heat or regionally sourced products (place-based identity) could overcome economic barriers and that consumers generally understood the volatility of oil prices. Both of these assumptions can be true based on variances in consumer values, socio-economic status, purchasing behavior, and situational context. The more pressing question is what percentage of people in the population follow certain decision-making rules and under what conditions might they change them (i.e., how many would be willing to switch from oil to wood pellet heating). Future research should continue to explore the role that place-based or value-based identities play in consumer decision-making, particularly as it applies to renewable energy adoption.

Contradicting beliefs among industry leaders regarding critical mass could potentially undermine the progress of wood pellet systems towards reaching critical mass by weakening public perception that widespread adoption of automated wood pellet heating technology is inevitable [7,37]. In this regard, perceptions held by producers themselves could be potential barriers to achieving critical mass or continued diffusion through the market. Consistent messaging is needed from all levels of producers focusing on agreed relative advantages of residential wood pellet heating: long-term affordability of wood heat, the volatility of oil prices, supporting local markets, and combating climate change through reduced fossil fuel use, would go a long way to achieving a more sustainable diffusion process.

Future research is needed to address the complex decision-making process of homeowners in choosing among home heating options, as past research indicates that the decision-making factors used by homeowners at one stage (e.g., early adopters) are different from the factors that motivate behavior at later innovation diffusion stages [14]. The industry may be particularly interested in whether the preference-driven group, those who prefer wood heat over other types of heat, is large enough for automated pellet heating to reach critical mass and transition into a self-sustained growth stage or if there are other values, such as ones related to climate change, that will stir motivation to purchase this technology. Future research should also seek to more clearly define the economic relationship between external factors such as oil price with the long-term growth of residential wood pellet heating technology. Future studies could also compare perceptions of consumer adoption behaviors by industry leaders to the actual beliefs of consumers. This would provide valuable insight into potential gaps between the consumer decision-making process and the perceptions of consumer beliefs and expectations held by industry leaders. Presently, there have been few studies that explore both industry and consumer perceptions of wood pellet technology, and those that exist are focused on economic and policy barriers rather than the consumer decision-making process [38].

Our findings have implications for those involved in renewable energy policy, especially state-level policy makers and renewable energy industry leaders. Our study confirmed several challenges and barriers in renewable energy diffusion and transition. Policymakers, in their decision making, need to take into consideration the time needed for a technology to take off and the likelihood of unexpected external disturbances or large policy shifts affecting that take off. The recent re-entrance of the U.S. into the Paris agreement will have yet undetermined effects on the wood pellet industry, but the policy could expand the exporting demand of the industry in the Northeast. Future studies could provide valuable insight into the role that broad climate policies like the Paris Climate Accord have on consumer decision-making and renewable energy adoption. Policy makers have been found to face a "lock-in" effect with existing technology, waiting for proven examples of success before considering replacement of outdated infrastructure [39–41].

This can be difficult for innovations that have slow and long periods of initial adoption and take-off. Supplementing the natural diffusion process with incentives such as state or federal rebate programs can help catalyze the take-off of a diffusion, especially one that shows signs of a slow start. Given the uncertainty that both producers and consumers feel about the future growth of the industry, it could remain stagnant without increased state and federal incentives. Increased incentive programs can alleviate financial barriers for both producers and potential future adopters, while also increasing the saliency of the technology as an individual method of reducing household carbon emissions. It is both tempting and dangerous to rely on immediate market conditions such as low oil prices to judge whether an innovation is worth investing in from a policy or incentive perspective. Policy makers could support the energy transition diffusion, specifically of automated wood pellet heating, in other ways. For example, programs could be designed to help train technicians and contractors in automated pellet heating system installation and troubleshooting. Participants mentioned carbon taxes or taxes on fossil fuels as being essential for achieving widespread adoption of their innovation. For industry practitioners, it is important to keep in mind that despite the challenges, slow diffusion does allow more time to improve product quality and customer service, making for a stronger industry in the long run.

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